

PETER COOK CENTRE

FOR CARBON CAPTURE & STORAGE RESEARCH

2013 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: Postgraduate student David Danaci is assembling the sample chamber of the Rubotherm magnetic suspension balance. The apparatus is used to determine the carbon dioxide and methane uptakes at high pressures. This information is required in order to ascertain whether a given adsorbent is suitable for carbon dioxide capture from natural gas sources.

Image supplied by the CO2CRC

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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 in two main programs which have significant overlap. The Capture Program is focused on the development of technologies to capture CO₂ from a range of industrial sources and to look at opportunities to utilise that CO₂. We are particularly focused on reducing the cost and environmental impact of CO₂ 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 CO₂ 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 our first year we have concentrated on the growth of expertise in the storage area, with Professor Ralf Haese coming on board with expertise in the geochemistry of subsurface structures. Ralf joins Dr John Moreau who works in geomicrobiology and a soon to be appointed reservoir engineer. The storage group joins an already strong and well-recognised group in the capture area consisting of myself, working in solvent systems, Professor Sandra Kentish in membranes, Professor Paul Webley in adsorbents and Professor Greg Qiao developing materials that underpin many of these areas.

One of the highlights this year has been the building and operation of two pilot plants, one at 20kg per day and one at 1 tonne per day scale, to demonstrate the post combustion capture of CO₂ from a coal fired power station using a precipitating carbonate systems. This system offers significant economic and environmental advantages over the traditional amine based processes, but also introduces some new challenges around the use of precipitating systems and the incorporation of promoters.

We are now completing a series of trials in the 1TPD pilot scale plant sponsored by ANLEC and BCIA to investigate the application of this technology in an industrial environment. This has been an exciting and interesting project that has generated a range of important learnings and a group of well trained and experienced engineers with experience in this technology.

Centre Performance Highlights

In our first year of operation we have published 17 articles in peer reviewed journals and one refereed conference publication.

Our researchers have a high profile at national and international conferences on carbon capture and storage with over 70 presentations at conferences, three of these were Key Notes and Plenary Lectures and 11 invited presentations.

Education and Training

In 2013 we had 13 postgraduate students and 14 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.

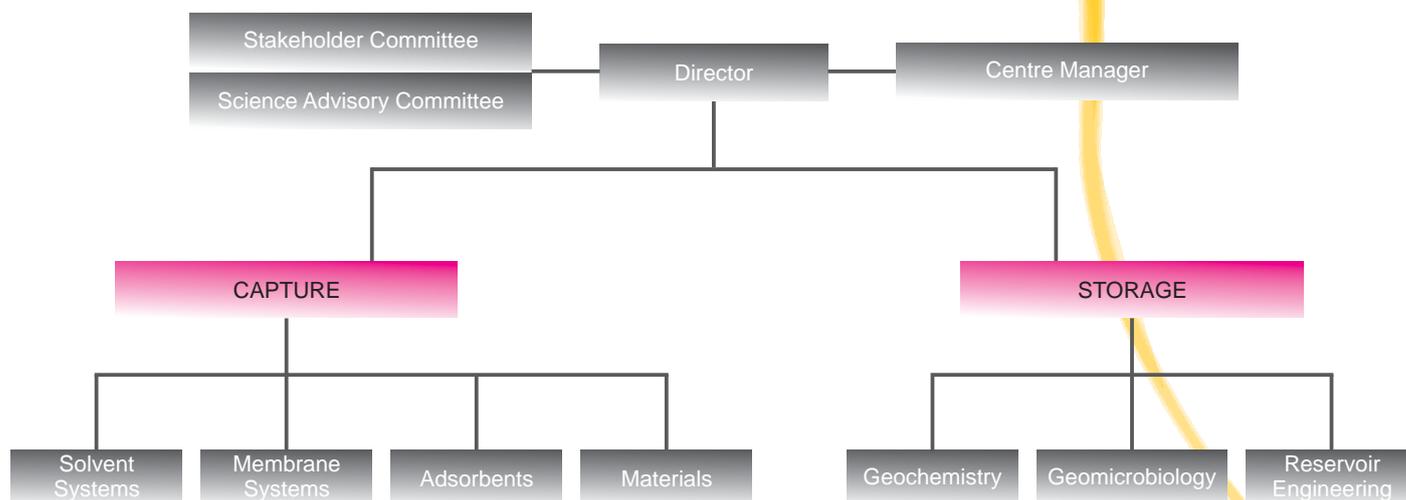
On behalf of the members of the Peter Cook Centre for CCS Research, I would like to thank the University of Melbourne, the CO2CRC, the State Government of Victoria and Rio Tinto for their financial support and valuable input to our Stakeholder Committee and Science Advisory Committee.

Professor Geoff Stevens
Director



Centre Director Geoff Stevens (right) with Dr William Lum on the day of his PhD completion.

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)
The 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, The Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Jon Davis
Chief Advisor, Energy and Climate Technology
Rio Tinto, Australia

Professor Janet Hergt (until June 2013)
Head, School of Earth Sciences
The University of Melbourne, Australia

Mr John Krbaleski (from November 2013)
Director, Energy Technology and Innovation
Department of State Development, Business and Innovation, Australia

Professor David Phillips (from July 2013)
Head, School of Earth Sciences
The University of Melbourne, Australia

Dr Peter Redlich (until October 2013)
Director, Energy Technology and Innovation
Department of Primary Industries, Australia

Invited attendees:

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

Dr Michelle de Silva, Manager (Committee Secretary; from April 2013)
The Peter Cook Centre for CCS Research
The University of Melbourne, Australia

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

Dr Julie-Anne White, Manager (Committee Secretary; until March 2013)
The Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Science Advisory Committee

The Science Advisory Committee (SAC) is an expert panel providing overarching advice on storage and capture research programmes, 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)
The Peter Cook Centre for Carbon Capture and Storage Research
The University of Melbourne, Australia

Professor John Burgess
Principal
Niche Tasks, Australia

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

Dr Jon Davis
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

Invited attendees:

Professor Geoff Stevens, Director
The Peter Cook Centre for Carbon Capture and Storage Research
The University of Melbourne, Australia

Dr Michelle de Silva, Manager (Committee Secretary)
The Peter Cook Centre for Carbon Capture and Storage Research
The University of Melbourne, Australia

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

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

Research within the Peter Cook Centre for CCS Research is divided into two programs:

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: To be appointed in 2014

Centre Manager

Dr Michelle de Silva (from April 2013)

Dr Julie-Anne White (until March 2013)

Centre Researchers

Research Scientists and Engineers

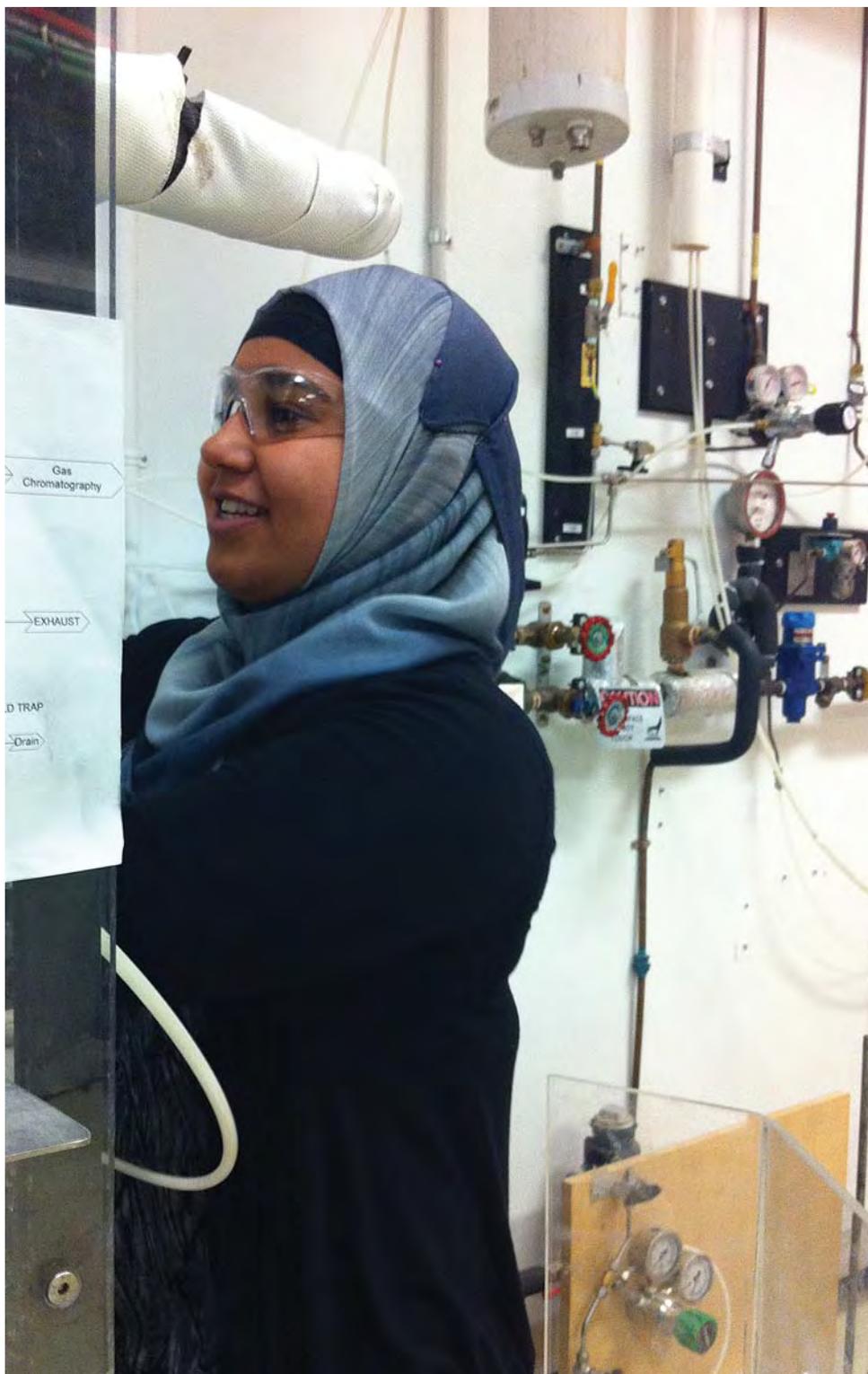
Dr Jay Black
Dr Gabe da Silva
Dr Qiang Fu
Dr Paul Gurr
Dr Shinji Kanehashi
Dr Andrew Lee
Dr Sang Yun (Andrew) Lee
Dr Josephine Lim
Dr William Lum
Dr Kathryn Mumford
Dr Nathan Nicholas
Dr Berkay Ozcelik
Dr Rackel San Nicolas
Dr Colin Scholes
Dr Jin (Eric) Shang
Dr Ranjeet Singh
Dr Kathryn Smith
Dr Shu Wang
Dr James Xiao
Dr Penny Xiao

Research Assistants

Ms Alita Aguiar
Mr Jeffri Gouw
Mr Indrawan Indrawan
Mr Navin Thanumurthy

Postgraduate Students

Mr Khalid Alharthi
Ms Hirra Azher
Ms Robyn Cuthbertson
Mr David Danaci
Mr Andri Halim
Mr Jingung Kim
Mr Brian Maring
Mr Nouman Mirza
Mr Andre Mu
Mr Augustine Ntiamoah
Mr Joel Scofield
Mr Willie Tang
Mr Hendy Thee



Postgraduate student Hirra Azher

CAPTURE PROGRAM

The Capture Program's primary aim is to reduce the cost of carbon dioxide (CO₂) capture from a range of sources including coal and gas fired power stations, from steel and cement production, as well as removal of CO₂ 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 CO₂ and have a portfolio of projects examining utilisation strategies.

