Institution: Imperial College London

Unit of Assessment: 13B Metallurgy and Materials

Title of case study: Solid Oxide Fuel Cells for High Efficiency Domestic Combined Heat and Power

1. Summary of the impact

Patents arising from EPSRC funded research by Kilner (PI) and Steele, Atkinson and Brandon (CoI's) resulted in the development of a unique metal-supported solid oxide fuel cell and formation of the spin out company Ceres Power in 2001. Ongoing development at Ceres Power has been supported by further underpinning research by the Fuel Cell group in the Department of Materials at Imperial and has produced a world-leading SOFC fuel cell module which provides the core component for a variety of applications and fuels, including: micro combined heat and power (mCHP); mobile auxiliary power units (APU); and remote power. Ceres Power has developed a mCHP unit containing the core module for residential applications powered by natural gas in collaboration with British Gas and Bord Gais (Ireland). The unit has an electrical efficiency of 45% and total efficiency of 90%. It reduces the energy bill by 25%, and saves around 1.5 tonnes of CO_2 per annum per household. The company is AIM listed and in 2011 had 160 employees, with a technology centre in Crawley and a manufacturing plant in Horsham. Over the period of the review the company has directly provided approximately 600 man years of employment in the UK.

2. Underpinning research

The Department of Materials at Imperial College London has a long-established, world-leading position in the general field of ion-conducting ceramics, with a particular emphasis on their application in SOFCs. A strategic theme in this research, which resulted in the specific innovation described here, was to reduce the SOFC operating temperature as much as possible. In the early 1990's, there was a resurgence of interest in the solid oxide fuel cell and the Department of Materials (Steele, Kilner, Atkinson) began a program of research to develop materials capable of operating at much lower temperatures. Conventional cells operated at between 700 and 1000ºC and were, in the main, all ceramic devices employing brittle glass seals. These devices were costly and mechanically weak with durability problems caused by the high temperatures of operation. The goal of the research was to find a materials set that could operate at temperatures as low as 500ºC, where much cheaper stainless steels could be used for support of the cell, interconnects and for the balance of plant. Through a basic research programme, this materials set was identified based around an optimised ceria gadolinia electrolyte (reference 1), a nickel-ceria anode and doped lanthanum ferrite (LSCF) cathode (reference 2). The core patent behind Ceres arose out of research conducted through EPSRC grant GR/N04638/01 OPTIMISATION AND EVALUATION OF INTERMEDIATE-TEMP (500 C)SOLID OXIDE FUEL CELL (IT-SOFC) STACKS (J A Kilner (PI), N P Brandon, B C H Steele, A Atkinson, all of Imperial College London) 1st October 2000 to 31st January 2004. This focussed on developing; the anode and cathode material for use with ceria electrolytes; the electrode, electrolyte and cell fabrication processes that enabled SOFC operation at 500-600ºC; and use of a metal support to produce a robust device free of the need for delicate glass ceramic seals (reference 3). At that time, a metal-supported SOFC was a radical new concept, as was the relatively low operating temperature of 500-600ºC for a SOFC, and this research was the first to demonstrate a working device. Now several companies and research groups worldwide are pursuing metal-supported SOFC technology, and the reduction of operating temperatures to 500ºC, or even lower.

Core patents behind Ceres Power fuel cell module technology were filed by Atkinson, Kilner et al., over the period 2000 to 2004, and subsequently granted from 2003 to 2006 (reference 4). Subsequent to the patent filing, papers were published by Atkinson, Kilner et al over the period 2004 onwards which addressed issues such as the properties of the LSCF cathode (reference 5) and the development of new materials for ITSOFCs (reference 6). Publication of some of this material was not possible before the patents were filed, but contributed to the patents. Other research has contributed to the ongoing technology development at Ceres Power. The core underpinning research that supported Ceres Power was carried out through a series of EPSRC funded programmes which included a grant to transfer the technology for the deposition of the cells onto the stainless steel substrates, from the Department of Materials to Ceres Power (Optimised thick film electrolytes for IT-SOFC manufacture, GR/S81476/01, J.A Kilner October 2003-October 2004).

3. References to the research

* References that best indicate quality of underpinning research.

