Imperial College London

Barrer Centre

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Annual Report 2018

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Director's foreward

Welcome to the first annual report from the Barrer Centre at Imperial College London. It's a great privilege for me to be able to lead this exciting new venture at Imperial, and to report back on the first couple of years of the Barrer Centre. It's usually not that hard to start something. To take up a new sport, to start learning a new skill, to take an interest in a new aspect of history or politics - whatever it might be, the start of some new thing is relatively straightforward. You decide what you're going to do, and then you get on with doing it. Except life doesn't actually work that way. If we're honest with ourselves, what is really simple is to think about starting something, or even to talk about starting something new... but many new initiatives fail at that point, during the thinking, the talking. Where it really starts to take some serious effort is in the doing. And this takes effort and teamwork to make the new venture robust, resilient, adaptive and capable of growth.

Why mention this? Because this is our Centre, the Barrer Centre - and this is our very first Annual Report. We stand at this critical point in what I hope will be a long and illustrious life of the Centre, and we have only just begun. In fact, the story of research into separation materials and technologies began many years ago at Imperial College, most notably with the pioneering research of Richard Barrer, former Professor of Chemistry and Head of the Chemistry Department. Richard's pioneering work with synthetic zeolites and gas permeation through rubbery materials marks him as one of the most recognised researchers in the field. With the kind permission of Richard's family, we were honoured to select Barrer as the identifying name of our Centre, bringing together a highly talented group of separation materials and technology researchers in the Department of Chemical Engineering with associate members spread throughout the College. You can read more about our research focus and the mission of our Centre later in this report, how as a Centre we are building on the incredible legacy of materials and membrane research at Imperial College, and driving it forward into the future. The obvious question then is what future are we driving towards, and why?

These are important questions, and as a group of engineering researchers we're clear about what we will achieve through this Centre. First and foremost, we will conduct breakthrough research at the forefront of human knowledge in the field of separation materials and technology. Much of our research has some applied focus, for example Qilei Song is leading his group to develop completely new porous materials that will change the current thinking, the paradigm, of portable and stationary energy storage. My own group has used totally novel, innovative approaches to making freestanding polymer membranes less than 10-nm thick - allowing us to probe the structure and transport properties of the selective layer in membranes, something that has never been possible before. We work to bring highly original, creative scientific thinking to bear on important engineering problems. Importantly, we don't stop there – we drive the fundamental research all the way to impact in ways that benefit society. Kang Li and his team fomed Microtech Ceramics, a rapidly growing start-up from the Centre that is making the next generation of automobile catalytic converters possible, all based on the fundamental science of membrane formation.

We are more than the sum of our parts. Together, we bring a unique collection of knowledge, experience and abilities to solve problems in collaborative teams. In this way, we will grow the Barrer Centre to become a global centre of excellence, known not as the biggest centre (although we may become that too), but more importantly as the place where the most original, insightful, creative and important research and innovation occurs. We work to make possible tomorrow things which are not possible today.

We are fortunate to have excellent research facilities, and especially to serve as a magnet for talented young researchers. Without the brilliant research students and postdoctoral researchers in our Centre, we could not achieve the amazing outcomes we do. This brings a responsibility to myself and the other Investigators in the Centre to provide academic leadership, personal and professional development and career mentoring. We take this very seriously. As researchers pass through our Centre and go out into the world, it is our ambition that they will be equipped to reach their full potential, and make the maximum possible impact in their careers. They will shape the industries and organisations they work in, and at the same time build and strengthen the awareness and recognition of the Barrer Centre. Our people, our science, and our translation, are the major avenues of impact that we will have as a Centre.

This is our first Annual Report. It's an opportunity to introduce our Centre and share some of our excitement for the work we do, and the positive energy we build doing it together. We've gone past thinking and talking, we've launched this Centre, we're getting on with the job of making something amazing. It's a challenge every step of the way, and I'm proud to be leading it.

Our aims and vision

"A key aim of the Centre is to stimulate, develop and deliver high quality research in all aspects of membrane and adsorption science and technology across all scales, ranging from the nanoscale to the macro-scale."