The program is focused around three 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

The major focus of the research in the solvent program is to develop low cost, environmentally acceptable capture processes based around absorption of CO₂ into liquids. The last year has focused on the development and demonstration of a carbonate precipitating solvent system at a laboratory scale (20 kg/day) and a pilot (1 T/day) scale. This work which was co-funded with the CO2CRC, ANLEC and BCIA and we envisage that the commercialisation of the outcomes will take place through a separate company ,UNOTECH, in 2014. This promoted carbonate system has been developed for the separation of CO₂ from flue gas from a

brown coal fired power station. The technology has been shown to be prospective, offering potential energy and capital cost savings over alternatives.

In order to compare a range of potential processes for a given operation, more robust and accurate tools are needed. For example, a robust rate based simulation of absorption and stripping is still not available for anything except MEA absorbents running at standard pressures and temperatures. Thus we are running a series of the projects to develop better thermodynamic and process models for these systems, particularly mixed solvent

systems.

A second series of programs are examining the application of a range of new emerging solvents and equipment. Including, for example, the use deep eutectic solvents which offer the potential of significant energy reduction with minimal environmental impact.

Project Updates

Rate based modelling of precipitating absorption columns
Robyn Cuthbertson, Kathryn Mumford, Geoff Stevens, Sandra Kentish
Absorption processes have traditionally been modelled by assuming vapour and liquid phases



Research assistant Indrawan Indrawan

Photograph credit: CO2CRC

are in equilibrium at each stage of the column. While this can be an effective model, systems that involve slow reactions can be far from equilibrium conditions. For these rate-controlled processes, a more rigorous methodology is required. Rate-based models assume equilibrium only at the gas-liquid interface and solve the mass and energy balances for each phase separately.

Aspen has recently incorporated a rate-based separation model into Aspen Plus, providing a valuable tool for rate-controlled process simulation of gas-liquid systems. Aspen does not yet include solids in its rate-based absorption unit due to the computational complexity of the precipitation process and the lack of a well-established mechanism. Precipitating systems must therefore continue to be modelled using the traditional equilibrium-method.

The purpose of this work is to develop a rate-based precipitating absorber model which can be incorporated into a full plant design. This is expected to improve the accuracy of optimisation studies and scale-up simulations of solvent carbon capture plants which incorporate precipitating absorbers.

The vapour-liquid equilibrium of potassium carbonate absorption processes
Andrew Lee, Sandra Kentish, Geoff Stevens
The removal of carbon dioxide from the flue gases of fossil fuel fired power plants has received significant interest in recent years due to rising concerns about greenhouse gases and global warming. One option being considered for the removal of carbon dioxide from flue gas stream is by chemical absorption into potassium carbonate solutions. The use of potassium carbonate has a number of advantages over alternative chemical absorbents (typically alkanolamines) such as higher absorption capacity, reduced corrosion, lower volatility and lower cost. However, the absorption rate of potassium carbonate solutions is significantly lower than that of alkanolamines, which has prompted research into the use of additives to increase the rate of absorption. Whilst significant effort has gone into studying the effects of rate promoters on the absorption kinetics of potassium carbonate solutions, few researchers

have studied the effects of these additives on the vapour-liquid equilibrium of these systems. The vapour-liquid equilibrium of carbon dioxide in promoted potassium carbonate solutions is being tested across a range of industrially relevant conditions using both static and semi-static approaches.

The use of deep eutectic solvents for CO₂ capture

Nathan Nicholas, Gabriel da Silva, Geoff Stevens

As the release of carbon dioxide into the atmosphere becomes an increasing global concern more research is being devoted to selectively removing CO₂ from industrial exhaust streams in an economical manner. At present aqueous amine based solvents are used but they have significant drawbacks, such as high volatility and the high heat capacity of water. To overcome these limitations a new generation of waterless solvents (such as ionic liquids) are being investigated.

Deep eutectics are a novel class of solvents comprised of two or more solid salts that, when combined in a certain molar ratio, form a eutectic mixture with a melting point significantly lower than either base component. These solvents are regarded as being 'ionic liquid like' and share many similar properties. However, eutectic solvents are easier to synthesise and can be produced from common biological molecules (such as choline chloride, urea and sugars) making them a greener alternative to ionic liquids. This project focuses on evaluating the suitability of current eutectic solvents, as well as developing tailored eutectic solvents, for use in CO₂ capture.

Performance and sustainability study of use of low-CO₂ concrete and linings for large scale CCS equipment

Rackel San Nicolas, Geoff Stevens
Geopolymer concretes, as a high-performance, low-CO₂ class of construction material synthesised from coal combustion by-products (in particular fly ash), provide very appealing synergies with a CCS plant associated with a coal-fired power station. The study in this area, towards the use of geopolymer as a construction

material has shown that geopolymer concretes provide structural rigidity and strength higher than other concretes for the solvent columns, but require a protective layer (either stainless steel or polymeric) to preserve the geopolymer concrete from the corrosive solvent. The two main points of this study are: the performance of the protected system against the aggressive solvent solution, and the stability of the system against high temperature exposure for extended periods of time, including temperature cycling effects when the column is started up or shut down. The stability of the bonding zone between the protective layer and the concrete will be specifically analysed, completed by the study of the thermal expansion properties of the layer along with the concrete as the equipment is heated and cooled. Different lining options are being tested, either a direct coating option with different resins (reinforced epoxy, polyurethane or silane-based resins), or rigid protective layers (steel or polyurethane liners).

The kinetics of potassium carbonate solvent absorption processes
Hendy Thee, Nathan Nicholas, Gabriel da Silva, Sandra Kentish, Geoff Stevens
Aqueous potassium carbonate has gained a widespread acceptance as a viable solvent for pre- and post-combustion carbon capture. In comparison to the benchmark industrial solvent for carbon dioxide absorption, monoethanolamine (MEA), potassium carbonate processes require less energy as the heat of absorption is 37% that of MEA. Furthermore, MEA degrades at high temperatures as well as in the presence of oxygen, forms corrosive and toxic organic products, and requires pre-treatment processes for sulphur dioxide removal. Despite its immunity to these constraints, a key limitation for a carbonate based solvent is the slow rate of reaction with CO₂. One way to overcome this problem is to blend the solvent with a promoter. Using a wetted-wall column and a stopped-flow device, the performance of promoters such as boric acid, amines, enzymes, amino acids and sulphates under industrial carbon capture conditions is being investigated. Developing a non-toxic and affordable promoter will facilitate the use of K₂CO₃ solvent systems for CO₂ capture.

Membrane Systems



Dr Josephine Lim (left) with postgraduate student Qi Zheng.

During this year we successfully tested a commercial nanofiltration membrane from Dow Chemicals on the Hazelwood rig. This builds on our prior work that has shown that such a membrane has potential to capture carbon dioxide in a facilitated transport mode from post combustion streams. The particular advantage in this case is the use of a membrane that is readily available commercially, thus bypassing the time consuming and expensive steps involved in taking a 'research scale' membrane to this level. The membrane performed well, but not at a sufficiently high permeability/selectivity to warrant further development.

In work related to natural gas systems, we completed a number of experiments to determine the effect of water vapour on cellulose acetate membrane performance. We are also completing work on the effects of impurities on perfluorocarbon membranes such as amorphous Teflon. While such membranes are more expensive, they are ideal for stranded gas applications where pretreatment needs to be minimised.

Within an ANLEC project, we have evaluated the potential for both nanofiltration and electrodialysis to recover amine salts from MEA solutions, using aged solvent provided from CSIRO from their Loy

Yang trials. Electrodialysis was able to remove up to 90% of the charged salts, but nanofiltration was less successful.

We are continuing our work on the use of metal organic framework (MOF) materials, sponsored by the Science and Industry Endowment Fund (SIEF), with a number of mixed matrix membranes evaluated that contain these materials.

Several PhD projects continue:

- a) Hirra Azher is examining the effectiveness of a range of membranes for removal and recovery of water from brown coal flue gases at elevated temperatures (BCIA sponsored)
- b) Khalid Alharthi is investigating the impact of fly ash on membrane performance
- c) Joel Yong has successfully coated carbonic anhydrase to a hollow fibre membrane using layer-by-layer techniques, for use in a membrane contactor format.
- d) Qi Zheng is evaluating the use of membrane technology to facilitate the delivery of carbon dioxide to microalgal ponds in a manner that reduces the net costs of both carbon capture and algal growth.

Project Updates

Development of novel mixed matrix membranes for CO₂ capture
Shinji Kanehashi, Berkay Ozcelik, Sandra Kentish

Recent interest in environmental problems is focused on global warming induced by carbon dioxide (CO₂) emissions from large fixed sources such as power plants and iron foundries. Membrane-based CO₂ 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. Preliminary results with MMMs containing mesoporous carbon nanoparticles show enhanced gas permeability with no loss in selectivity. We are investigating this interesting result in terms of membrane morphology and physical properties.

In addition, we aim to fabricate thin film nanocomposite (TFN) membranes by interfacial polymerization (IP). Originally, IP technology has been applied to the fabrication of reverse

osmosis or nanofiltration membranes for water treatment. In this work, thin polyamide layers (around 100 nm) containing nanoparticles will be fabricated by IP and their gas separation performance under both dry and wet conditions will be examined.

