Institution: Loughborough University

Unit of Assessment: B12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Fuel cell research powers zero-emission vehicles

1. Summary of the impact (indicative maximum 100 words)

Research in Proton Exchange Membrane Fuel Cells at Loughborough University (LU) has led to commercial and innovative impacts on a global scale which have included the development of the world's first purpose-built hydrogen fuel cell motorbike, the world's first manned fuel cell aircraft and a zero emission fuel cell hybrid London taxi, with major international companies, such as Suzuki, Boeing and Lotus. These developments have arisen due to the creation of the spin out company Intelligent Energy (IE). The company currently employs some 350 personnel, has a total shareholder investment over £100M and was valued at $0.5B in 2012.

2. Underpinning research (indicative maximum 500 words)

From 1988 to 2001, LU's Department of Chemistry collaborated with the Department of Aeronautical and Automotive Engineering in one of Europe's first research and development programmes working on the development of proton exchange membrane (PEM) fuel cell technology for application in transport and stationary uses. This section summarises the underpinning research since 1993.

The research was supported by various sources including the EPSRC, DSTL and industry. The focus was on high power density and on making fuel cells small enough, light enough and robust enough to enable zero-emission vehicles to operate viably. The context was – and remains – a desire for zero-emission (at the tailpipe) vehicles with an attractive range, rapid refuelling and ability to cope with impure hydrogen fuel and the effects of city (and battlefield for the military) air.

The Loughborough team constructed the UK's first kilowatt-level PEM fuel cell stack in 1995 and launched a University spin out company, Advanced Power Sources (APS). By 2001 private finance capital had been attracted to invest in a new company, Intelligent Energy (IE), which acquired APS and secured an irrevocable, worldwide licence to exploit the fuel cell related know-how of APS. It was the first UK company established to specifically address the development and commercialisation of PEM fuel cells.

Researching and developing methods of preventing CO (carbon monoxide) contamination on both the fuel (anode) side and the air (cathode) side is a key challenge pursued at Loughborough. CO is present in the city environments zero emission vehicles will travel in, at least during the first few years until the benefits from using such vehicles are realised. The research looked at the design, evaluation and modelling of a CO selective oxidation reactor in 1996-2000 **[3.1]**. On behalf of the military, the research also encompassed the effects of battlefield contaminants on the performance of PEMFCs in 1995-1998 **[3.2]**. Battlefields can also contain high levels of CO that can impair the fuel cell's performance. The research also led to advanced techniques for purging the anode side of the fuel cells in the stack, which results in the avoidance of the build-up of any contaminants present in the hydrogen fuel allowing cheaper, industrial grade hydrogen to be used.

Early prototype fuel cells produced at LU had cylindrical geometry, later evolving to cuboidal. The breakthrough was the creation of thin, lightweight, metallic bi-polar plates that enabled the use of the fuel cells in transportation **[3.3, 3.4]**. These achieved the best power density in the world as the result of low volume bipolar plates coupled with novel low-weight cooling methods **[3.5]**.

The research also discovered advanced humidification techniques that obviate the need for external humidification, a major saving in space and weight for the fuel cell system package; an extremely important factor in transportation applications in 2000 **[3.6]**.

Loughborough University's key researchers in this work were: Dr. Phil Mitchell (PhD and Lecturer 1980 until 1998 at LU, now Chief Technology Officer of IE); Dr. Paul Adcock (PhD and Senior

Lecturer 1984 until 2001 at LU, now Director of Research of IE); Dr. Chris Dudfield (PhD and Research Associate 1993 until 2001 at LU, now Technical Director - Corporate Development of IE); Dr. Jon Moore (PhD and Research Associate 1992 until 2001 at LU, now Communications Director of IE); Dr. Simon Foster (PhD and Research Associate 1993 until 1995 at LU, now Technology Specialist of IE); Prof. Rui Chen (PhD, Research Associate, now professor at LU 1999 to present).

3. References to the research (indicative maximum of six references)

3.1 C.D. Dudfield, R. Chen, P.L. Adcock, A compact CO selective oxidation reactor for solid polymer fuel cell powered vehicle application, Journal of Power Sources 86 214–222 (2000). DOI: 10.1016/S0378-7753(99)00427-9. *Journal impact factor: 4.95; 81 citations.*

3.2 Jon M. Moore, Paul L. Adcock, J. Barry Lakeman, Gary O. Mepsted, The effects of battlefield contaminants on PEMFC performance, Journal of Power Sources 85 254–260 (2000). DOI: 10.1016/S0378-7753(99)00341-9. *Journal impact factor: 4.95; 137 citations.*

3.3 D.R. Hodgson, B. May, P.L. Adcock, D.P. Davies, New light weight bipolar plate system for polymer electrolyte membrane fuel cells, Journal of Power Sources 96 233-235 (2001). DOI: 10.1016/S0378-7753(01)00568-7. *Journal impact factor: 4.95; 131 citations.*

