Institution: University of Bath

Unit of Assessment:12: Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Creation of industrial products, processes and company growth from research on highly structured materials for gas adsorption and separation

1. Summary of the impact

Research at the University of Bath on highly structured materials for adsorbing and separating gases has created business and economic impact via:

- Inward investment of £2.5 million in a University spin-out small and medium enterprise (SME), n-psl (Nano-Porous Solutions Ltd), whose business is developing new products for energy efficient gas separation for environmental and medical applications. Turnover of the new company is now > £1 million pa and growing, and has created significant inward investment opportunities from the USA for two of n-psl's customers, Parker Hannifin Manufacturing and Ultra Electronics, in military and personnel protection applications.
- Improvement to existing products of an established SME (MAST Carbon International Ltd). Industrial testing of a new process, co-invented by MAST and the University, which contains the improved products; the new process is for specific gas separation aimed at meeting legislative emission limits, creating healthier workplaces, and recovery and reuse of valuable resources.
- Creation of 28 new jobs, 24 within n-psl and four within MAST, together with the enhanced security of three within Parker Hannifin Manufacturing in the UK and several others at MAST.

[Comment: Although beyond the cut-off date for impact achievement, as at 31 October 2013 n-psl had been acquired by the FTSE 100 listed international engineering group, IMI plc.]

2. Underpinning research

Background: The underpinning research concerns the development of novel adsorbent materials for specific gas separation and purification. By researching nano-porous internal structures set within optimised external structures, the aim has been to obtain high separation performance but at a very much reduced pressure drop. Low pressure drops are desirable because less energy is consumed to perform each gas separation or purification. In turn, less carbon dioxide associated with primary energy provision would be released into the natural environment. Adsorbents are most commonly available in granular form. Energy is lost, manifested as pressure drop, as gases are passed through vessels containing such materials. Pressure drop occurs from skin friction (energy loss as gas flows over material surfaces) and via form drag (energy loss as gas flows through tortuous paths around granular materials). For granular materials, form drag is much higher than skin friction. The University's research has been directed at designing materials that eliminate as much form drag as possible and hence the focus has been on structured materials that comprise straight channels, in the form of hollow fibres or monoliths, thereby eliminating tortuous gas flow paths.

Key researchers: The following academic staff in the Department of Chemical Engineering's Advanced Materials & Porous Solids Research Group have been in post throughout both the research and the REF periods: Professor BD Crittenden (Group Leader & Professor throughout), Dr TJ Mays (Lecturer to 2002, Senior Lecturer from September 2002) and Dr SP Perera (Lecturer to 2004, Senior Lecturer from September 2004). In addition, Professor ST Kolaczkowski (Professor throughout) was involved in some of the initial research.

Nature of the research insights or findings: Results from fundamental research, published between 1998 and 2000 [1, 2], revealed considerable promise for the University's novel monolith concept. This early research soon led to industrial interest and collaboration with a range of industrial organisations through an EPSRC/DTI LINK grant awarded in 1997 to develop activated carbon monoliths (ACMs) that could be used to capture volatile organic compounds (VOCs) within factory environments. The LINK project aims were to improve health in the workplace, meet legislative emission limits, and recover solvents for reuse within the factory. The principal collaborator was MAST Carbon Ltd (now MAST Carbon International Ltd). A key research finding made by the University was that the new straight channel monolith materials could compete equally in terms of separation performance with their granular counterparts but with the major advantage of a substantially reduced pressure drop [3]. The LINK project created a new commercial process that won the Severn Trent Water Safety Award at the Institution of Chemical Engineers Gala Awards in 2002. US and European patents for this new process, on which MAST and Bath staff are named as joint inventors, were granted in 2005 and 2008, respectively. Supported by EPSRC in 2004-2007, the University continued to pursue fundamental research aimed at understanding how the ACMs were able to perform so well. For example, it was important to determine how the hundreds of flow channels in a monolith would perform as a collective set [4].

The route to commercialisation included Teaching Company Scheme (TCS), Technology Strategy Board (TSB), and Knowledge Transfer Partnership (KTP) projects with MAST Carbon. TCS project 4211 (2003-2005) was rated Grade 1 ‘excellent’ and led to publication of TCS Case Study No. 6003. TSB project K3510G (2007-2010) was awarded so that demonstration units of the new VOC recovery process could be tested in the field. This TSB project (£2.3 million total value) involved the University’s researchers, MAST Carbon Ltd, Wellman Defence Ltd and four other industrial companies. KTP project 7128 (2009-2011) was shortlisted at the IChemE Gala Awards in 2010.