Fabrication of ultra-thin film composite membranes via CAP-ATRP for CO₂ capture
Jinguk Kim, Qiang Fu, Sandra Kentish, Greg Qiao

Composite membranes consisting of a thin selective top layer supported by a non-selective porous substrate have been shown to provide significant permeability as well as high selectivity for gas separation. Gas molecules of interest are selectively separated through the top layer and the intermediate gutter layer makes the surface smooth to allow deposition of the thin selective layer. In addition, fabrication of ultra-thin films is being considered to enhance the gas permeation rate and to reduce the membrane fabrication cost. In order to fabricate the ultra-thin defect-free films, a macrocross-linker including polar groups such as ether oxygens of ethyl ether with polymerisable pendants was synthesised. The synthesised macrocross-linker was coated on a gutter layer made of bromo functionalised poly(dimethylsiloxane) deposited onto a microporous support. The kinetic profile of the thin film growth from the planar substrate showed asymptotic growth with a different polymerisation time. To control further film growth, thin films can be reinitiated, leading to the formation of thicker polymer films consisting of the same or a different macrocross-linker. The experimental results show controllable deposition of the ultra-thin film at the nano-scale and the possibility of ultra-thin film composite membranes for CO₂ separation.

Purification of MEA solutions using nanofiltration and electro dialysis
Josephine Lim, Alita Aguiar, Colin Scholes, Sandra Kentish, Geoff Stevens
Monoethanolamine (MEA) is commonly used in natural gas sweetening to selectively absorb CO₂ from a mixed gas stream. It has high CO₂ 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 SO₂ and NO₂) 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 electro dialysis as an *in situ* treatment of degraded MEA solution was investigated. The results show that nanofiltration can be used to obtain 90% HSS removal using KOCH SelRO® MPF-34 membranes. High HSS removal can also be achieved by electro dialysis, when operated in a batch mode. However, the extent of the removal in a continuous mode operation was found to be related to a number of factors such as the applied current density and the effective membrane area.

Development of novel polymeric membranes for CO₂ capture

Joel Scofield, Sandra Kentish, Greg Qiao
The efficiency of CO₂ separation from other light gases, such as nitrogen, may be improved through the development of new and modified materials. Models which can predict gas separation performance can assist in the implementation of membrane technology on a large scale while providing an interface between material selection and performance. Initial modelling studies focused on applying equations of state, specific to long chain polymers, to simple materials which possess good separation performance and compare the performance with other models.

One class of membrane materials which show good separation performance are block copolymers, in particular those containing polyether segments, due to the favourable interactions between CO₂ and the ether moieties. Incorporation of a highly permeable material into the copolymer is expected to increase the permeability whilst maintaining the selectivity. Block copolymers have been shown to self-assemble into a variety of structures which may lead to improvements in gas transport properties. Previous work has demonstrated the influence of morphology on gas separation for systems containing crystalline and permeable blocks. This work will investigate the impact self-assembly has on the gas performance of a permeable and selective block copolymer.

Membrane pilot plants for CO₂ 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 CO₂ 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 CO₂ separation
Colin Scholes, Sandra Kentish, Geoff Stevens
Membrane gas-solvent contactors are a hybrid technology that use solvent absorption to capture CO₂, 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 revolutionize solvent absorption processes for both absorption and desorption. The key is development of the membrane material that can ensure a high CO₂ mass transfer to minimize 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 CO₂ flux.

Mixed gas and vapor 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 CO₂ separation performance for most membranes due to the presence of competitive sorption. If vapors 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 vapors can also lead to swelling or plasticization of the membrane and ultimately membrane failure. Understanding and modeling 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.

Adsorbent Systems

This research program has two major components: (a) development and testing of processes for CO₂ capture from post-combustion flue gas and (b) development and testing of materials and processes for CO₂ capture from natural gas streams.

Program (a) is focusing on two distinct process options for CO₂ capture based on the mode of regeneration of the adsorbent: vacuum swing adsorption (VSA) and temperature swing adsorption (TSA). In vacuum swing adsorption, we have developed and tested process cycles based on a physisorbent, 13X zeolite, to produce a stream of >90% CO₂ purity from a wet flue gas stream. Our major challenge is to avoid the deep vacuum levels required (<10kPa) to regenerate the adsorbent. The research required to achieve this relates to more sophisticated cycle development as well as modifications to the material. To accomplish this, two PhD students, Augustine Ntiamoah, and Jianhua Ling are working under the supervision of postdoctoral fellow Dr Penny Xiao, using our newly constructed 4bed pressure swing apparatus to develop and test new processes.

In our temperature swing adsorption (TSA) program, we have developed novel cycles and a simulation tool to help us evaluate the potential of these processes. Brian Maring, a PhD student working on simulation tools for adsorbent evaluation, has developed and assessed several new TSA cycles for CO₂ capture while Jianhua Ling and Augustine Ntiamoah has tested cycles in the laboratory. We have performed temperature swing testing of zeolite NaUSY between 100 and 200°C and achieved purities of 95% CO₂ with low regeneration energy. In the immediate future we plan to test chemisorbent polyethyleneimide (PEI) at temperatures from 90 to 140 C which can potentially use waste heat for regeneration.

Program (b) is focusing on materials and processes for CO₂ capture from natural gas. The main challenge is to capture CO₂ at the high well-head pressures without co-adsorbing methane which would subsequently be lost in the desorption step. To this end, we have developed "trapdoor" zeolite materials which exclusively adsorb CO₂ and completely block methane. This year we have synthesized sufficient batches of this material to test in our lab apparatus with good results. Postdoctoral fellow, Dr Jin Shang has focused on LTA zeolite for this application. The rates of

adsorption are slow however and we are now focusing on increasing the adsorption kinetics. Postdoctoral fellow Dr Ranjeet Singh and PhD student David Danaci are currently developing modified chabazite adsorbents with faster kinetics to overcome these problems. We have also developed new process cycles to minimize methane loss and these cycles are being tested in our high pressure PSA apparatus using NaUSY zeolite.

Project Updates

CO₂ capture from natural gas: Development of adsorbents and accompanying processes David Danaci, Ranjeet Singh, Penny Xiao, Paul Webley

There are some natural gas sources with high CO₂ content, and it is deemed uneconomical to purify these gases using the conventional amine scrubbing process. Adsorption, more specifically, pressure swing adsorption (PSA) can be a feasible alternative, as the energy requirements for the process are much lower in comparison. The challenge, however, is that separation must be carried out at high pressure in order to maintain the pressure of the natural gas for transport and processing.

At low pressures, the CO₂ loading on the adsorbent becomes saturated and there is insignificant methane loading. As you increase the pressure, the methane loading increases, and can become quite significant at high pressures. Hence, these kinds of 'equilibrium separation' adsorbents are not suitable for high pressure separations as the product gases are not able to reach the required purity.

This project aims is to investigate the other two mechanisms of adsorption, kinetic separation and molecular sieving. These alternatives are less prone to increased methane uptake, and the latter has zero methane uptake. There is limited work currently available in the literature on these methods, especially for natural gas separations and it is the aim of this work to identify suitable kinetic or molecular sieving materials that can be used to separate the CO₂ from natural gas and then develop a suitable PSA process to undertake this separation.

CO₂ capture from wet flue gas using a modified activated carbon as adsorbent Jianhua Ling, Penny Xiao, Ranjeet Singh, David Danaci, Augustine Ntiamoah, Paul Webley

Activated carbon is found to be a promising adsorbent for direct flue gas CO₂ capture applications because of its relatively low cost and hydrophobic nature. However, the selectivity of CO₂ over N₂ is much lower, leading to lower purity of the CO₂ product. This project is focused on the synthesis and testing of a "modified activated carbon" through the incorporation of

new functional groups to enhance the CO₂ selectivity and hydrophobic properties of the material.

A new simple PSA/VSA model and adsorbent screening methodology

Brian Maring, Paul Webley

There are hundreds of adsorbents proposed for pressure/vacuum swing adsorption (PSA/VSA) CO₂ capture applications, however, there is still no widely accepted benchmark for adsorbent comparison. Materials are generally first synthesized at small scales at which isotherm measurements can be taken but are insufficient to perform laboratory scale PSA/VSA experiments, making process simulations very important in the evaluation of new materials. Although detailed adsorption simulation software packages are available, they run very slowly, have many input variables, and require expert users. Because of these computational difficulties, researchers often resort to crude isotherm analysis which is overly simplistic and can be misleading.

We have developed a new simple PSA/VSA model which we use to rapidly screen materials. Our model dramatically reduces the complexity and number of input parameters required for a PSA/VSA simulation while still capturing important trends and approximating experimental data. The model can also be used to determine optimal process conditions for a given separation and to identify the material properties most important for improving process performance.

Development of optimal adsorption cycles for carbon dioxide capture from flue gases Augustine Ntiamoah, Penny Xiao, Brian Maring, Paul Webley

Much of the consumer energy needs of the world are met from the combustion of coal and other fossil fuels in power plants, and in the process, large quantities of carbon dioxide (CO₂) are emitted into the atmosphere. With the heightened awareness of the effect of such massive injection of CO₂ on the global climate, efforts are currently being made to improve on various CO₂ capture techniques as remedial options, with commercialization as the ultimate goal. This research is designed to investigate the technical feasibility and cost effectiveness of several new vacuum and temperature swing adsorption cycles for CO₂ capture from post-combustion flue gases. The final objective is to develop an optimal adsorption-based CO₂ capture process that is capable of improved performance compared to current systems.

Advanced adsorbents for gas separations

Jin (Eric) Shang, David Danaci, Frank He, Ranjeet Singh, Penny Xiao, Paul Webley
Efficient purification of natural gas and separation of similar size molecules in gas mixtures is increasingly important in our drive to

develop a more sustainable way of living in an energy-constrained world. Adsorption technology is one of the most promising technologies for gas separation. There are three mechanisms governing the adsorption separation process – equilibrium, kinetic, and steric. All of these mechanisms involve adsorbents which are “passive”. That is, the structure of the adsorbent does not change during the separation process (other than undesirable fouling or sintering). We rely on changes to the gas (temperature, pressure or composition) to adsorb and then desorb molecules of interest giving rise to processes such as temperature swing adsorption (TSA), pressure swing adsorption (PSA) and composition swing adsorption (CSA; more commonly termed elution chromatography) respectively.

The goal of this project is to develop a next generation class of “active” adsorbents to permit highly selective separations of molecules of similar size. A unique “molecular trapdoor” mechanism discovered in our laboratory in 2012 (Journal of the American Chemical Society (2012) 134, 19246-19253) will be investigated and exploited to allow us to develop a better understanding and control of the properties of these adsorbents. The project will focus on molecular-level understanding of the separation mechanism from advanced experimental methods (including synchrotron XRD, PALS, SEM, TEM, BET, NMR, GC, XPS, FT-IR, TGA)

and simulation (including DFT and force field methods) and use this understanding to synthesize, characterize and test these materials for their application in separations of similar size molecules such as natural gas purification amongst other separations.