3.4 D.P. Davies, P.L. Adcock, M. Turpin and S.J. Rowen, Bipolar plate materials for solid polymer fuel cells, Journal of Applied Electrochemistry **30** 101-105 (2000). DOI: 10.1023/A:1003831406406. *Journal impact factor: 1.75; 249 citations.*

3.5 D.P. Davies), P.L. Adcock, M. Turpin, S.J. Rowen, Stainless steel as a bipolar plate material for solid polymer fuel cells, Journal of Power Sources **86** 237–242 (2000). DOI: 10.1016/S0378-7753(99)00524-8. *Journal impact factor: 4.95; 285 citations.*

3.6 PL Adcock, PJ Mitchell, SE Foster, Electrolytic and fuel cell arrangements, US Patent 6,040,075, Loughborough University, 2000.

Selected Grants

G3.1 Technology Strategy Board (TP/6/S/K3032H), Prof R Chen, “Prediction and management of fluid transport in PEM fuel cells, Programme of Design Engineering & Advanced Manufacturing: Management of complex fluid flow conditions”, £1,900,000 (2006-2010).

G3.2 Transport iNet, PI: Intelligent Energy, LU participation: Prof R Thring, “Fuel Cell ‘Engine’ Controller and System Integration”. Fuel cell taxi. £227,800 (2011-2012).

G3.3 Technology Strategy Board (TP F0205E), PI: Intelligent Energy, LU participation: Prof R Thring, “Fuel Cell Motorbike Fleet Demonstration”. £1,085,779 (2011-2012).

G3.4 EPSRC (GR/H16575/01), Dr P Adcock, “Design and construction of a solid polymer fuel cell based power source and associated fuel processing unit”. £183,374 (1991-1995).

G3.5 EPSRC (GR/K59507/01), Dr P Adcock, “Computer modelling of solid polymer fuel cells”. £218,409 (1996-1998).

G3.6 EPSRC (GR/K87524/01), Dr P Mitchell, “Low cost component design for solid polymer fuel cells”. £95,857 (1996-1998).

G3.7 EPSRC (GR/L60074/01), Dr M Turpin, “Carbonaceous bipolar plates for solid polymer fuel cells”. £233,142 (1998-1999).

G3.8 EPSRC (GR/K36362/01), Dr P Adcock, “ROPA: Ccaling up of solid polymer fuel cells & design of a light weight 2kwe demonstration stack”. £117,136 (1995-1997).

G3.9 EC (Contract No JOE3-CT95-0002), LU participation: Dr P L Adcock, “MERCATOX - Development and evaluation of an integrated methanol reformer and catalytic gas clean-up system for a SPFC electric vehicle”, £425,250 (1996-1999).

G3.10 National Power (GT00596), Dr P Adcock “University Technology Centre”. £178,354 (1998-2003).

G3.11 British Gas (348529/U13), Dr P Adcock, “Solid Fuel Cell Stack”, £75,814 (1994-1995).

G3.12 National Power (T000208479), Dr P Adcock, “Electric Vehicle”, £81,121 (1995-1996).

G3.13 MOD (ssdh300031), Dr P Mitchell, “Solid Polymer Fuel Cell”. £86,500 (1995-1998).

G3.14 National Power (LC/3/0037), Dr P Adcock, “Environmental Compa”. £88,868 (1993-1996).

G3.15 Ford Motor Company (472V56231), Dr PL Adcock, “Study of Solid”, £90,000 (1990-1993)

G3.16 Power-Gen (DGL50436), Dr P Adcock, "Electric Vehicle Principles". £101,175 (1996-1998).

4. Details of the impact (indicative maximum 750 words)

We now present evidence to show how our research, as cited in s2 and s3, has led to substantial commercial and innovative impacts on a global scale which have included the development of the world's first purpose-built hydrogen fuel cell motorbike, the world's first manned fuel cell aircraft and a zero emission fuel cell hybrid London taxi, with major international companies, such as Suzuki, Boeing and Lotus.

LU's fuel cell research, as cited in s2 and s3, has led to a steady accumulation of impact with global reach since the spin out company Intelligent Energy (IE) was created **[5.1]**. Note that prior to IE an earlier University spin out company, Advanced Power Sources (APS), was established and carried out developmental work, however, this predates the impact period for the REF and hence details are not included here.