Professor Andrew Livingston and
Professor Kang Li
Barrer Centre Co-Directors

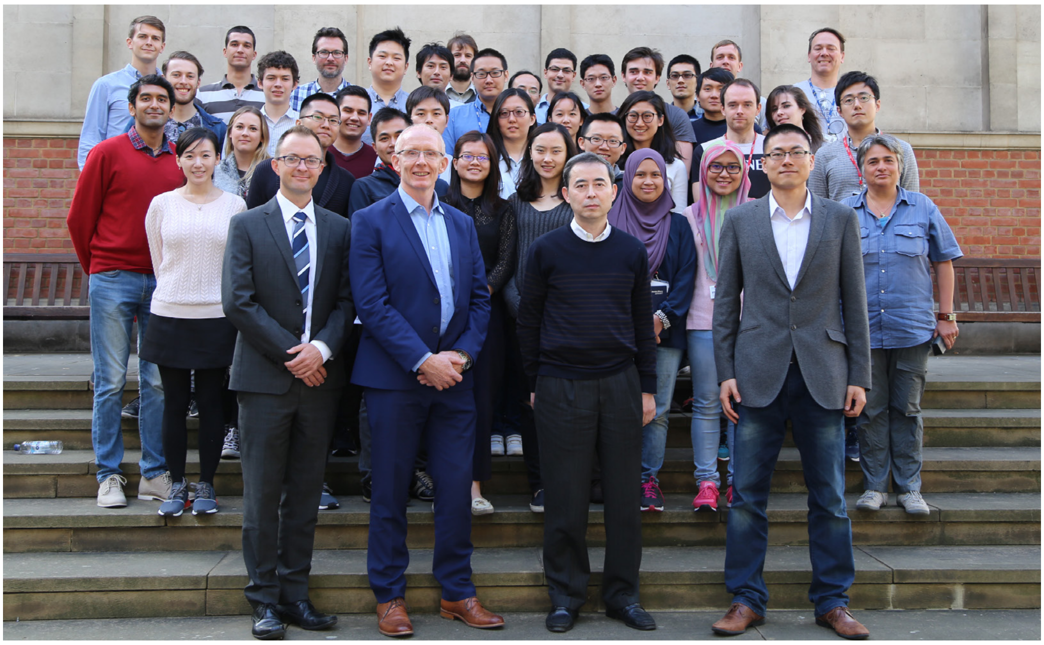
The Barrer Centre's mission is to undertake ground breaking research, setting the agenda for materials science and engineering which leads to innovations in separation processes. In particular the Centre will focus on paradigm changing membrane and adsorption science and technology; and on the translation of our research into beneficial impacts on industry and society. We will work across polymeric and inorganic materials, partnering with industry sectors including oil and gas, chemicals, pharmaceuticals, water and agricultural.

The Barrer Centre brings together leading researchers from the Department of Chemical Engineering at Imperial College London involved in membranes, adsorbents and separation materials to achieve breakthrough research, particularly in water recovery and environmental protection, energy conversion, molecular separation, food technology, bioprocessing and biomedical devices.

The Barrer Centre promotes the mutually beneficial sharing of ideas, data, experience, and expertise between academics and external organisations as well as the public. The Centre seeks to build a highly trained separation research team, through specialist training in all aspects and across all scales of membrane and adsorption science and technology, ranging from nanoscale- which will include designing novel materials and the understanding of the separation mechanisms to the macro-scale- with the manufacturing of full-scale membranes and adsorbents.

The Barrer Centre aims to play a pivotal role in developing a scientifically rooted membrane industry in the UK serving the separation research landscape in the UK and globally. The Centre's researchers network, communicate and collaborate with a wide spectrum of stakeholders including industrialists, interested individuals, government representatives, and researchers from other academic institutions, to enhance discovery and innovation within the separation field.

Our People



Centre Director
Professor Andrew Livingston

Centre Co-Director
Professor Kang Li

Principal Investigators
Dr Bradley Ladewig
Dr Camille Petit
Dr Qilei Song

Centre Manager
Mrs Angela Lonergan

Research Fellow
Dr Ludmila Peeva

Postdoctoral Research Associates
Dr Danilo Cuccato
Dr Ruijiao Dong
Dr Piers Gaffney
Dr Kang Huang
Dr Zhiwei Jiang
Dr Daeok Kim
Dr Jihoon Kim
Dr Tao Li
Dr TianYin Liu
Dr Jason Stafford
Dr Bo Wang
Dr Jia Xu
Dr Lei Yang
Dr Naveed Zaidi
Dr Anna LiVolsi

PhD students
Luqman Bin Mohd Azmi
Yaala Assiri
Ethan Butler
Chen Chen
Yunsi Chi
Marcus Cook
Jack Cordrey
Angus Crake
Elton Dias
Mahmood Abdulsalam Ebrahim
Arwyn Evans
Ruiyi Liu
Nur Izwanne Binti Mahyon
Shanxue Jiang
Sofia Marchesini
Marine Michel
Marc Plunkett
Nicholaus Prasetya
Mohamad Bin Rabuni
Ravi Shankar
Giulia Schukraft
Vatsal Shah
Ben Slater
Rui Tan
Nwachukwu Uzo
Anqi Wang
Jet Yeo
Adam Oxley
Siyao Li
Maria Burggraef

Launch event and the International Advisory Board

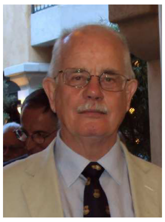
Participants in the Barrer Symposium, marking the launch of the Barrer Centre

The Barrer Centre was formally opened with a Barrer Symposium in October 2016, held at 170 Queen's Gate, a stunning grade II listed Victorian town house which forms part of the western edge of the Imperial College South Kensington campus.

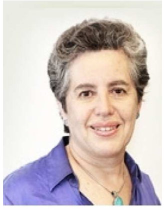
A wide range of scientists, engineers, industrialists and sponsors attended the event, and it was particuarly fitting that representatives of the family of Richard Barrer were also in attendance.

Several of the talks at the Symposium were recorded and are available from the Barrer Centre website. These include Professor Andrew Livingston introducing the Aims and Hallmarks of the Barrer Centre.

All of the investigators in the Centre presented outlines of their research plans and vision, and the symposium included some presentations and facilitated discussion sessions led by members of the Advisory Board. The Advisory Board comprises internationally leading scientists and engineers who have made enormous contributions to the science and engineering of separation materials. They were carefully chosen to represent the spectrum of research that the Barrer Centre covers, while also bringing unique global insights that ensure the Centre remains squarely focussed on the most critically important research.