Synthesis of adsorbents for gas separation
Ranjeet Singh, Paul Webley
Porous adsorbents are extensively studied for their adsorption and separation properties. Recently, capturing carbon dioxide and its subsequent sequestration has gained considerable importance. A number of adsorbents are such as zeolites, activated carbons, metal organic frameworks (MOFs), etc are being examined. Zeolites are microporous aluminosilicates with well-defined three dimensional pore structure that have demonstrated high stability under process conditions. They offer good selectivity for CO₂ over activated carbons and MOFs. Furthermore, depending on the type of gas molecule, the zeolite pore-size can be tuned by changing the inorganic cations, modifying the Si/Al ratio, heat-treatment or by silica deposition. Currently, small pore zeolites such as Chabazite, zeolite A as well as Faujasite are being considered in capturing CO₂ from flue gas and natural gas scenarios. Although zeolites are well studied, their capabilities in gas separation by pore-engineering are not explored exhaustively. Fine

tuning the pore structure to selectively adsorb one gas over another would be a great advantage in gas separation processes.

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

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. Adsorption processes provide a more cost effective and viable alternative for air separation. Currently, nitrogen selective adsorbents are employed for this purpose. As atmospheric air contains four times more nitrogen, oxygen selective adsorbents are sought to further improve the efficiency of adsorption processes.

Metal organic frameworks (MOFs) have received much attention recently due to their high surface areas and flexibility in terms of pore size and functionality. Owing to their similarities to heme groups in haemoglobin, porphyrin molecules are utilised as ligands in the synthesis of a class of MOFs which showed improved oxygen selectivity as well as capacity. Simulation models are also developed to evaluate the performance and suitability of these MOFs for air separation from atmospheric air.



PhD scholar Willie Tang

Photograph credit: CO2CRC

Materials Development



Dr Paul Gurr at the CO2CRC Symposium. Dr Shinji Kanehashi (left) and Hirra Azher (right) can be seen in the background.

The Materials Development team made major technological breakthroughs in 2013. The team focus has been in the design and fabrication of composite membranes with a high performance top separation layer. The breakthrough involves the Continuous Assembly of Polymers (CAP) membrane technology (Australian Provisional Patent Application No. 2013904395), which is specially designed to form ultra-thin surface layers with a thickness of as low as 50 nanometers. The new composite membrane exhibits at least a 3-fold improvement in performance compared to conventional gas membranes. The significance of the CAP membrane design incorporates three fundamental aspects. Firstly, for a high gas flux, a selective membrane layer of less than 100 nm is generally needed with a high crosslinking density. No existing system has the simultaneous thickness control and cross-linking as afforded by the CAP membrane process. In this process the choice of membrane precursors is unlimited and is not restricted by the size of the membrane required. Secondly, most industrial processes for thick film coatings require a very flat surface (such as spin coating for small areas or doctor blade coating). CAP films can be made on curved surfaces while maintaining uniform film thickness. Thirdly, CAP membrane films can be grown on almost any surface, which make the design of the composite membrane versatile.

2013 also saw significant advancements in other design approaches of composite membrane formation. These include the addition of specially synthesized polymer additive (*Journal of Materials Chemistry A*, 2013, 1, 13769-13778) and soft nanoparticles (*Polymer*, 2013, 54, 520-529) to the top separation layer to increase the performance of the membranes. In 2013, one of the membrane team members, Andri Halim, graduated after completing his PhD.

Project Updates

High molecular weight amorphous poly(ethylene oxide)/Pebax® thin film composite membrane for CO₂ 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 CO₂ separation from light gas N₂. The novel multi-block HMA-PEO copolymers ($M_n \approx 10$ kDa) were synthesized *via* condensation polymerization. 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 CO₂ from N₂ 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 CO₂ permeance (*ca.* 1,000 GPU) as a result of the addition of HMA-PEO. Furthermore, the selective layer presented outstanding CO₂ separation properties: CO₂ permeability of 780 Barrer and CO₂ permeance of 2,000 GPU with CO₂/N₂ selectivity of 40. These results surpassed the most recent upper bound and make novel HMA-PEO an attractive additive for advanced CO₂ separation membranes.

Thin-film composite membranes consisting of triblock copolymers for CO₂ 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 CO₂ 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 (TCM's) 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 CO₂ permeability whilst maintaining the relative flow of other gases (CH₄, N₂). We investigated a series of well-defined polymers consisting of chemically and thermally resilient polyimide (PI) linked to flexible and permeable PDMS. TCM's were prepared by spin-coating solutions of these polymers onto PAN/PDMS substrates and their gas performances were determined for five different gases (CO₂, N₂, CH₄, H₂ and O₂). 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. TCM's were successfully prepared using polyimides with increased permeability to CO₂ 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-bromoisobutryl 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 ¹H nuclear magnetic spectroscopy (NMR). The macroinitiator was then chain extended via 'grafting through' of monomethacrylate PDMS with photoactive 2-(methylacryloyloxy)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 ¹H and ¹³C 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.



Professor Ralf Haese (left) with Antonio Ribeiro from Aztec Well Construction.

STORAGE PROGRAM

The Storage Program is focused on developing a deeper understanding of the process of storing CO₂ 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 CO₂ storage sites through the provision of research, technical review and advice. Research and development projects aim to reduce the risks associated with CO₂ storage, for example, by assessing seal integrity, by predicting the dynamics and reactivity of the CO₂ plume and by developing technologies and procedures to improve injectivity, subsurface monitoring options and CO₂ leakage mitigation measures. The CO₂ Storage research team is multidisciplinary with particular strengths in geochemistry, geomicrobiology, numeric modelling of reservoir processes and geophysics including seismic interpretation.

Geochemistry

The Geochemistry Research stream focuses on three major projects involving research support from the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC). Throughout the year, the projects progressed well resulting in the following outcomes.

1. The Reactive Reservoir Rocks project is in its final stage and it is expected that three peer-reviewed publications will be accepted for a special volume in the journal *Chemical Geology*.

2. The project on Geochemical Impacts of CO₂ Storage in Freshwater Aquifers has recently been extended by ANLEC R&D to accommodate software development by Lawrence Berkeley National Laboratory. The new modelling capability will allow us to simulate multiphase coupled reactive-transport involving CO₂ with impurities in the subsurface for the first time.

3. Data and sample collection at a drill site in the Darling Basin (NSW) is currently underway through a project with the NSW government. The data will be used to model fluid-rock reactions under CO₂ storage conditions and to evaluate a new tracer technology to determine the degree of formation water contamination from drill mud.



Dr Jay Black

Project Updates

Mineral dissolution rates under CO₂ storage conditions

Jay Black, Ralf Haese

The modeling of geochemical changes under CO₂ 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. Secondly, the very high CO₂ concentration in a CO₂ storage aquifer poses specific conditions which may inhibit or accelerate mineral dissolution rates. Given these uncertainties, laboratory-based mineral dissolution experiments need to be carried out accounting for CO₂ storage conditions. In the 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 CO₂ 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 modeling geochemical reactions in CO₂ storage aquifers.

Long-term changes in the reservoir mineralogy imposed by different levels of CO₂ – 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 CO₂ 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 CO₂. Gas samples from different sections of the Pretty Hill Formation show a large range of current CO₂ 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 CO₂ over geologic time. Specifically, we have been determining mineralogical and petrophysical changes and compare the observational data to the modelled evolution of the reservoir.

Geochemical impacts and monitoring of CO₂ 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 aims to identify risks and recommend mitigation strategies in relation to CO₂ storage in the freshwater-dominated Surat Basin (Queensland). The results from this project will reduce operational and early investment risks for industry, reduce the risk of public opposition to CO₂ 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 CO₂ in the Precipice Sandstone and the Hutton Sandstone reservoirs;
3. Develop a reactive transport model for CO₂ and impurities (SO_x, NO_x, O₂) determining reactions affecting injectivity and the long-term containment of chemicals; and
4. Determine potential impacts of leakage on overlying freshwater aquifers and develop monitoring indicators.

Geochemistry of CO₂ storage in the Darling Basin (NSW)

Jay Black, Ralf Haese

This project is looking at the formation water composition in the Darling Basin and undertaking geochemical modelling to predict fluid-rock reactions under CO₂ 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 CO₂ storage conditions, however, drill mud frequently contaminates near-wellbore formation water diminishing sample integrity. Here we 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). Our predicted outcomes 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.



Collaborating engineers and scientists at the CO2CRC Otway Subsurface Storage Laboratory in Victoria. From left to right: Eleena Wykes (Geoscience Australia), Dr Jay Black, Janice Trafford (Geoscience Australia), Alison Hortle (CSIRO), Teagan Exposito (Geoscience Australia), Prof Ralf Haese, Dr Linda Stalker (CSIRO).

Geomicrobiology

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. Our research at the Otway CO2CRC site has culminated in a first scientific peer-reviewed publication which will be completed in 2014 with its lead author our PhD student Andre Mu. Research in the Geomicrobiology stream is collaborative, with involvement in the Darling Basement project led through the Geochemistry group. This work will involve microbiological research on sediment core and groundwater samples returned from the Darling Basin drill site.

Project Update

Microbial responses to dense phase CO₂ Andre Mu, Ralf Haese, Timothy Stinear, John Moreau

Subsurface CCS strategies are currently being implemented to reduce CO₂ emissions to the atmosphere. The aim of this study is to determine the effects of dense phase CO₂ 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 *Proetobacterial*

sequences and the apparent decline of *Firmicute*-like sequences post-CO₂ injection suggests possible selective adaptation or recovery to changes in ground water chemistry as a result of CO₂ sequestration. Research efforts are also directed towards investigating the impacts the loss of single carbon cycling genes central to the Acetyl-CoA pathway of the predominant, autotrophic *Firmicute* genus, *Carboxydocella*, has on the physiology of the microbial community. Understanding the impacts of dense phase CO₂ on microbial ecology at the genetic level can provide crucial insights to the formation and regulation of biofilms under CO₂ stress whereby microbial biofilms serve as an intervention option by reducing the porosity at potential leakage sites.

AWARDS & ACHIEVEMENTS

Academic and Research Staff

Dr Kathryn Mumford received the "Best Judged Capture Poster" for her presentation Development of novel solvent systems, *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Dr Nathan Nicholas received the "Best Capture Presentation" for his presentation in the session - CCS New Ways to Make it Happen at the *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Dr Rackel San Nicolas won the Carbon Management Canada (CMC) grant in 2013, supporting an International Exchange Program between graduate students, post-doctoral students or research associates from the three partner organisations: The UK Carbon Capture and Storage Research Centre (UKCCSRC), The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) and The Stanford Centre for Carbon Storage (SCCS) with Canadian academics. She spent three weeks in Quebec, Canada with Professor Guy Mercier and his team in the Institut National de Recherche Scientifique Eau-Terre-Environnement (INRS-Ete).

Dr Kathryn Smith was awarded a 2013 Australia China Emerging Future Leaders in Low Emissions Coal Technology Fellowship to meet with Chinese and Australian experts in low emission coal technology. This fellowship allowed her to attend a strategic workshop and the 7th Australia-China Joint Coordination Group on Clean Coal Technology (JCG) Meeting in Melbourne, 22-23 October.