IE currently employs some 350 personnel **[5.1]** and it is anticipated by the company that this will rise to 400. The majority are in the UK (Loughborough), with other bases in the US, Japan and India. In 2011/12, shareholder investment was in excess of £100M since incorporation. It had a 269% revenue growth, 150 patents granted and 298 others pending in 76 patent families filed around the world **[5.1]**. The company was valued at $0.5B in 2012. R&D expenditure accounted for more than 30% of total turnover **[5.2]**. In 2013, the company completed its largest ever capital raise of $51 million for the next stages of the company's development [**5.3**].
Strong links and collaboration exist between LU and IE on fluid transport, fuel cell control and system integration, materials, reliability, etc **[5.1]**. The company has conducted numerous projects with LU covering, for example, fluid flow, materials, vehicle control, reliability, and heat transfer, and fully expects such collaborative agreements to continue in the future **[5.1]**.

The research into thin metal bi-polar plates, the techniques that obviate the need for external humidification and those that prevent the build-up of contaminants, as cited in s2 and s3, came to fruition in first APS's and then IE's development of fuel cell stacks and vehicles. The research findings underpin the work to make fuel cells and their vehicles 'real world'.

In 2008, a 70 kW IE fuel cell system powered Boeing's inaugural flight of the world's first manned fuel cell aircraft **[5.4]**. In the same year a three-year Technology Strategy Board funded partnership with PSA Peugeot Citroen culminated in the H2Origin hybrid battery and a 10 kW fuel cell powered van that had a 300 km range **[5.5]**.

By 2011 the partnership with Suzuki led to a major breakthrough, the fuel cell powered Burgman scooter that achieved 'whole vehicle type approval'. It is the first (and to date) only fuel cell vehicle to achieve the certification approving it for production and sale in Europe. Vehicles such as prototypes or demonstrators that do not have this status must be inspected and tested one by one. In summer 2012 IE announced a 50:50 joint venture – Smile FC System Corporation, based in Japan – with Suzuki Motor Corporation to manufacture air-cooled fuel cell technologies for various industries **[5.6]**.

Funding from the UK's Technology Strategy Board enabled a major collaboration between IE and Lotus Engineering, LTI Vehicles and TRW Conekt. The result was a zero emission fuel cell hybrid London taxi that had all the features and functionality of a diesel taxi **[5.7]**. It can operate for a full day without the need for refueling, is capable of achieving a top speed of over 80 mph, refuels in about five minutes and produces no emissions other than water vapour. A fleet of five hybrid fuel cell taxis were deployed to transport VIPs around the capital during the 2012 Olympics, with hydrogen refuelling stations at Heathrow Airport and in the City of London **[5.8]**. In 2012, a partnership was formed with the global multi-industry consultancy Ricardo, which gives each other the status of 'preferred supplier' as they further the development and use of fuel cell systems. Alongside transportation, other applications being explored include scalable power cores for consumer electronics (e.g. mobile phone charger) into the consumer market from 2013 onwards **[5.9]**.

The company's competitive advantage is based on its expanding IP portfolio, knowledge base and

research capability, further mitigating risk through partnerships with industry-leading or specialist companies. The company operates a "Licensing +" business model, thus the bulk of the improved financial performance results from licensing and technology transfer revenue **[5.10]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

The following sources of corroboration can be made available at request:

5.1 IE support letter – dated 4th July, 2013.

5.2 Report and Financial Statements Annual Report 2012. Intelligent Energy Holdings plc.

5.3 Intelligent Energy Holdings plc. completes $51 million capital raising, http://www.intelligent-energy.com/about-us/media-room/news/company-news/2013/10/17/intelligent-energy-holdings-plc-completes-51-million-capital-raising

5.4 Boeing project, joint research with Intelligent Energy, 70 kW fuel cell system in light aircraft. http://www.wired.com/autopia/2008/04/in-an-aviation/

5.5 Ultra-low emission vans of the future, PSA project, joint research with Intelligent Energy, http://www.intelligent-energy.com/automotive/case-studies/psa

5.6 Intelligent Energy and Suzuki Motor Corporation Announce Completion of Ready-to-Scale Fuel Cell Production Line in Japan, http://www.intelligent-energy.com/about-us/media-room/news/company-news/2013/02/20/intelligent-energy-and-suzuki-motor-corporation-announce-completion-of-ready-to-scale-fuel-cell-production-line-in-japan

5.7 Fuel Cell Black Cab prototype First Drive, http://www.cleangreencars.co.uk/jsp/cgcmain.jsp?lnk=401&featureid=1170

5.8 London black taxi cabs to run on hydrogen by 2012 Olympics, http://www.environmenttimes.co.uk/news_detail.aspx?news_id=668

5.9 Intelligent Energy, Ricardo to offer FCEV engineering capability, http://www.sciencedirect.com/science/article/pii/S1464285912702997

5.10 The future of power? From green cars, to clean generators and even your phone Intelligent Energy's fuel cells lead the way, http://www.thisismoney.co.uk/money/markets/article-2410098/Intelligent-Energy-Fuel-cells-lead-way-cars-generators-phones.html