Dr Richard Baker
Founder, Membrane Technology and Research Inc.
Advisory Board Chair



Professor Suzana P. Nunes
Professor
King Abdullah University of Science and Technology, Saudi Arabia

Professor G. Q. (Max) Lu
Vice-Chancellor
University of Surrey, UK

Professor Matthias Wessling
Vice-Rector for Research and Structure
RWTH Aachen, Germany

Professor Marco Mazzotti
Professor
ETH Zurich, Switzerland

Professor Michael Guiver
Professor
Tianjin University, China

Richard Barrer and the Barrer Lecture


Image © Royal Society of Chemistry Library Archives

Richard Maling Barrer FRS (16 June 1910 – 12 September 1996) was born on an isolated sheep farm outside Masterton, New Zealand. Due to the remote location, he was home-schooled by his mother until the age of nine.

He studied Chemistry as an undergraduate at Canterbury College (now The University of Canterbury in New Zealand). In 1932 he received an 1851 Exhibition Scholarship, supporting his studies in the Colloid Science Laboratory at Cambridge University.

This early scholarship support of Richard by the 1851 Exhibition Scholarship shows a remarkable parallel with Imperial College London, which also benefited from the foresight, vision and generosity of Prince Albert, who passionately promoted the 1851 Great Exhibition and used the resulting profits to establish the great learned institutions in South Kensington including the Natural History Museum, The V&A Museum, and of course Imperial College London.

At Cambridge, Richard was also a talented runner, winning the 1934 Oxford-Cambridge race and being awarded a Full Blue in Athletics. Richard was awarded his PhD from Cambridge in 1935. He was a research fellow at Clare College, Cambridge 1937–1939, Head of Chemistry at Bradford 1939–1946, taught at Bedford College, University of London 1946–1948, Professor of Chemistry at University of Aberdeen 1948–54. In 1954 Richard was appointed Professor of Physical Chemistry at Imperial College London, where he would remain for the remainder of his career.

Richard is credited with breakthrough research in polymer membranes and molecular transport in microporous media and establishing the field of zeolite research and its applications in industry. He authored more than 400 scientific papers, 3 monographs and held 21 patents, and the Barrer Prize is awarded by the Royal Society of Chemistry, the Society for Chemical Industry and the British Zeolite Association in his honour.

The 'Barrer', the unit of gas permeability which is still used today, is named after him.

The Annual Barrer Lecture

Befitting the tremendous contribution of Richard Barrer and recognising how unique his contributions are, it was resolved at the formation of the Centre that a Barrer Lecture should be held only once per year, to be delivered by an internationally leading individual.

The inaugural Barrer Lecture was given by **Dr Richard Baker**, chair of the Advisory Board, founder of the membrane company MTR Inc. and himself a former PhD student of Richard Barrer. This Barrer Lecture was deliverd following the formal launch of the Barrer Centre, and gave a sharp and incisive overview of the development of the membrane industry, drawing in particular on Richard Baker's experience founding and leading his own membrane research company in California. This lecture can be viewed online.

The second Barrer Lecture was presented by **Professor Vicki Chen**, formerly Director of the UNESO Membrane Centre at the Univeristy of NSW, Australia (Vicki is now Dean of Engineering, Architecture & IT at The University of Queensland). Vicki explored new membranes and membrane processes for critical environmental challenges, and her lecture can also be viewed online.

Livingston Group

The Livingston Group develops advanced membranes, materials and systems for organic solvent nanofiltration and biomolecular separations.

About the Livingston group
The Livingston Group works in the Barrer Centre on problems related to molecular separations in liquids. We seek to create new membrane materials and membranes, to characterise these ever more accurately so that we can simulate their behaviour more closely, and to unravel their performance so that we can improve and optimise membrane behaviour. Following up on the fundamentals, we also work to develop new membranes through to pilot scale modules that are ready for commercialisation. The team has developed some of the highest permeance membranes yet reported for organic solvents, and in the last two years we have turned our research energies into improving the molecular selectivity of these membranes, working to achieve ever-sharper resolution between solute molecules. We seek to apply our membranes in new technology platforms that enable advances in the chemical science, and actively look for new areas where our membranes might make the difference. Presently, we are working intensively on iterative synthesis by nanostar sieving, a platform we have developed to produce defined monomer sequence biological (peptide, oligonucleotide) and synthetic polymers. Excitingly, a team of Livingston Group current staff and alumni have created a new company, EXACTMER, using the new “Founders Choice” route from Imperial Innovations. EXACTMER has licensed an IP portfolio from Imperia College and work to commercialise this in the fabrication of exact polymers.

Spotlight
Our work on developing membranes with performance in ever-tougher environments reached new heights over the last two years – we created a PEEK membrane, reported in the Journal of Membrane Science in 2017, which continued stable operation in DMF at 140°C. Following on from this we were able to apply these PEEK membranes in a highly demanding environment where two consecutive chemical reactions are carried out in continuous flow, also in DMF at elevated temperature, showing for the first time how solvent exchanges can be carried directly from a high boiling point to a low boiling point solvent (Angewandte Chemie, Int. Edn, 2017). This last year we also described in Advanced Materials (2018) our discovery that the support layer for interfacial polymerisation films has a marked and predictable effect on the water flux in water desalination - more open supports reduce the lateral distance for water transport and improve membrane permeance.