Kathryn also received the "Best Capture Presentation" for her presentation in the session - CO₂ Capture: Making it Happen at the *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Postgraduate Students

The Eugen Singer Award is given to a University of Melbourne student engaged in the study of polymers including their production and processing. In 2013, Andri Halim was the recipient and used the award, along with a Melbourne Abroad Travelling Scholarship to present his research at *13th Pacific Polymer Conference (PPC 2013)*, Kaohsiung, Taiwan,

17-22 November and to visit the Membrane Laboratory in Hanyang University, Seoul, South Korea.

Jinguk Kim was awarded a student poster prize for his presentation at the *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.

Brian Maring was awarded the Best Demonstrator in Chemical and Biomolecular Engineering Semester 2 2013.

Andre Mu was awarded a competitive travel scholarship for an international exchange program to the University of Calgary by Carbon Management Canada (through the Natural Sciences and Engineering Research Council of Canada; NSERC). The purpose of the exchange program was to conduct research with Dr Gerrit Voordouw, and establish a collaboration between the CO2CRC and Carbon Management Canada. Andre was also awarded the P. J. Adams Graduate Research Award by the Head of the School of Earth Sciences (University of Melbourne)



Dr Kathryn Smith

Academic Promotions

Qiang Fu was promoted to Level B research fellow

University Portfolio Holders

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

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

Sandra Kentish, Head of Department of Chemical and Biomolecular Engineering

Serving the Scientific Community

Conference Contributions

Sandra Kentish
Co-Chair (with Professor Stephen Gray) of *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November

Editorial Board Appointments

Sandra Kentish
Editorial Board Member of *Food Engineering Reviews*, 2008-present

Editorial Board Member of *Recent Patents on Chemical Engineering*, 2007-present

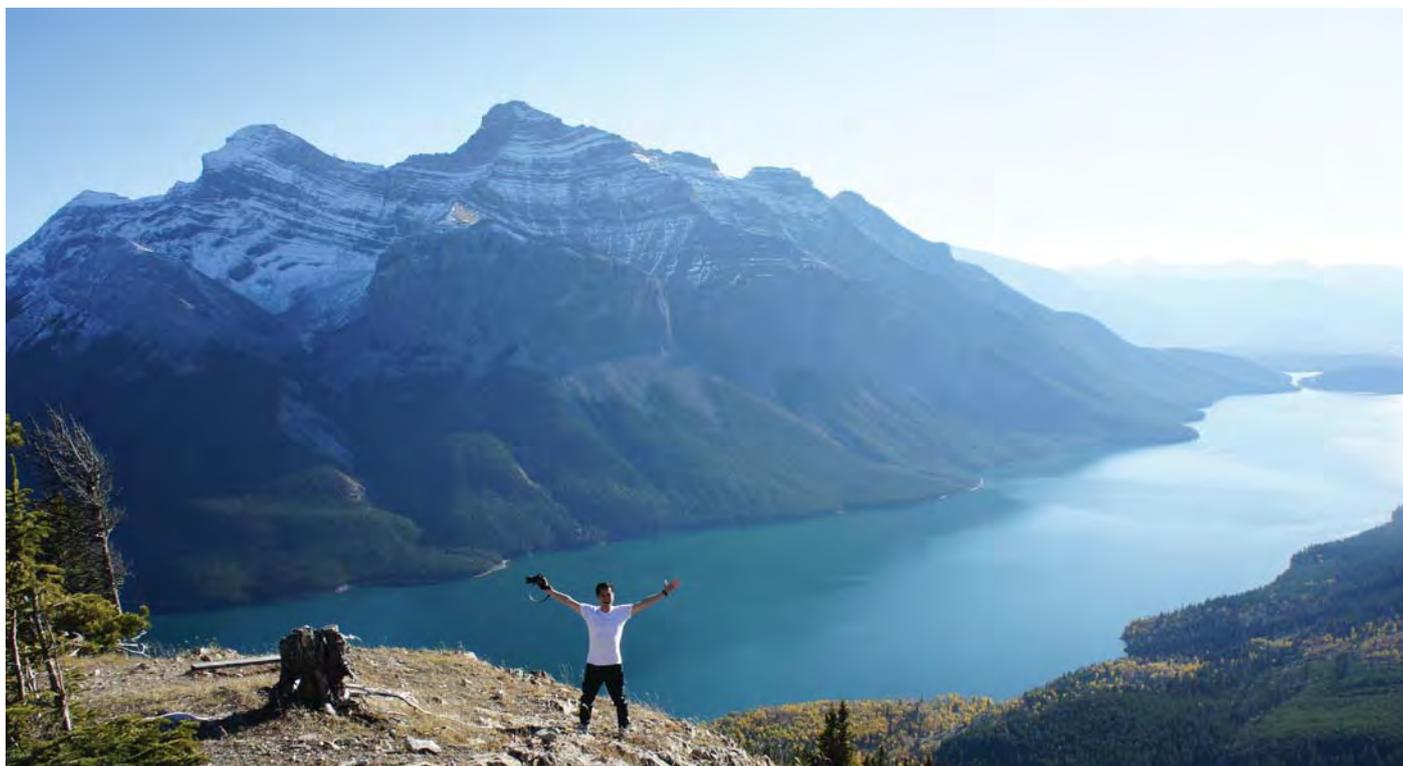
Greg Qiao
Member of the International Advisory Board for *Macromolecular Bioscience* (Wiley)

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

Geoff Stevens
Member of the Editorial Board of the *Chemical Engineering Journal*, 1999-present

Member of the Editorial Board of the international journal *Solvent Extraction and Ion Exchange*, 1996-present

Member of the Editorial Board of the international journal *Hydrometallurgy*, 1994-present



PhD student Andre Mu at Mount Aylmer, Banff National Park, during his exchange visit to the University of Calgary, Canada.

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

Geoff Stevens
International Editor, *Chemical Engineering
Research and Design*, *Transactions of the
IChemE*, 1999-2013

Associate Editor of the international journal
Solvent Extraction and Ion Exchange, 1996-
present

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

Other Roles

Peter Cook
Member, Advisory Board, Saskpower Boundary
Dam Project, Canada

Chair, Securing Australia's Future Working
Group 6 - Engineering energy: unconventional
gas production, The Australian Council of
Learned Academies (ACOLA)

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

Member, Securing Australia's Future Working
Group 6 - Engineering energy: unconventional
gas production, The Australian Council of
Learned Academies (ACOLA)

Rackel San Nicolas is a Committee member on
Alkali Activated Materials (TC 224-AAM) of
*Réunion Internationale des Laboratoires et
Experts des Matériaux*, systèmes de
construction et ouvrages (RILEM), 2013- 2015

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-
present

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 China-Australia Polymer Meeting was part
of the 1st Australia-China Polymer Mission, a
group mission funded by the Australia China
Science and Research Fund, which saw a
delegation of leading Australian polymer
scientists - led by Professor Greg Qiao - visit
key polymer research institutions in China.

The group mission also led to a Special Issue of
the Australian Journal of Chemistry with Greg as
the guest editor

<http://www.publish.csiro.au/pid/7316.htm>.

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 2013.

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, the Peter Cook Centre for CCS Research hosted a workshop in March 2013. Participants from the Chinese Academy of Sciences, Tsinghua University and the National Institute of Clean-and-low-carbon Energy (NICE) travelled to Australia to meet with researchers from the University of Melbourne, the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Zeobond Pty Ltd (developers of environmentally sustainable cement).

This workshop helped to form a strategic alliance between Chinese and Australian researchers in the area of carbon dioxide capture, more particularly, in solvent absorption technologies. There were wide ranging discussions of the most pressing areas for future research in the field to enable the development of the next generation of solvent systems for implementation both in China and Australia. Currently, such systems are low risk but remain energy intensive. The aim is to identify key research avenues to capture carbon dioxide more cost effectively, with greater energy efficiency and with less adverse impact on the environment.

During the three day Workshop the participants from China toured the research facilities at the University of Melbourne. They had discussions with senior members of the CO2CRC, the University of Melbourne, CSIRO and Zeobond Pty Ltd regarding opportunities for joint projects. Formal presentations outlining the work taking

place in China and Australia were delivered to allow participants to gain familiarity with each others' research. There was ample time allowed for informal discussion so that individuals could explore the synergies of their research areas and identify areas of potential collaboration. It also proved a useful forum for the Australian participants to make new networking connections with each other in addition to those with the Chinese researchers.

Australia China Science and Research Fund Group Mission

As a follow up to the JCG Workshop, members of the Peter Cook Centre for CCS Research joined the CO₂ Capture R&D Group Mission to China in June 2013. The mission was sponsored through a grant from the Australian Government's Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education Australia-China Science and Research Fund to the CO2CRC. The mission was led by Prof Dianne Wiley for the CO2CRC. Visits in China were also facilitated through the University of Melbourne/Tsinghua University exchange agreement.

The group mission discussed joint research and development programs with an industrial organisation active in CCS (China Guodian) and cemented links with leading academic institutions in CO₂ Capture: Tsinghua University, Chinese Academy of Sciences, NICE and Northeastern University.

As a result of the mission, project leader Prof Zhai and Prof Wang from Northeastern University visited the Carbon Capture Laboratory of Prof Paul Webley in October 2013. During this visit they sought to understand our capabilities and discussed further collaboration. In addition, a scientific visitor from Northeastern University, Dr Da Jiang visited the University of Melbourne to conduct work on CO₂ capture from December 2013 to February 2014.

It is critical to engage with global leaders in Carbon Capture and Storage to enhance our research capabilities in CCS. China has taken a leading position in this field and relevant industrial and R&D Institutions in China offer



Exploiting the Centre's access to Victoria's state of the art demonstration facilities, the Chinese participants at the JCG Workshop visited the La Trobe Valley to learn about the Hazelwood Capture Facilities and Pilot Plant at Loy Yang.

From left to right: Dr Xinglei Zhao, Prof Jian Chen, Dr Yonglong (Andrew) Li, Prof Geoff Stevens, Prof Weiyang Fei, Dr Guangsheng Luo, Prof Chao Yang



Members of the Peter Cook Centre Capture Program joined the ACSRF Group Mission to China. They are shown here visiting China Guodian.

ideal opportunities to both develop and demonstrate capture technologies at a variety of scales. Funding from the Australia China exchange funds through 2013 have certainly aided the Centre's engagement opportunities with leading Chinese CCS researchers which helps us to achieve our goal of delivering the next generation of CCS technologies to Australia, and indeed globally.

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.

In addition one of our early career researchers, Dr Rackel San Nicolas, and one of our postgraduate students, Andre Mu, were successful in obtaining Carbon Management Canada (CMC) international exchange grants to work in Canadian Laboratories (see the Awards and Achievements section for further details).