Research success with the monolith structures stimulated further fundamental research on low pressure drop materials at the University from around 2003, leading to the patented invention of hollow fibres that incorporate functional materials [5, 6]. This research led, *inter alia*, to the invention of an electrically regenerable adsorption unit for air purification and for VOC removal and recovery. The University’s research on the new fibres was recognised by the Royal Society which made its highly prestigious Brian Mercer Award for Innovation to Dr Perera in 2007. The patent rights have now been assigned by the University to the spin-out company (n-psl) whose sole business is founded on the University’s hollow fibre inventions. The novel fibres invented at the University are finding their main use in compressed air treatment where the potential is to reduce energy consumption by 50% over existing methods because the pressure drops are so low. A Carbon Trust project with Bath and n-psl in 2008-2009 concluded that the reduced energy consumption would translate into a minimum accumulated saving in emissions of CO_2 of over 4 million tonnes by 2050.

3. References to the research (* references that best indicate quality)

1*. YY Li, SP Perera and BD Crittenden. Zeolite monoliths for air separation, Part 1: Manufacture and characterisation, 1998, Chemical Engineering Research & Design, **76**, 921-930. DOI: 10.1205/026387698525720

2. LY Lee, SP Perera, BD Crittenden and ST Kolaczkowski. Manufacture and characterisation of silicalite monoliths, 2000, Adsorption Science and Technology, **18**, 147-170. DOI: 10.1260/0263617001493350

3. BD Crittenden, A Patton, C Jouin, SP Perera, SR Tennison and JA Botas Echevarria. Carbon monoliths: a comparison with granular materials, 2005, Adsorption, **11**, 537-541. DOI: 10.1007/s10450-005-5981-9

4*. BD Crittenden, O Camus, SP Perera, TJ Mays, F Sánchez-Liarte, SR Tennison, S and E Crezee. Non-uniform channels in adsorbent monoliths, 2011, AIChE Journal, **57**, 1163-1172. DOI: 10.1002/aic.12335

5. SP Perera and CC Tai, Hollow fibres, WO 2007/007051 (2011). DOI: D01D5/247

6*. JM Nevell and SP Perera. Novel adsorbent hollow fibres for oxygen concentration, 2011, Adsorption, **17**, 273-283. DOI: 10.1007/s10450-011-9323-9

4. Details of the impact

The University’s research into novel, highly structured materials in the form of hollow fibre and monolithic adsorbents has led to products and processes aimed at energy efficient gas separation and purification, meeting legislative emission limits, creating healthier workplaces, and recovering valuable resources for reuse. Consequently, our research has led to important business and economic impact in two small-to-medium size enterprises, namely, Nano-Porous Solutions Ltd (n-psl) and MAST Carbon International Ltd, as well on the businesses of their clients.

Nano-Porous Solutions Ltd (n-psl): Following the prestigious Royal Society Brian Mercer Award for Innovation to Dr Perera in 2007, n-psl was first registered in the same year as a University of Bath spin-out, new business in Gateshead, Tyne and Wear. n-psl moved into its first industrial premises in January 2008, where its business began by recruiting technical, production and sales staff. Meaningful inward investment, growth and employment in n-psl also started to take place in 2008. The Finance Director of n-psl has commented that [A]:

> '*inward investments to exploit Bath's nano-porous materials technology have now included over £2 million from industry and venture capitalists as well as £500k from the Royal Society Investment Fund*.'

Furthermore, Bath's research has created in n-psl a company that [A]:

> '*now has 24 employees and an annual turnover in excess of £1 million which is continuing to grow.*'

Using Bath's original research, n-psl has developed product lines that include ultra-high purity compressed air dryers, CO_2 adsorption dryers, and equipment for the removal of volatile organic compounds (VOCs) that are emitted from a broad range of sources [A]. Patent rights have been assigned by the University to n-psl [B]. Using materials developed at Bath, n-psl's product range has continued to grow. Proving trials include a demonstrator with Slovakian compressor manufacturer Ekom for dental air drying and ventilator applications, and demonstrators for water and hydrocarbon removal in railway applications in the USA. Dental dryers have already been supplied to the American market [A].