Joining the group
Jia Xu spend a year with us Sept 2017 – Sept 2018 as an Academic Visitor.

Postdocs
Dr Danilo Cuccato
Dr Daeok Kim
Dr Ji Hoon Kim
Dr Naveed Zaidi
Dr Anna LiVolsi

PhDs
Jack Cordrey
Jet Yeo
Adam Oxley (joined Oct 2018)
Siyao Li (joined Oct 2018)
Maria Burggraef (joined Dec 2018)

Alumni - Postdoc
Dr Patrizia Marchetti (PhD then Post Doc) went to Bachem in Switzerland

Alumni - PhDs
Marcus Cook graduated and moved to South Wales to make geomembranes with a rapidly growing SME
Ruiyi Liu went to work for a consultancy firm in London
Marc Schaepertoens went to work for Evonik in Marl
Yuqiong Li went to work for Institute of Materials Science in Singapore
Zhiwei Jiang graduated and accepted a post-doc in the Livingston Gorup.

New projects

- Project with Millipore working on peptide synthesis using nanostar sieving
- BP ICAM Project to explore properties of Impene, ultra-thin carbonised films
- BP ICAM Project to develop effective separations for alcohol recovery from fermenations as part of biofuel production
- Eli Lilly Project to develop applications of organic solvent nanofiltration in pharmaceutical synthesis
- Exxon Project to create new membranes for Exxons imaging liquid separations vision
- EPSRC Impact Acceleration Award to upscale iterative synthesis of unimolecular PEGs
- ERC Advanced Grant for creation of Exact Polymers - Exactymers
- EPSRC-NSF joint grant with Prof Benito Marinas at Illinois and Prof Will Dichter at Northwestern to create new membranes based on ultra-thin COF films
- KAUST funded PhD with Prof Suzana Nunes at KAUST to develop OSN membranes for high temperature operations.

EPSRC Platform Grant

Professors Andrew Livingston and **Kang Li** (Barrer Centre Co-Directors) and **Professor Alexander Bismark** (Centre Associate Member, Professor of Chemical Engineering at Imperial College London and Head of the Institute of Materials Chemistry & Research, University of Vienna) were awarded a highly prestigous EPSRC Platform Grant in early 2018, on the topic "System Builders - Device Assembly from Nanoporous Materials Developed from Current Platform Grant (EP/J014974/1)".

These grants are amongst the largest, most competitive and highly-sought after EPSRC funding awarded in the UK to established, recognised leaders with a track record of research excellence. In this case, the EPSRC Platform Grant is valued at £1,547,752.

The previous EPSRC Platform Grant held by these investigators "Molecular Builders: Constructing Nanoporous Materials" has been successful in developing innovative new materials with controlled micro-porous structure which have demonstrated outstanding performance. These were successfully commercialised through an Imperial spin out company, Membrane Extraction Technology (now owned by Evonik Industries) who began production on a small scale. The team is aiming to revolutionise the device fabrication and application platforms by manufacturing composite materials and incorporating these into micro-devices such as columns, monoliths and modules. Researchers will use these devices to deal with separation problems that current membranes cannot reach, such as synthesis of pharmaceuticals in continuously operating reactors, production of DNA and RNA for therapeutic needs, and the separation of gases.

President's Medal for Research Support Excellence

Angela Lonergan is the Manager of the Barrer Centre and has worked as a Project Manager in the Department of Chemical Engineering at Imperial College for several years. In 2017 she was awarded the top recognition for Research Support Excellence, the President's Medal.

On receiving the award, Angela said "I was very surprised and honoured to be nominated by the Department for the award. It's great that support staff get recognised for their contribution to research activities."

"Outreach was an area of my work that was highlighted in my nomination, and it's an activity that I particularly enjoy. It's an opportunity for our researchers to get out of their labs and engage the public in our excellent research."

Professor Andrew Livingston and Professor Kang Li awarded the President's Medal for Outstanding Research Team

President's Medal for Outstanding Research Team

In 2017 **Professors Andrew Livingston** and **Kang Li** were recognised with the most prestigous Imperial College research award, the President's Medal for Outstanding Research Team.

The Medal for Outstanding Research Team celebrates the achievements of research teams at Imperial, recognising outstanding research that delivers impact, a team's international standing and their beneficial contribution to Imperial. The long-standing collaboration was recognised at the time, with particular mention made of the fact that Professors Livingston and Li had published more than 500 journal articles, founded two start-up companies and graduated more than 50 PhD students since 2003.

Professor Livingston remarked on the award: "It is an honour for us all to be singled out for special recognition in an environment such as Imperial where everyone is excellent. There are highlights such as papers in Science and Nature Materials, success of start-up companies, and other awards."

"However, the biggest success for Kang and I is tracking the successful careers of our students and post-docs who have gone on to start their own research groups as academics, or become practitioners of chemical engineering in industry."