Engaging with the United Kingdom

Professor Peter Cook undertook a lecture tour around the United Kingdom in September 2013 at the invitation of the UK Carbon Capture and Storage Research Centre (UKCCSRC). He gave a series of presentations on CCS at the Universities of Cambridge, Edinburgh and Nottingham and also to the British Geological Survey.

Engaging with the USA

The Peter Cook Centre served as a host for postgraduate student Christopher Zahasky from Stanford University during his three-month visit to Melbourne. Chris worked on the topic of pressure and fluid composition responses to CO₂ leakage up faults as part of his MSc thesis.

Professor Ralf Haese served as his supervisor and reservoir engineers from CSIRO collaborated on this project through the CO2CRC.

Multi-phase flow simulations were run in order to analyse CO₂ leakage fluxes and leakage plume dimensions under a range of reservoir and fault zone conditions. Detailed pressure and fluid composition analysis was then performed by examining the differences in the upper aquifer zone between the cases when CO₂ and fluid are leaking from the storage reservoir and when there is no leakage from the storage reservoir. Pressure and fluid composition responses are examined as a function of time, distance from fault zone, total leakage plume size and leakage fluxes under different reservoir and fault zone conditions.

Chris' visit brought a number of benefits for all participants. Researchers of the Peter Cook Centre enjoyed having an enthusiastic student who shared and inspired through his modeling skills, an area in which we want to expand. Chris, on the other hand, took advantage of the geological data around the CO2CRC Otway site and used them for framing a case study. Chris completed his project by presenting a poster at an international CO₂ storage monitoring workshop organized by the International Energy Agency (IEA).

Engaging locally

Securing Australia's Future Working Group

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. The results from this Expert Group have been published as a book, available from www.acola.org.au.

The launch of the report resulted in 157 print and broadcast media items and led to four policy recommendations made by the Office of the Chief Scientist. Its findings have had a significant impact upon both State and Federal

government discussions of future policy in this area as well as on industry, which has seen it as a profoundly important component of the current debate on issues such as fracking and unconventional gas.

As a result of her participation in the Working Group, Sandra Kentish was invited to give presentations on these topics at a Royal Society of Victoria Forum Victoria's Energy Future: Prospects and Challenges, and the National Centre for Groundwater Research and Training Thought Leadership Series: Unconventional Gas. Another outcome of this work is Sandra's collaboration with Professor Robert Clark, Chair of Energy Strategy and Policy at the University of New South Wales and others, on a book intended to guide government policy titled Transport Fuels for Australia's Gas Resources.

The University of Melbourne Science Discovery Tours

Twice a year the University of Melbourne organises Science Discovery Tours for undergraduate Science students. In 2013 members of the Peter Cook Centre for CCS Research hosted a group of students and student advisors on a tour of its facilities.

The tours are tailored to second and third year students to visit sites relevant to their disciplines. The aim of the tours is to show students research and career opportunities in an engaging and realistic format.

The students spend an afternoon visiting facilities, interacting with graduate research students and academics working in these labs. For most students it is their first experience of visiting a working research laboratory and students relish the opportunity to get some insight into the working environment and hear from staff and research students about their experiences. For the Centre it provides us the opportunity to interact with future postgraduate students and ignite in them an interest in working in the CCS space.



Professor Peter Cook at the Saskpower Boundary Dam Symposium, Canada.



Professor Sandra Kentish addresses participants at the JCG Workshop in March 2013.

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 |
|-------------|--|---|
| 20 February | Prof Ralf Haese | Geochemical impacts of CO ₂ storage on formation water and reservoir rocks |
| 17 April | Mr Joel Scofield | Defined block copolymers for gas separation membranes |
| 15 May | Mr Brian Maring | A new simplified pressure/vacuum swing adsorption model for rapid adsorbent screening for CO ₂ capture applications |
| 19 June | Dr Andrew Lee | Modelling the thermodynamic equilibrium of promoted potassium carbonate solvents |
| 17 July | Dr Sang Yun (Andrew) Lee | The impact of water vapour on the membrane carbon capture processes |
| 21 August | Prof Paul Webley | Adsorbents and processes for CO ₂ separation |
| 4 September | Dr Niko Kampman Cambridge University, UK Christopher Zahasky Stanford University, USA | Downhole fluid sampling of a natural CO ₂ reservoir, Green River, Utah Above zone pressure and fluid composition responses to leakage up faults |
| 16 October | Dr Kathryn Smith Dr Dongfang Guo | Capturing CO ₂ using a precipitating potassium carbonate solvent CO ₂ capture at the Huaneng Clean Energy Research Institute (CERI) |
| 18 December | Dr Shinji Kanehashi | Development of various composite membranes for CO ₂ capture |

PRESENTATIONS

Keynote and Plenary Lectures

Kentish, S. (2013) The practical implementation of membrane technology for industrial outcomes. *AMS-8: The 8th Conference of the Aseanian Membrane Society*, 16-19 July 2013. (Plenary lecture)

Shang, J. (2013) "Molecular Sieving" revisited: Does size really matter? *2013 Australian Synchrotron User Meeting*, Melbourne, VIC, Australia, 21-22 November. (Plenary lecture)

Webley, P.A. (2013) Adsorption processes for CO₂ separation/capture. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Keynote lecture)

Conference and Meeting Presentations

Alharthi, K., Lee, A., Stevens, G. and Kentish, S. (2013) The effect of wet fly ash on CO₂ capture via membranes. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Anderson, C., Hooper, B., San Nicholas, R., Smith, K., Mumford, K. and Stevens, G. (2013) The UNO MK 3 supplementary research program. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Azher, H., Scholes, C., Stevens, G. and Kentish, S. (2013) Permeation properties of polymeric membranes at elevated temperatures. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Azher, H., Scholes, C., Stevens, G. and Kentish, S. (2013) Permeation and sorption properties of polymeric membranes at elevated temperatures. *AMS-8: The 8th Conference of the Aseanian Membrane Society*, Xi'an, China, 16-19 July 2013.

Azher, H., Scholes, C., Stevens, G. and Kentish, S. (2013) Water permeation and sorption properties of polymeric membranes at elevated temperatures. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.

Black, J.R. and Haese, R.R. (2013) Chlorite dissolution kinetics under CO₂ storage conditions. *Goldschmidt Conference*, Florence, Italy, 25-30 August.

Black, J. and Haese, R. (2013) CO₂-Water-Rock Interactions: Mineral dissolution rate comparisons under CO₂ storage conditions. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Chowdhury, M., Chafee, A. and Webley, P. (2013) Physico-chemical characterisation and gas sorption studies of iron and cobalt containing metallocenes' impregnated into mesoporous SBA-15. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Danaci, D., Singh, R. and Webley, P. (2013) Improved kinetics on trapdoor chabazite via dual cation exchange. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Danaci, D., Singh, R., Xiao, P. and Webley, P. (2013) Halide modification of zeolite-Y for improved hydrophobicity. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Dong, X., Xiao, G., Xiao, P., Li, G., Ntiamoah, A., Webley, P. and Zhai, Y. (2013) CO₂ capture from high humidity flue gas streams with VSA using activated carbon as adsorbent. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)

Ennis-King, J., La Force, T., Boreham, C., Bunch, M., Dance, T., Freifeld, B., Haese, R., Paterson, L., Stalker, L. and Zhang, Y. (2013) Combining downhole data to reduce modelling uncertainties in the CO2CRC Otway Project. *IEAGHG Combined Modelling and Risk Management Meeting 2013*, Trondheim, Norway, 10-13 June.

Fong, J.L.Y., Hoadley, A., Anderson, C., Xiao, G. and Webley, P. (2013) Techno-economic assessment of hybrid capture using VSA, cryogenics and membranes. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Fu, Q., Kentish, S. and Qiao, G. (2013) Highly permeable membrane materials for CO₂ Capture. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Fu, Q., Halim, A., Kentish, S.E. and Qiao, G.G. (2013) Multi-block poly(ethylene glycol)/Pebax®2533 blend thin film composite membranes for CO₂ separation. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.

Gouw, J., Mumford, K. and Stevens, G. (2013) Incorporation of impurities into potassium carbonate system modelling. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Gurr, P., Kentish, S. and Qiao, G. (2013) Thin-film composite gas separation membranes incorporating well defined crosslinkable PDMS-PS-PEG block polymers by ATRP. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.

Gurr, P., Scofield, J., Kentish, S. and Qiao, G. (2013) Synthesis and preparation of composite gas separation membranes incorporating triblock poly(6-FDA-co-TMPD) polyimide and polydimethylsiloxane. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Haese, R. (2013) Highlights and outlook of the reactive reservoir rocks project. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.

Haese, R., Black, J., Moreau, J., Boreham, C. and Knight, J. (2013) Determining formation water composition and fluid-rock reactions under CO₂ storage conditions as part of the NSW Darling Basin Drilling Program. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Halim, A., Fu, Q., Gurr, P.A., Blencowe, A., Kentish, S.E. and Qiao, G.G. (2013) Novel grafted star polymers for advanced composite gas separation membranes. *13th Pacific Polymer Conference (PPC 2013)*, Kaohsiung, Taiwan, 17-22 November.