The fibre technology assigned by the University to n-psl has also been adopted by other companies, notably Parker Hannifin Manufacturing Ltd, also based in Gateshead, and Ultra Electronics in Gloucester. Parker has collaborated with Bath since 2004 and has used Bath's technology to create a novel multilayer hollow fibre adsorbent device for chemical, biological, radiological and nuclear (CBRN) filtration. The company won $980k from the USA Defence Threat Reduction Agency for this development [C]. The Research Manager at Parker comments that [C]:

> '*Following on from its own independent work, dhFNS* [domnick hunter Filtration and Separation Division of Parker Hannifin Manufacturing Ltd] *have also collaborated extensively with the University of Bath and their spin-out venture n-psl, further investigating hollow fibre technology for not only CBRN applications but also for potential* CO_2 *capture systems and devices for compressed air dehumidification. Over a period of 3 years Parker has invested over $400k in the research program.*'

Parker adds further [C]:

> '*working with the University of Bath…also assisted in securing the positions of three R&D personnel at our Gateshead facility and will hopefully allow us to recruit more in the future* ...
>
> *… recent collaboration has seen the Chemical Engineering Department contracted to produce a performance model of our CBRN device. The successful modelling effort has proven vital in the development of our life saving collective protection equipment.*'

The superior performance of novel materials developed at Bath for CBRN applications has made an impact on other organisations and Dstl (Porton Down), for example, is now seeking to find out how the new materials could be used in its respirators [D].

Ultra Electronics (Precision Air & Land Systems) has worked with n-psl to develop a small regenerative air drying filter for pneumatic ejection systems in military aircraft and for drying oxygen in military fuel cells. The New Products Manager at Ultra comments that [E]:

> '*… the regenerative filter technology* [using adsorbent fibres invented through the original research] *was a key factor in winning a major contract* [with Raytheon Company]*, which over the life of the equipment would be worth tens of millions of pounds.*'

MAST Carbon International Ltd: MAST, an SME based in Basingstoke, has collaborated with Bath researchers from about 1996. The company's business is in the supply of advanced carbon materials for separations, reactions and environmental protection. One of MAST's products is the low pressure drop activated carbon monolith (ACM). Bath's research on ACMs, which was carried out in collaboration with MAST from 1997, stemmed from the University's original research on inorganic adsorption monoliths in 1996 and led to the development of a new process to recover (VOCs) in the factory workplace. The European patent naming Crittenden and MAST staff as inventors of this new process was granted in 2008 [F].

Alongside invention and development of the new process, Bath's research also led to improvements to the design of the company's ACMs which are used within the process. The Managing Director of MAST has commented that [G]:

> '…*your research team's research skills and knowledge led to a significant improvement to our existing ACM design. To be precise, the cell density of our ACMs was increased from 250 to 600 cells per square inch based on your research that showed that this change would improve the efficiency, effectiveness and dynamics of the solvent* [VOC] *recovery process. It was this improved design that was used for the industrial scale equipment tested by ConvaTec.*'

Development of the industrial scale equipment (50 m^3 h^{-1} of air) shipped for testing at ConvaTec's premises in South Wales in 2010 was funded by the TSB. ConvaTec mounted equipment trials to demonstrate that it could be used to meet Environment Agency legislative limits on the emissions of ethanol used by the company to dry polymers used in the manufacture of wound dressings. The equipment, constructed by Wellman Defence (Portsmouth) and incorporating 14 ACMs supplied by MAST to Bath's improved design, costs around £105k (£30k for parts and £70k for design and construction man-hours). MAST comments further [G]:

> '…*your team's research leading to our better understanding of how our monoliths work led recently (2012) to my company's success in winning a £1.5 million Energy Technology Institute Award with Inventys to build a 50 kW demonstrator that uses 600 of the improved ACMs to recover carbon dioxide from power station flue gases… …Your team's research has also had an impact on our employment levels. Throughout our collaboration with your research team we have been able to sustain the employment of several of our employees and to create four new posts, no mean feat for an SME with only 15 employees in total.*'

MAST concludes [G]:

> '…*the fundamental research of your research team at the University of Bath had a major impact on our initial work on adsorption, and continues to have a significant impact on our ongoing work in the field of advanced adsorbents which now encompasses fields as diverse as biomedical blood filtration, chemical and biological defence and catalysis alongside the original air purification studies.*'

5. Sources to corroborate the impact

A. Corroborating statement from Finance Director, Nano-Porous Solutions Ltd, 16 September 2013.

B. EP 1913183 B1 (granted 2011) and WO 2008/110820 A1 (pending, filed in 2008).

C. Corroborating statement from Research Manager, Parker Hannifin Manufacturing Ltd, 10 September 2013.

D. Corroborating statement from Principal Scientist (Adsorption Science), Dstl, 11 September 2013.

E. Corroborating statement from New Products Manager, Ultra Electronics, 22 January 2013.

F. EP 1372817 B1 (granted in 2008).

G. Corroborating statement from Managing Director, MAST Carbon International Ltd, 15 September 2013.