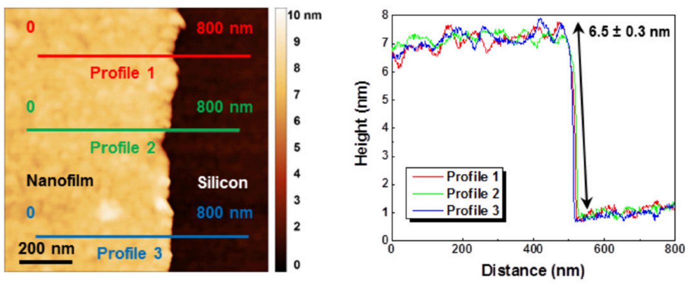
Unpacking the mysteries of thin film composites

Background

Membrane processes have been widely employed in separation industries since they consume less energy when compared to conventional evaporation processes. Thin film composite (TFC) membranes are commonly used in the desalination industry via reverse osmosis process, which comprise a skin layer separating dissolved ions from seawater and a support layer providing the mechanical strength to withstand high applied pressures. Although TFC membranes have been used for decades, the characteristics of the skin layer and the impact of the support layer on membrane performance are still mysteries. This is due due to the relatively uncontrolled process of fabricating the polyamide layer via interfacial polymerisation (IP) on the surface of the support layer. During the IP process, the properties (i.e., surface roughness, hydrophilicity, porosity, etc.) of the support layer could significantly influence the characteristics (i.e., thickness, surface area, etc.) of the skin layer, making it difficult to study either independently. Therefore, the deconstruction of the TFC membranes is the key to resolving the mysteries.

Our approaches

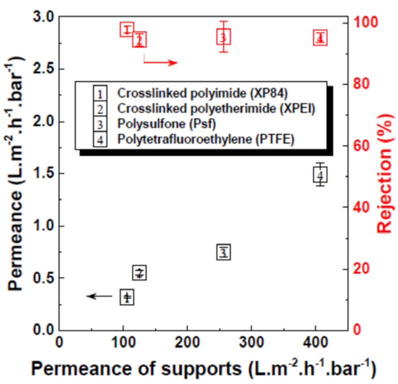
In contrast to the conventional IP reaction, we have isolated the fabrication process of the skin layer from the support layer by making it on a sacrificial layer or at a free liquid-liquid interface. These approaches provide an identical medium for the interfacial reaction regardless of the support layer, which allows investigation of the individual impact of the skin layer and the support layer. Moreover, these approaches provide a sufficient amount of reactant even at low concentrations, which leads to the formation of the ultrathin polyamide layer for fast liquid transport.



Height profile revealing the thickness of the freestanding polyamide film.

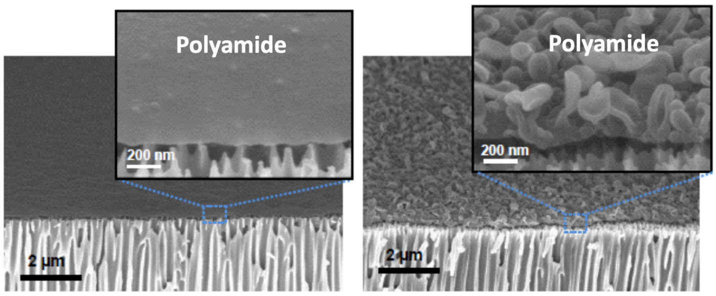
Our findings

By isolating the fabrication of the polyamide layer from the support layer, we found the support layer actually contributes significantly to the overall membrane performance, more than we ever thought. The support layer contributes in two ways. Firstly, while the polyamide layer is made under identical conditions at the free interface and transferred onto different supports, the support layer with high pure water permeance facilitates fast overall water transport for the resulting TFC membranes. This is due to a shorter lateral distance the water molecules have to travel to encounter a pore for further transport on a more porous support.



Performance of TFC membranes against the permeance of the pristine supports

Secondly, when the identical polyamide layers are attached onto polymer and inorganic (alumina) supports respectively, the inorganic support provides a constant membrane permeance over time, whereas the polymer support suffers from permeance decay. This is attributed to the incompressibility of the inorganic support and the physical ageing of the polymer support. At high pressures over a long period operation, the polymer supports compact and cause a reduction in the permeance.



Smooth and crumpled polyamide films

By conventional IP, the skin polyamide layer appears thick and rough, for which the morphology is highly uncontrollable due to a lack of control of the reaction kinetics. In our approach, the thickness of the skin polyamide layer could be precisely controlled down to ca. 6nm while maintaining the surface roughness down to sub-nm. By employing the ultrathin polyamide layer as the separating layer of the membranes, the liquid permeance accelerates by twice as compared to the commercial standard membranes while maintaining the same solute rejections . More importantly, these ultrathin polyamide films are impressively robust and can be formed freestanding across a ca. 1.5 cm diameter wire lasso. This allows the ultrathin films to be folded and stacked into crumpled textures for increasing permeable area, leading to a tremendous enhancement of liquid transport. For instance, the composite membranes comprising the crumpled polyamide films could process acetonitrile with a permeance at ca. 110 liter per meter square per hour per bar, which is more than two orders of magnitude higher than the commercial membranes.Our work unpacks the mysteries of the composite membranes, revealing their formation mechanism and individual impact of each composite. What is more important is the ability to precisely control the morphology of the active layer and transferring them onto more porous supports. This provides an opportunity to maximize the liquid transport for reducing energy transfer, and a potential candidate for the next generation membranes.

For the future

Besides the demand of high liquid transport, the other key in membrane applications is the precise sieving between solute molecules. In contrast with desalination which requires almost 100% rejection of ions for the production of fresh water, precise sieving requires discrimination between solute molecules, allowing only the smaller ones penetrating through but retaining the larger ones. To achieve this goal, the membrane material has to be rigid with precisely controlled pore size, appearing intact and stable in the solvent. A potential candidate is carbon nanosheets which can be made by the pyrolysis of the free-standing polyamide films. This is our goal in the future work, exploring the feasibility of fabricating carbon nanosheets and applying them into precise separation processes.