- Halim, A., Fu, Q., Gurr, P.A., Blencowe, A., Kentish, S.E. and Qiao, G.G. (2013) Novel grafted star polymers for advanced composite gas separation membranes. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.
- Harkin, T., Qader, A., Hooper, B., Anderson, C., Xiao, G., Gouw, J., Indrawan, I., Howard, P. and Stevens, G. (2013) Trials, triumphs and trajectory of the UNO MK 3 Pilot Plant. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Higgs, K., Haese, R., Golding, S., Schacht, U., Kirste, D. and Watson, M. (2013) How do CO₂-content, reservoir heterogeneity and fluid composition affect CO₂-induced diagenesis? *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Ho, M., Wiley, D., Xiao, G., Webley, P. and Hoadley, A. (2013) Techno-economic evaluation of VSA-MEA solvent capture process. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Horner, K. and Haese, R. (2013) Fluid and mineral CO₂ trapping capacity in low-salinity sandstone formations. *IAH 2013: Solving the Groundwater Challenges of the 21st Century*, Perth, WA, Australia, 15-20 September.
- Horner, K. and Haese, R. (2013) Fluid and mineral CO₂ trapping capacity in low-salinity sandstone formations. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Indrawan, I., Mumford, K., Kentish, S. and Stevens, G. (2013) SO_x and NO_x removal in UNO MK 3 post combustion CO₂ capture. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Kanehashi, S., Li, X. and Kentish, S. (2013) Development of mixed matrix membranes using nanoparticles for CO₂ capture. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Kentish, S. (2013) Membrane capture research. *Australia-China Joint Coordination Group on Clean Coal Technology (JCG) Australia-China Workshop on Carbon Capture*, Melbourne, VIC, Australia, 6-8 March.
- Kentish, S. (2013) Polymeric membrane technology for carbon dioxide capture applications - Recent results. *Chemeca 2013: Challenging tomorrow*, Brisbane, QLD, Australia, 29 September-2 October.
- Kentish, S. (2013) Using membranes to capture carbon dioxide from Australian power stations. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Kentish, S.E. and Beck, V. (2013) Unconventional gas: Shale gas and coal seam gas. *Victoria's Energy Future: Prospects and Challenges; Royal Society of Victoria Forum*, Melbourne, VIC, Australia, 25-26 October. (Invited speaker)
- Kentish, S., Kezia, K., Lee, J., Ogieglo, W., Benes, N. and Hill, A. (2013) The transport of small molecules through reverse osmosis membranes. *9th World Congress of Chemical Engineering 2013*, Seoul, Korea, 18-23 August.
- Kim, J., Fu, Q., Kentish, S. and Qiao, G. (2013) Fabrication of PEG-based ultra thin film composite membranes for CO₂ separation. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November. (Poster presentation)
- Kim, J., Fu, Q., Kentish, S. and Qiao, G. (2013) PEG-based ultra thin film composite membranes via CAP-ATRP for CO₂ separation. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Kirste, D., Haese, R.R. and Boreham, C. (2013) Tracing residual gas saturation and geochemical reactions at the CO2CRC Otway Site Stage 2B. *10th Applied Isotope Geochemistry Conference (AIG-10)*, Budapest, Hungary, 22-27 September.
- La Force, T., Zahasky, C., Haese, R., Watson, M., Dance, T., Ennis-King, J. and Benson, S. (2013) Above zone pressure and fluid composition responses to leakage up faults. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Lee, A. and Stevens, G. (2013) A study of the vapour-liquid equilibrium of carbon dioxide in promoted potassium carbonate solutions. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Li, G., Shang, J., Xiao, P., Singh, R., Danaci, D., Webley, P. and May, E. (2013) Separation of nitrogen/methane on organic cation zeolites for natural gas purification. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)
- Lim, J., Aguiar, A., Scholes, C., Stevens, G. and Kentish, S. (2013) MEA reclamation using electrodialysis. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Lim, J., Scholes, C., Stevens, G. and Kentish, S. (2013) MEA reclamation using nanofiltration. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.
- Ling, J., Danaci, D., Singh, R., Xiao, P. and Webley, P. (2013) Synthesis of a novel microporous carbon for CO₂ capture from flue gases using a free-activated protocol. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Maring, B. and Webley, P. (2013) A new temperature swing adsorption configuration for high purity and recovery CO₂ capture from flue gas with increased throughput. *AIChE 2013 Annual Meeting*, San Francisco, CA, USA, 3-8 November.
- Maring, B. and Webley, P. (2013) A new temperature swing adsorption configuration for high purity and recovery CO₂ capture from flue gas with increased throughput. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Mirza, N., Stevens, G. and Nicholas, N. (2013) Kinetic study of CO₂ capture with reline. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Mu, A., Boreham, C., Leong, H., Stinear, T., and Moreau, J.W. (2013) Microbial community dynamics in a deep subsurface aquifer targeted for CO₂ sequestration. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Mumford, K., Gouw, J., Indrawan, I., Rayer, A., Thee, H., da Silva, G., Quyn, D. and Stevens, G. (2013) Development of novel solvent systems. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

- Nicholas, N., Mirza, N. and Stevens, G. (2013) Increasing the CO₂ capacity of deep eutectic solvents via the addition of amino acids. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Ntiamoah, A., Xiao, P., Webley, P. and Ling, J. (2013) CO₂ capture by adsorbents: Investigating the potential of utilising power plant waste-heat. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Qiao, G. (2013) Strategies towards high performance composite membranes for gas separations. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Qiao, G. (2013) Strategies towards high performance composite membranes for gas separations. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.
- San Nicolas, R., Gordon, L. and Provis, J. (2013) Efficient and environmentally friendly way to build large scale carbon capture and storage equipment. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Scholes, C., Stevens, G. and Kentish, S. (2013) Membrane contactors for CO₂ Capture. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.
- Scholes, C., Stevens, G. and Kentish, S. (2013) Membrane gas – solvent contactors for CO₂ capture. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Scotfield, J., Gurr, P., Kentish, S. and Qiao, G. (2013) Well defined poly(ethylene glycol) based copolymer membranes for effective CO₂ gas separation. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Scotfield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2013) Gas permeation properties of defined poly(dimethylsiloxane)-poly(ethylene glycol) diblock copolymers. *8th International Membrane Science & Technology Conference (IMSTEC2013)*, Melbourne, VIC, Australia, 25-29 November.
- Shang, J., Li, G., Singh, R., Xiao, P., Liu, J.Z. and Webley, P.A. (2013) Separation of CO₂ and CH₄ using a novel 'molecular trapdoor' zeolite: Materials and process study. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)
- Shang, J., Li, G., Singh, R., Xiao, P., Liu, J.Z. and Webley, P.A. (2013) Separation of CO₂ and CH₄ using a novel 'molecular trapdoor' zeolite: Materials and process study. *The 7th Asia Oceania Forum for Synchrotron Radiation Research (AOFSSR 2013)*, Egret Himeji, Japan, 21-24 September. (Poster presentation)
- Shang, J., Tang, W., Danaci, D., Singh, R., Xiao, P. and Webley, P. (2013) Adsorption and separation of O₂ and N₂ using porphyrin-based adsorbents: a density functional theory study. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Singh, R., Danaci, D. and Webley, P. (2013) Influence of particle size and pore structure on adsorption properties of small-pore zeolites. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Singh, R., Xiao, P., Xiao, G., Webley, P.A., Nanoti, A., Goswami, A., Dasgupta, S. and Garg, M.O. (2013) Removal of CO₂ from biogas by vacuum swing adsorption (VSA) technology. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)
- Smith, K., Quyn, D., Indrawan, Thanumurthy, N., Gouw, J., Nicholas, N., Lee, A., Mumford, K., Anderson, C., Hooper, B., Kentish, S. and Stevens, G. (2013) Pilot plant for capturing CO₂ using a precipitating potassium carbonate solvent. *Chemeca 2013: challenging tomorrow*, Brisbane, QLD, Australia, 29 September-2 October.
- Smith, K., Quyn, D., Indrawan, Thanumurthy, N., Gouw, J., Nicholas, N., Lee, A., Mumford, K., Anderson, C., Hooper, B., Kentish, S. and Stevens, G. (2013) Pilot plant for capturing CO₂ using a precipitating potassium carbonate solvent. *Chemeca 2013: Challenging tomorrow*, Brisbane, QLD, Australia, 29 September-2 October.
- Smith, K., Thanumurthy, N., Indrawan, I., Gouw, J., Mumford, K., and Stevens, G. (2013) Latest results from a pilot plant for testing a precipitating potassium carbonate process for CO₂ absorption. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November.
- Smith, K., Xiao, G., Mumford, K., Gouw, J., Indrawan, I., Thanumurthy, N., Quyn, D., Cuthbertson, R., Rayer, A., Nicholas, N., Lee, A., Da Silva, G., Kentish, S., Harkin, T., Qader, A., Anderson, C., Hooper, B., Stevens, G. (2013). Demonstration of a precipitating potassium carbonate process for CO₂ capture. *4th Sino-Australian Symposium on Advanced Coal and Biomass Utilisation Technologies*, 9-11 December, Wuhan, China.
- Stevens, G.W. (2013) CO2CRC solvents program. *Australia-China Joint Coordination Group on Clean Coal Technology (JCG) Australia-China Workshop on Carbon Capture*, Melbourne, VIC, Australia, 6-8 March.
- Tang, W., Singh, R., and Webley, P. (2013) Pore size modification of zeolites for air separation applications. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Tang, W., Danaci, D., Singh, R., Xiao, P. and Webley, P. (2013) Vacuum swing adsorption process using oxygen selective polymers for O₂/N₂ separation. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Thanumurthy, N., Indrawan, I., Smith, K. and Stevens, G. (2013) Analytical techniques for measuring the performance of a precipitating solvent absorption process. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)
- Thee, H., Nicholas, N., Smith, K., Da Silva, G., Kentish, S. and Stevens, G. (2013) A kinetic study of CO₂ capture with potassium carbonate solutions promoted with various amino acids. *Chemeca 2013: Challenging tomorrow*, Brisbane, QLD, Australia, 29 September-2 October.
- Webley, P.A. (2013) Adsorption process and materials development for CO₂ capture: An overview. *Australia-China Joint Coordination Group on Clean Coal Technology (JCG) Australia-China Workshop on Carbon Capture*, Melbourne, VIC, Australia, 6-8 March.

Xiao, G., Gouw, J., Indrawan, I., Stevens, G., Harkin, T., Howard, P., Hooper, B. and Qader, A. (2013) CO2CRC/GDF SUEZ UNO MK 3 Pilot Plant campaign results and simulations. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Xiao, G., Xiao, P., Zhang, J., Hoadley, A. and Webley, P.A. (2013) An adsorbent/MEA hybrid process for post-combustion CO₂ Capture. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)

Xiao, P., Shang, J. and Webley, P. (2013) Effect of operating temperatures on PVSA performance for CO₂ and CH₄ separation using 'Trapdoor' adsorbent. *2013 CO2CRC Research Symposium*, Hobart, TAS, Australia, 19-20 November. (Poster presentation)

Xiao, P., Singh, R., Xiao, G., Danaci, D., Li, G., Shang, J. and Webley, P.A. (2013) Capture of CO₂ from natural gas by pressure swing adsorption technology using zeolite NaUSY as adsorbent. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)

Xu, D., Xiao, G., Xiao, P., Zhang, J., Li, G., Ntiamoah, A. and Webley, P.A. (2013) CO₂ capture from high humidity flue gas streams by vacuum swing adsorption technology (VSA) using activated carbon as adsorbent. *11th International Conference on the Fundamentals of Adsorption (FOA11)*, Baltimore, MD, USA, 19-24 May. (Poster presentation)

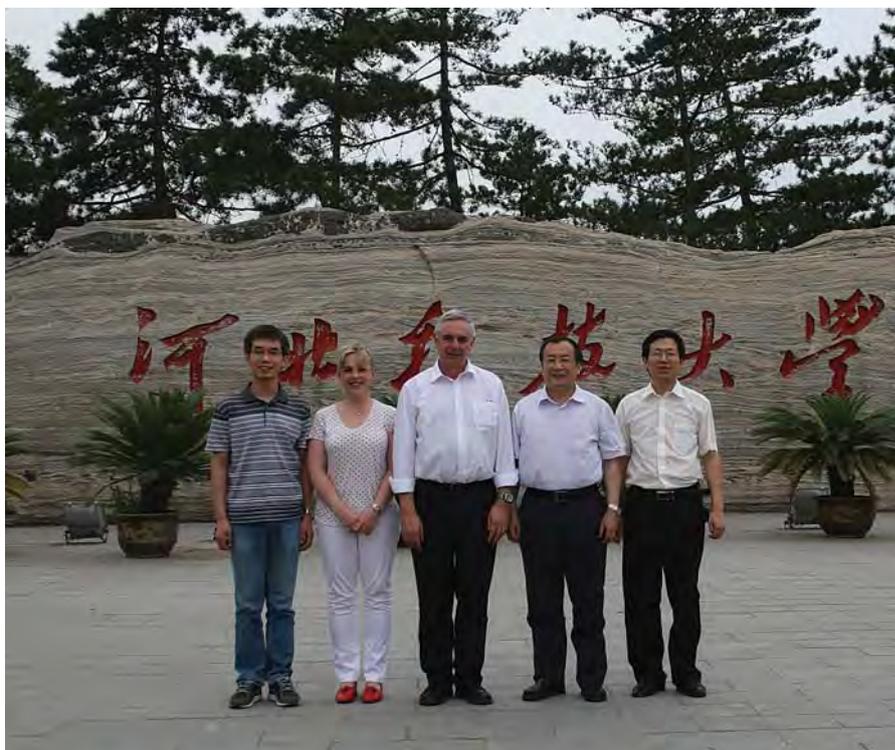
Invited Lectures and Seminars

Haese, R.R. (2013) Carbon fluxes across boundaries. Inaugural Seminar, The University of Melbourne, VIC, Australia, 11 April.