1. *Steele, B.C.H. “Appraisal of Ce1-yGdyO2-y/2 electrolytes for IT-SOFC operation at 500ºC”, Solid State Ionics Volume: 129 Issue: 1-4 Pages: 95-110 (2001) DOI: 10.1016/S0167-2738(99)00319-7 .
2. *Dusastre, V.,Kilner, J.A. "Optimisation of composite cathodes for intermediate temperature SOFC applications", *Solid State Ionics*, 126 [1-2] 163-174 (1999) DOI: 10.1016/S0167-2738(99)00108-3.
3. Esquirol, A., Brandon, N. P., Kilner, J. A., Mogensen, M. "Electrochemical characterization of La0.6Sr0.4Co0.2Fe0.8O3 cathodes for intermediate-temperature SOFCs", *Journal of the Electrochemical Society*, 151 [11] A1847-A1855 (2004) DOI: 10.1149/1.1799391.
4. B.C.H., Atkinson, A., Kilner, J.A., Brandon, N.P., Rudkin, R.A. , *Fuel Cells* Steele, US patent US6794075(B2). Sept 21 2004. The image of the patent is archived here.
5. *Oishi, N., Atkinson, A., Brandon, N.P., Kilner, J.A., Steele, B.C.H. “Fabrication of an anode-supported gadolinium-doped ceria solid oxide fuel cell and its operation at 550ºC”, *Journal of The American Ceramic Society* Volume: 88 Issue: 6 Pages: 1394-1396 2005 DOI: 10.1111/j.1551-2916.2005.00251.x.
6. Tarancon, A., Skinner, S.J., Chater, R.J., Hernandez-Ramirez, F., Kilner, J.A. “Layered perovskites as promising cathodes for intermediate temperature solid oxide fuel cells”, *Journal of Materials Chemistry* 2007, 17, (30), 3175-3181 DOI: 10.1039/B704320A.

4. Details of the impact

The underpinning research led to the invention and patenting of a new class of fuel cell, namely a metal-supported SOFC operating at 500-600ºC [A,B]. The core patent has been granted on a worldwide basis, and further patents have followed. The key commercial impact of the invention was the formation of a spin-out company, Ceres Power, in 2001 which has provided continued employment to over 100 people amounting to approximately 600 man years since 2008 (the review period). The new type of fuel cell invented by the Imperial team is particularly well suited to operation on hydrocarbon fuels (such as natural gas, LPG and diesel reformate) and its robust construction allows its application, as the core fuel cell module, in several large volume consumer applications. Ceres Power has developed a domestic mCHP unit around the 1 kWe core fuel cell module which operates on mains natural gas and generates all of the heating and hot water and the majority of the electricity needs of a typical UK home. The wall-mounted unit is designed to replace a conventional central heating boiler and uses the same gas, water and electricity

connections. The unit (Figure 1) has a high electrical efficiency of 45%, and total efficiency of 90%, which reduces the energy bill by 25%, and saves around 1.5 tonnes of CO_2 per annum per household, thereby reducing greenhouse gas emissions. This is being developed with British Gas [C] and Bord Gais based on a forward order for 37,500 units. The core SOFC module is compact, robust, cheap, fuel-flexible and has an output that makes it suitable for non-UK markets and other applications. These include auxiliary power units in large trucks or small boats, operating on reformed diesel, and off-grid power operating on LPG for use in remote locations or for uninterruptable electricity supply in collaboration with Calor.

On-going research in the Materials Fuel Cell group has continued to inform the Ceres Power development programme through sponsored research and technical meetings with the founders. Ceres Power listed on the London AIM market in 2005, and in 2011 employed around 160 technical and commercial staff in its UK manufacturing facility in Horsham, and its technology centre in Crawley[D]. On 25th April 2012 Ceres signed an agreement with the Itho-Daalderop Group B.V. to distribute Ceres fuel cell CHP products into the residential mass market within the Benelux countries. [E]. On restructuring of the company in 2013, staff numbers have been reduced and the operating costs have also been reduced by 44% to £10.2M.