Li Group

The Li Group explores a wide range of gas and liquid separation membranes, including the use of graphene oxide and advanced materials.

About the Li group
The Li group is recognised as one of the pioneering groups in inorganic hollow fibre synthesis. Their recent advancement in the fabrication of high quality single-layer, multi-layer or multi-channel inorganic hollow fibre substrates/membranes with controllable morphology, microstructure and multi-functionality unfolds its applications to a wide range of complexed molecular separations and catalytic reactions. The group also has broad research interests in new membrane fabrication techniques and in synthesis and characterisation of new functional porous materials and membranes for water, energy and environment.

Spotlight
Recent research achievements from our group are in (1) transformative platform technique for membrane fabrication, (2) Non-destructive 3-D image analysis of multi-functional ceramic hollow fibres and (3) micro-patterned synthesis of MOF membranes. We have recently discovered a transformative membrane fabrication technique, named as the combined crystallisation and diffusion (CCD) method. This method is based on an elegant freezing approach, which allows the combination of small pore size and open structures with easy quality control and process reproducibility. The membrane products made through such a technique presents so far the best performance for some types of membranes, especially PVDF membranes. We have also established the theoretical basis for the technique so that one can apply the principles to a variety of membrane materials. The research has resulted in an international patent and two important papers in Nature Communications (2016) and Journal of Membrane Science (2018). Dr Li was invited to deliver a keynote talk on this work at EWM Conference 25- 28 May, 2017, Singapore. The work on non-destructive 3-D image analysis of multi-functional ceramic hollow fibres is in collaboration with University College London (UCL) and European Synchrotron Radiation Facility (ESRF). In this collaboration, a multi-length scale X-ray Computed Tomography (X-CT) technique was employed to probe a 3D structure of our multi-functional hollow fibres which have been used as a solid oxide fuel cell for energy conversion. The research has been published in Energy Environ. Sci., (2018) and Dr Li delivered an invited talk on this work in MEMPEP 2018, Zakopane, Poland.
Our work on micro-patterned metal-organic framework (MOF) were carried out using UiO-66 as the membrane material. The technique is attractive in miniaturization of MOF membrane systems, as an ultrathin UiO-66 membrane with a thickness down to 250 nm can be grown on a substrate with a complex pattern with molecular sieving properties. The related work has been published in Angew. Chem. Int. Ed. (2018) and presented as an invited plenary talk at MELPRO 2018, Prague.

Joining the group
Since the foundation of the Barrer Centre, two talented researchers have joined our group. Marc Plunkett completed his MEng in Strathclyde in 2016. He is currently investigating metal based membranes to be used for enrichment of contaminants presented in hydrogen produced from fossil fuels to a level which can be detected by conventional techniques. Vatsal Shah started his PhD in October 2017. He completed his MEng in our department and currently is a PhD student in our group, working on CCD method.

Alumni
Over the past two years, our postdoctoral researchers have moved on to the next stage of their professional career. Dr Xinlei Liu is now a research fellow at Delft University of Technology (Netherlands). Dr Zhentao Wu joined Aston University (UK) as a Lecturer in Chemical Engineering. Also, several students have completed their PhDs and started their research careers in various universities and companies: Farah Aba (Petronas, Malaysia), Jeng Yi Chong (Nanyang Technological University, Singapore), Jing Ji (Bath University, UK), Melanie Lee (National University of Singapore, Singapore).

Grants and Awards
- Industrial Case award: Pd membranes for H_2 permeation, £108,580
- PhD studentships awarded to Vatsal Shah (Department full PhD studentship),
- System Builders - Device Assembly from Nanoporous Materials Developed from Current Platform Grant (EP/J014974/1), £1,547,752 (with Andrew Livingston and Alex Bismarck)
- Nur Izwanne Mahyon: Best International Student Oral Presentation – International Membrane Science and Technology Conference (IMSTEC 2016), Adelaide, Australia.
- Nur Izwanne Mahyon: Best Poster Presentation – Malaysia – Singapore Research Conference 2017 (MSRC 2017), Cambridge, United Kingdom.

Ladewig Group

Metal organic frameworks are developed as adsorbents and in membranes, with a particular focus on responsive materials.

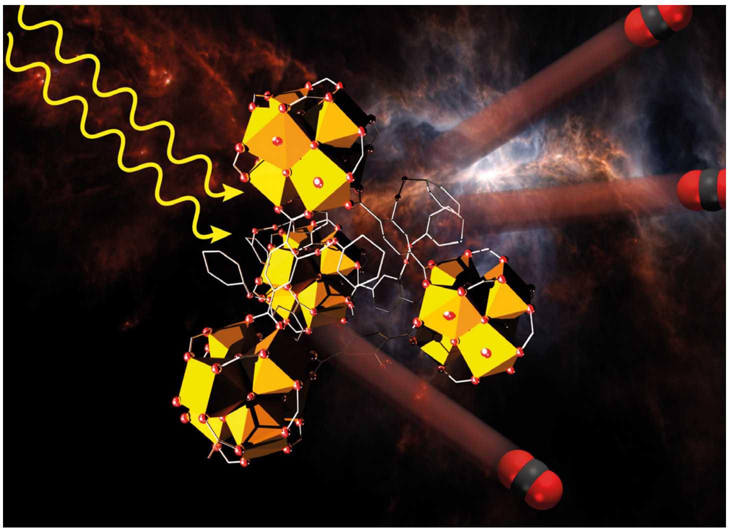
The Ladewig group was formed when Dr Ladewig moved from Monash University in Australia to Imperial College in 2015. It has a principal focus on membranes for clean energy and environmental applications, with a particular focus on the use of metal organic frameworks and other modern porous materials.