Kentish, S.E. (2013) Engineering energy: Unconventional gas production. Unconventional Gas: Thought Leadership Series, National Centre for Groundwater Research and Training, Perth, WA, Australia, 17 June.

Kentish, S.E. (2013) Victorian Gas Market Review – A response. Committee for Economic Development of Australia, Melbourne, VIC, Australia, 5 December.

Mu, A. (2013) Metagenomics of the Earth's subsurface - CO₂ geosequestration. 2013 Metagenomics@Melbourne symposium, Melbourne, VIC, Australia, 27 November.



Centre Director, Professor Geoff Stevens was invited to speak at Hebei University of Science and Technology, Shijiazhuang, China as part of the ACSRF Group Mission.

From left to right: A/Prof Shufeng Shen, Dr Kathryn Mumford, Prof Geoff Stevens, Prof Yifeng Yu, A/Prof Zhenhua Shang

Stevens, G.W. (2013) Australia's needs in capture. CO2CRC Program Advisory Committee (PAC) Meeting, Melbourne, VIC, Australia, 30-31 May.

Stevens, G.W. (2013) Capture of CO₂, the next generation. CO2CRC Program Advisory Committee (PAC) Meeting, Melbourne, VIC, Australia, 30-31 May.

Stevens, G.W. (2013) Development of capture technology from post combustion capture sources. CarbonNet, Melbourne, VIC, Australia, 7 June.

Stevens, G.W. (2013) Global warming, greenhouse gases, energy usage and separations technology. Australia China Science and Research Fund (ACSRF) Group Mission, CO2CRC Collaboration with Tsinghua University, NICE and other partners to establish joint R&D programs in the field of CO₂ Capture, Hebei University of Science and Technology, Shijiazhuang, China, 17-21 June.

Stevens, G.W. (2013) Capture of CO₂ from flue gas using solvents. Australia China Science and Research Fund (ACSRF) Group Mission, CO2CRC Collaboration with Tsinghua University, NICE and other partners to establish joint R&D programs in the field of CO₂ Capture, Tsinghua University, Beijing, China, 17-21 June.

Stevens, G.W. (2013) Development of capture technology from post combustion capture sources. Australia China Science and Research Fund (ACSRF) Group Mission, CO2CRC Collaboration with Tsinghua University, NICE and other partners to establish joint R&D programs in the field of CO₂ Capture, Tsinghua University, Beijing, China, 17-21 June.

Stevens, G.W. (2013) Global warming, greenhouse gases, energy usage and separations technology. Department of Chemical and Biomolecular Engineering Departmental Seminar, The University of Melbourne, VIC, Australia, 12 November.

PUBLICATIONS

Refereed Journal Articles

Anderson, C., Harkin, T., Ho, M., Mumford, K., Qader, A., Stevens, G. and Hooper, B. (2013) Developments in the CO₂CRC UNO MK 3 process: A multi-component solvent process for large scale CO₂ capture. *Energy Procedia*, 37, 225-232.

Fu, Q., Halim, A., Kim, J., Scofield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2013) Highly permeable membrane materials for CO₂ capture. *Journal of Materials Chemistry A*, 1, 13769-13778.

Guo, D.F., Thee, H., Tan, C.Y., Chen, J., Fei, W.Y., Kentish, S., Stevens, G.W. and da Silva, G. (2013) Amino acids as carbon capture solvents: Chemical kinetics and mechanism of the glycine + CO₂ reaction. *Energy & Fuels*, 27, 3898-3904.

Haese, R.R., LaForce, T., Boreham, C., Ennis-King, J., Freifeld, B.M., Paterson, L. and Schacht, U. (2013) Determining residual CO₂ saturation through a dissolution test – Results from a CO₂CRC field experiment. *Energy Procedia*, 37, 5379-5386.

Halim, A., Gurr, P.A., Blencowe, A., Bryant, G., Kentish, S.E. and Qiao, G.G. (2013) Synthesis and self-assembly of polyimide/poly(dimethylsiloxane) brush triblock copolymers. *Polymer*, 54, 520-529.

Lee, S.A., Stevens, G.W. and Kentish, S.E. (2013) Facilitated transport behavior of humidified gases through thin-film composite polyamide membranes for carbon dioxide capture. *Journal of Membrane Science*, 429, 349-354.

Li, L.X., Yao, J.F., Xiao, P., Shang, J., Feng, Y., Webley, P.A. and Wang, H.T. (2013) One-step fabrication of ZIF-8/polymer composite spheres by a phase inversion method for gas adsorption. *Colloid and Polymer Science*, 291, 2711-2717.

Maring, B.J. and Webley, P.A. (2013) A new simplified pressure/vacuum swing adsorption model for rapid adsorbent screening for CO₂ capture applications. *International Journal of Greenhouse Gas Control*, 15, 16-31.

Paterson, L., Boreham, C., Bunch, M., Dance, T., Ennis-King, J., Freifeld, B., Haese, R., Jenkins, C., LaForce, T., Raab, M., Singh, R., Stalker, L. and Zhang, Y. (2013) Overview of the CO₂CRC Otway residual saturation and dissolution test. *Energy Procedia*, 37, 6140-6148.

Quyn, D., Rayer, A.V., Gouw, J., Indrawan, I., Mumford, K.A., Anderson, C.J., Hooper, B. and Stevens, G.W. (2013) Results from a pilot plant using un-promoted potassium carbonate for carbon capture. *Energy Procedia*, 37, 448-454.

Scholes, C.A., Anderson, C.J., Cuthbertson, R., Stevens, G.W. and Kentish, S.E. (2013) Simulations of membrane gas separation: chemical solvent absorption hybrid plants for pre- and post-combustion carbon capture. *Separation Science and Technology*, 48, 1954-1962.

Scholes, C.A., Anderson, C.J., Stevens, G.W. and Kentish, S.E. (2013) Membrane gas separation – Physical solvent absorption combined plant simulations for pre-combustion capture. *Energy Procedia*, 37, 1039-1049.

Scholes, C.A., Ho, M.T., Wiley, D.E., Stevens, G.W. and Kentish, S.E. (2013) Cost competitive membrane-cryogenic post-combustion carbon capture. *International Journal of Greenhouse Gas Control*, 17, 341-348.

Scholes, C.A., Stevens, G.W. and Kentish, S.E. (2013) Modeling syngas permeation through a poly dimethyl siloxane membrane by Flory-Rehner theory. *Separation and Purification Technology*, 116, 13-18.

Shang, J., Li, G., Singh, R., Xiao, P., Liu, J.Z. and Webley, P.A. (2013) Determination of composition range for "molecular trapdoor" effect in chabazite zeolite. *Journal of Physical Chemistry C*, 117, 12841-12847.

Webley, P. (2013) Improving CO₂ sequestration. *Bulletin of the American Meteorological Society*, 94, 161.

Xu, D., Xiao, P., Zhang, J., Li, G., Xiao, G.K., Webley, P.A. and Zhai, Y.C. (2013) Effects of water vapour on CO₂ capture with vacuum swing adsorption using activated carbon. *Chemical Engineering Journal*, 230, 64-72.

Refereed Conference Paper

Smith, K., Quyn, D., Indrawan, Thanumrthy, N., Gouw, J., Nicholas, N., Lee, A., Mumford, K., Anderson, C., Hooper, B., Kentish, S. and Stevens, G. (2013) Pilot plant for capturing CO₂ using a precipitating potassium carbonate solvent. In *CD-ROM Proceedings of Chemeca 2013: Challenging tomorrow*, Brisbane, QLD, Australia.

Other

Cook, P. (2013). Direct action may succeed where tax fails. In *The Australian*, December 27.



Jeffri Gouw

FINANCIAL SUMMARY

Peter Cook Centre for CCS Research - 2013 Calendar Year Income and Expenditure

| | CCS Research Projects (includes CO2CRC, ANLEC and BCIA funding) | | Peter Cook Centre Stakeholders' Support (DSDBI, CO2CRC, UoM, Rio Tinto) | University of Melbourne Extra Support (incl PhD Stipends, Prof Salary) | TOTAL |
|-------------------------------|---|-----------|--|---|-------------|
| | Cash | In-Kind | | | |
| Storage Program Income | \$60,240 | \$138,820 | \$484,375 | \$0 | \$683,435 |
| Storage Program Expenditure | \$72,317 | \$138,820 | \$250,663 | \$0 | \$461,799 |
| Net Surplus/(Deficit) Storage | (\$12,077) | \$0 | \$233,712 | \$0 | \$221,636 |
| Capture Program Income | \$2,316,714 | \$138,820 | \$0 | \$12,327 | \$2,987,971 |
| Capture Program Expenditure | \$2,124,699 | \$138,820 | \$0 | \$12,327 | \$2,795,955 |
| Net Surplus/(Deficit) Capture | \$192,015 | \$0 | \$0 | \$0 | \$192,015 |

CONTACT DETAILS

Professor Geoff Stevens, Director

Peter Cook Centre for Carbon Capture and Storage Research
Department of Chemical and Biomolecular Engineering
The University of Melbourne
Victoria 3010 Australia

Tel: 61 3 8344 6621

Fax: 61 3 8344 8824

Email: gstevens@unimelb.edu.au

www.petercook.unimelb.edu.au



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