Figure 1: A Ceres metal supported cell with the CHP unit in the background

Development of SOFC systems is a very competitive field of research in terms of fundamental science, technology development, and commercialisation. Ceres was nominated by the Institute of Materials Mining and Minerals for the Queen Elizabeth Prize for Engineering in 2013 and John Kilner was awarded the platinum medal [F]. The Imperial /Ceres development of metal-supported cells has had a major impact on world development of SOFCs. This was recognised in 2012 by an independent review of the Ceres technology undertaken by an international expert in SOFCs Dr Nguyen Minh [G]. Some of his findings are:

"*Unique cell/stack designs based on thin stainless steel foil interconnect and laser drilled substrate, imparting high levels of mechanical robustness and thermal cyclability and creating compact, lightweight sub-systems.*"; "*Increased cell/stack reliability due to durable and stable seals formed by welding and compression (vs. delicate glass seals commonly used in conventional SOFCs).*"; "*Low-cost, volume manufacturability based on conventional processes such as metal forming and screen printing with ability for high levels of automation.*"; "*Patents and know-how covering laser drilled foil substrate, cell configuration, stack design, manufacturing procedures and conditions provide significant protection against competition*". [G]

Because of these major advantages many researchers and developers (e.g. Topsoe Fuel Cells, Denmark) are currently pursuing metal-supported cell technology operating at approximately 600°C. Thus the research in this impact statement has led the field by approximately 10 years and there have been many imitators (e.g. a recent EU Project METSOFC, 2008-2011). However, no other developer has yet succeeded in matching the performance of the Ceres Power cells. As a result of this world-leading performance Ceres is now moving to embrace a global market for its

products and in July of this year announced a commercial and technical partnership agreement with South Korea's largest boiler manufacturer, KD Navien. The press release states "KD Navien is the dominant boiler manufacturer in South Korea with the largest market share of all installed boilers. It is also a major exporter to key markets around the world, particularly the US". [H]

In summary Ceres Power is a UK based SME, with globally leading fuel cell technology based on research at Imperial College London, and a strong foothold in the burgeoning market for low carbon technologies such as mCHP.

5. Sources to corroborate the impact

A. "Development of Highly Robust, Volume-Manufacturable Metal-Supported SOFCs for Operation Below 600°C", R. Leah, A. Bone, A. Selcuk, D. Corcoran, M. Lankin, Z. Dehaney-Steven, M. Selby and P. Whalen, *Electrochemical Society Transactions*, 35 (1) 351-367 (2011). [ISBN: 978-1-60768-236-3]

B. EPSRC case study on the impact of its research which discusses Ceres Power and the role played by underpinning research at Imperial College funded by EPSRC http://www.rcuk.ac.uk/documents/energy/fuelcells.pdf. Archived here on 28/10/2013

C. British Gas ordered 37,500 Ceres units for the UK market and made an investment of around £20 million. http://www.cerespower.com/store/files/12-BG%20development%20supply%20and%20distribution%20agreement.pdf Archived here on 28/10/1013

D. Ceres Power "employs more than 160 people with its operations based in the UK, comprising a Technology Centre in Crawley and a volume fuel cell manufacturing facility in Horsham" page 2 Ceres Power 2011 Annual Report http://www.cerespower.com/store/files/269-Ceres%20Power%20Annual%20Report%202011%20FINAL.pdf Archived here on 28/10/1013

E. Itho-Daalderop will distribute Ceres fuel cell CHP products into the residential mass market within the Benelux countries, the third largest boiler market in the European Union with over 650,000 units sold annually http://www.cerespower.com/store/files/285-New%20strategic%20partner%20to%20access%20Benelux%20market%20.pdf Archived here on 28/10/ 13

F. Prof John Kilner Awarded the Institute of Materials, Minerals and Mining 2012 Platinum Medal (…His company, AIM, founded in 2000 now has over 100 employees and is recognised as a world leader in SOFC…". http://www.iom3.org/content/award-winners-2012 *(Archived at* https://www.imperial.ac.uk/ref/webarchive/8tf*)*

G. Independent assessment of the Company's core technology by an international expert in fuel cells and related technologies. http://www.cerespower.com/store/files/292-Ceres%20Power%20technical%20update%20and%20expert%20report%2018Sep12%20FINAL.pdf Archived here on 28/10/1013

H. Ceres signs commercial and technical partnership agreement with South Korea's largest boiler manufacturer, KD Navien. http://otp.investis.com/clients/uk/ceres-power/rns/regulatory-story.aspx?cid=142&newsid=352685 (Archived at https://www.imperial.ac.uk/ref/webarchive/0tf*)*