We are working on a diverse range of materials and applications, involving several key collaborations with colleagues within the Barrer Centre, within Imperial College more broadly, and internationally. One collaboration is with the group of A/Prof Matthew Hill at CSIRO Australia and Monash University, working on adsorbents and membranes for chiral molecular separations. These are highly challenging separations with important applications in the fine chemical and pharmaceutical industries. This project includes two jointly funded PhD students (Marine Michel and Ben Slater), both of whom are based at Imperial College and have spent extended periods conducting experiments at CSIRO in Australia. This project has yielded some exciting results both in the membrane aspects (as yet unpublished) and in the MOF material development (published in Journal of the American Chemical Society), and both Marine and Ben will finish their PhDs in 2019. The next phase of this project will be to involve industry partners in setting the further directions, as there is significant potential to partially replace expensive chromatographic separations with a membrane technology based on our findings.

Some of the most exciting fundamental discoveries in our group have come from work by Nicholaus Prasetya on photoresponsive MOF materials and membranes. This work, started in Australia in collaboration with A/Prof Matthew Hill and continued here at Imperial, explores the potential for gas separations using light as the stimulus to induce gas desorption or spontaneously change the molecular diffusivity in photoresponsive porous materials. Some recent publications have highlighted our results, including our publication in *Journal of Materials Chemistry A* which was featured on the inside back cover of Issue 34 (14 September 2018). This work is innovative and original, especially the photoresponsive membranes as our group has built up the only test apparatus in the world for these type of membranes.

Since the Barrer Centre was founded in 2016, two new PhD students have joined the group. **Shanxue Jiang** completed his Bachelor degree at the highly regarded University of Science and Technology in China and then his Masters at Columbia University. In his PhD research at Imperial College he is developing novel ion-exchange membranes based on highly scalable one-pot synthesis approaches, with a major focus on the elimination or reduction of toxic organic solvents from the manufacturing process.

Luqman Bin Mohd Azmi has a Bachelor of Chemical Engineering rom The University of Queensland and his Masters degree from Universiti Sains Malaysia, and he is developing adsorbents and membranes for the removal of chemicals of emerging concern from natural water sources, with a particular focus on the post-synthetic modification of highly-water-stable metal organic frameworks. Luqman's PhD is fully funded by the Malaysian sovereign wealth fund manager, Yayasan Khazanah.



Highly stable Azo-UiO-66, a photoresponsive MOF which spontaneously desorbs carbon dioxide when illuminated with UV light.

Inside back cover image from Journal of Materials Chemistry A. doi: 10.1039/C8TA03553A

Petit Group

The Petit Group exploits a range of tailored porous materials for molecular separations and catalysis.

About the Petit group
Dr Petit joined the Department of Chemical Engineering at Imperial to start her own research group in 2013. Our first PhD students and postdoctoral researcher joined in 2014. In our group, we design, synthesise, characterise and test porous materials (i.e. sorbents) that can address separation challenges related to environmental, water and energy sustainability. When relevant and possible, we confer our materials a catalytic property in addition to their sorptive nature as a way to intensify processes. This leads to the creation of multifunctional materials. Our main focus is on porous nitrides (i.e. boron nitride and carbon nitride), metal organic frameworks (MOFs) and composites for applications in molecular separations and solar energy conversion.

Spotlight
Our group has quickly developed expertise in an intriguing material called boron nitride – also named 'white graphene'. We are particularly interested in its porous form, which can be used for gas sorption, heterogeneous catalysis, drug delivery and other applications. We have patented a method to synthesise porous boron nitride with record high surface area and a tuneable pore structure. Our findings have also been published in ACS Nano (in the top 20 overall scientific journals, ACS Nano, 11, 10003-1001). We are now exploring large-scale production of the material with two industrial partners. Dr Petit has been invited to give a plenary talk on this work at the next Fundamentals of Adsorption international conference in 2019.

Joining the group
Since the foundation of the Barrer Centre, two talented researchers have joined our group. **Ravi Shankar** completed his MEng in our Department in 2016. He is currently investigating the potential of porous boron nitride for solar energy conversion. **Giulia Schukraft** started her PhD in early 2018. She completed her BSc and MSc at EPFL. She is studying the formation of heterojunctions based on 2D MOFs for CO_2 capture and photoreduction.

Alumni
Over the past couple of years, our postdoctoral researchers have moved on to the next stage of their professional career. Dr Ryan Luebke is now a Technology Commercialization Specialist at Cornell University (USA). Dr Kostas Christoforidis and Dr Salman Shahid have started their academic career as research group leaders at the University of Thrace (Greece) and the University of Bath (UK), respectively.

Grants
- 2018: BP-ICAM grant and Engineering and Physical Sciences Research Council (EPSRC) Impact Acceleration Account grant to investigate the scale-up of porous boron nitride.
- 2017: EPSRC grant as part of the UK Carbon Capture and Storage Research Centre to accelerate CO_2 sorbents development.
- 2017: Royal Society of Chemistry outreach fund to develop an hands-on activity to raise awareness on the importance of environmental protection, highlight the role of scientists in this regard, provide basic knowledge of related porous materials chemistry.

Awards - ***Camille Petit***
- 2017 ExxonMobil European Science & Engineering Program Award (for *"outstanding research in Functional Nanomaterials for Energy & Sustainable (Petro)Chemistry"*; 1 award bi-annually; £40,000)
- 2017 AIChE 35 Under 35 Award (for *"significant contributions to the field of Chemical Engineering and AIChE"*; 35 people selected each year, inaugural award)
- 2017 IOM3 Silver Medal (for *"outstanding contribution to a field of interest within the Materials, Minerals or Mining sector"*; 1 award each year)

Ravi Shankar
- Best poster presentations (Imperial PhD Symposium, 2017)

Angus Crake
- Best oral presentation (PhD student, ChemEngDay UK, 2018)
- Runner-up prize for oral presentation (Materials Science and Technology Literature Review Prize, IOM3, 2017)
- Runner-up prize for poster presentation (ChemEngDay UK, 2017).

Arwyn Evans & Sofia Marchesini
- IChemE Separations Special Interest Group travel bursary (2016, 2017)

Song Group

Advanced porous materials and polymers for use in emerging energy applications

The Functional Membrane and Energy Materials Group is a new group led by **Dr Qilei Song** in the Barrer Centre at Imperial College London. The group has broad research interests in design, synthesis, and characterisation of functional porous materials and membranes for energy applications, including renewable energy production, advanced batteries for energy conversion and storage, and industrial energy-intensive gas separations including CO2 capture.

The group are carrying out interdisciplinary research at the interface of chemistry, materials, and chemical engineering and collaborate extensively with chemists and materials scientists in the UK and worldwide. Activities include design, synthesis and characterisations of novel microporous materials, such as polymers of intrinsic microporosity, metal-organic frameworks, and nanostructured carbon materials. Materials are fabricated into membranes for gas and liquid separations, electrode materials and ion-selective membranes in rechargeable batteries for energy conversion and storage. Extensive physical and chemical characterisation of materials are performed providing a fundamental understanding of structures and their structure-property-function relationships.

Spotlight
Recent research activities from the group are mainly focused on the development of microporous membranes from a range of cutting edge porous materials such as metal-organic frameworks, polymers of intrinsic microporosity, and porous organic cages. One study on polymer/MOF composite membranes was published in Nature Energy (2017), involving collaboration with Kyoto University. The work was featured on Imperial College News. Our recent work on the development of novel membranes from porous organic cages in collaboration with the group of Prof. Andrew Cooper at University of Liverpool leads to two papers published in Advanced Materials (2016) and Angew Chem Int Ed (2017).

We demonstrated the first example of formation of selective membranes of 2-nm sized molecular cages, and their disordered or ordered packing behaviour plays a critical role in the formation of amorphous membranes or oriented 2D crystals with continuous channels for molecular transport. The fundamental research on the formation of membranes from novel porous materials have broad implications on developing next-generation membranes for molecular separations and energy applications.

Joining the group
The research group consists of one postdoc, three PhD students, and several MSc and UG students.

Dr Lei Yang joined the group in July 2018 as a postdoc researcher to work on organic redox flow batteries. He received his PhD at the University of Chinese Academy of Science. **Anqi Wang** started his PhD in February 2018 working on design and synthesis of porous polymers for energy applications. He received his BEng at Zhejiang University in 2016, and MSc in Department of Chemical Engineering at Imperial College. **Rui Tan** started his PhD in October 2017 under the co-supervision of Dr Qilei Song and Prof. Nigel Brandon. Rui received his B.S. in Energy Materials and Devices at Central South University, and MSc in Advanced Materials at Peking University, Shenzhen Graduate School. His PhD research is focused on developing functional materials for solid-state batteries and redox flow batteries. **Dezhi Liu** just started his PhD in October 2018. He received BEng in Chemical Engineering at DalianUniversity of Technology and MEng at University of Rochester. His PhD is focused on microporous membranes for separation applications.

Alumni
Since the establishment of the research group, several MSc students have graduated from the group and some of them are working at leading global companies in the chemical and oil &gas industry.
Xiaoqi Li, MSc 2016, Evonik (Shanghai)
Nan Ding, MSc 2016, BASF (Shanghai)
Qiao Zhang, MSc 2016, Schlumberger (Shanghai)
Tianhe Zhang, MSc 2017, Johnson and Johnson (Shanghai)
Barbara Primera Darwich, MSc 2017, PhD student at EPFL.
Xinyu Zhang, MSc 2018, SinoPec (Beijing)
Zhiyu Fan, MSc 2018
Yanchi Liu, MSc 2018

Projects/grants/awards
The group was awarded a seed-funding grant on redox flow battery from EPSRC centres CAM-IES and SuperStore.
PhD studentships awarded to Anqi Wang (Department full PhD studentship), Rui Tan (full PhD studentship funded by the China Scholarship Council).
IChemE Nicklin Medal to Dr Qilei Song.

Publications

The Barrer Centre publishes in a wide range of scientific and engineering journals. The list below covers publications from the founding of the Centre through to August 2018.

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