Institution: University of Southampton		
Unit of Assessment: 08 Chemistry		
Title of case study: 08-01 Ilika Plc: Delivering economic impact through novel combinatorial approaches to solid state materials.		
Period when the underpinning research was undertaken: 2000 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor Brian Hayden Dr Samuel Guerin	Professor of Physical Chemistry Post-doctoral Research Fellow	1988 – 2020 1999 – 2006
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The unique application of combinatorial chemistry in materials science at the University of Southampton's (UoS) School of Chemistry has underpinned the sustained success and growth of University spinout company Ilika Plc. The co-establishment of the Ilika/UoS Advanced Composite Materials Facility enabled the development, manufacture and launch of Stereax, a new class of solid-state batteries. This patented technology has been key to Ilika generating revenues of GBP11.4m over the impact period, supporting 45 jobs (and creating 11), and attracting GBP25m in investment, with a market capitalisation of GBP284m, up from GBP19.2m in 2013. The company's high-throughput materials platform has supported technological innovation in the clean energy, automotive, medical technology and transport sectors, and influenced the investment priorities of large multinational companies.

2. Underpinning research

The use of combinatorial chemistry, i.e. the rapid synthesis and screening of libraries of related molecules or materials, in industry was traditionally associated with heterogeneous catalysis and drug discovery in the pharmaceutical industry. The recognition that the technique could be applied to materials science to create new functional solid-state materials with tuneable properties and applications spanning the electronics, energy and polymers sectors gave rise to a significant body of multidisciplinary research at UoS' School of Chemistry. This followed a successful GBP6m bid to the UK Joint Infrastructure Fund [**G1**] to establish a Combinatorial Centre of Excellence at Southampton in 2000.

Professor Brian Hayden and Dr Samuel Guerin developed new combinatorial approaches to solid state materials discovery based on vacuum-deposited thin films on silicon micro-fabricated structures for synthesis, characterisation and functional screening of these materials [**3.1**, **3.2**]. Unlike alternative methods, their approach did not rely on sequential deposition and subsequent heat treatment to produce the thin film materials [**3.1**]. They designed a high-throughput optical screen that successfully reduced costs and accelerated the screening of libraries of electroactive materials, in particular fuel-cell electrocatalysts and battery materials [**3.2**]. This novel technology provided the base intellectual property for the spin-out, in 2004, of Ilika Technologies Ltd, founded by Hayden. Patents based on [**3.1**] and [**3.2**] had been filed in 2003 and were later granted between 2011 and 2013.

Hayden took up the role of Ilika's Chief Scientific Officer, while remaining employed at UoS, and Guerin left UoS to become a research scientist at the company, where he is now Science Director. As a result, research led by Hayden within the School of Chemistry continued to progress the patented technologies along Ilika's materials development pipeline in order to enhance and broaden the company's offering in the energy and electronics sectors. This included studies in which Hayden's group investigated methods for dispersing precious metals on both carbon and oxide supports for the development of low-temperature fuel-cell electrocatalysts [**3.3**]. The researchers also explored optimal processes for high-throughput synthesis and screening of hydrogen-storage alloys [**3.4**], and the development of phase change

memory devices. The company was floated on the London Stock Exchange's Alternative Investment Market (AIM) in 2010, becoming Ilika Plc.

This research-led technology development was further accelerated through the establishment of the GBP6.4m Advanced Composite Materials Facility (ACMF) at UoS in November 2014, co-funded by EPSRC (GBP3.2m), Ilika (GBP2.5m) and UoS (GBP0.7m) and opened by the Universities and Science Minister [**G2**]. Under the directorship of Hayden, the facility marked the transfer back of experience gained at Ilika in the discovery, optimisation and synthesis of new materials. Its first priority was the development and manufacture of Ilika's unique solid-state batteries.

The rise in interest in sustainable mobility has driven the development of solid-state batteries due to their significantly larger volumetric energy density and superior durability over current lithium-ion batteries. However, their power density tends to be limited by the large charge transfer resistance at their electrolyte interfaces. As part of a collaboration between Ilika and Toyota, who were interested in solid-state battery technology for electric vehicles, Hayden's group developed a high-throughput approach that was capable of delivering fast charge transfer reactions [**3.5**]. UoS and Ilika researchers also carried out research into new materials for opto-electronics (an Ilika/Seagate collaboration), and the development of tuneable dielectrics [based on **3.6**] for applications in 5G communications (Ilika/Murata) and alloys [**3.7**] for the aerospace sector (Ilika/Boeing).

As an indication of the depth of the continuing collaboration between UoS and Ilika, 33 papers have been co-authored by Ilika and UoS researchers since 2014 (total of 50 since 2006), and UoS and Ilika researchers are named as co-inventors on 25 patents since 2014 (total of 45).

3. References to the research

3.1 S. Guerin, B. E. Hayden, J. Comb. Chem. 8 (2006) 66-73. "Physical vapor deposition method for the high-throughput synthesis of solid-state material libraries". https://doi.org/10.1021/cc050117p

3.2 K. Brace, B. E. Hayden, A. E. Russell, J. R. Owen, Adv. Mater. 18 (2006) 3253-3257. "A parallel optical screen for the rapid combinatorial electrochromic analysis of electrochemical materials". https://doi.org/10.1002/adma.200600786

3.3 B. E. Hayden, Accounts of Chemical Research 46 (2013)1858–1866 "Particle Size and Support Effects in Electrocatalysis". https://doi.org/10.1021/ar400001n

3.4 S. Guerin, B. E. Hayden and D. C. A. Smith, J. Comb. Chem. 10 (2008) 37–43. "High-Throughput Synthesis and Screening of Hydrogen-Storage Alloys". https://doi.org/10.1021/cc700104s

3.5 C. Yada, C. E. Lee, D. Laughman, L. Hannah, H. Iba, and B. E. Hayden; J. Electrochem. Soc. 162 (2015) A722-A726 "A High-Throughput Approach Developing Lithium-Niobium-Tantalum Oxides as Electrolyte/Cathode Interlayers for High-Voltage All-Solid-State Lithium Batteries" https://doi.org/10.1149/2.0661504jes

3.6 M. Mirsaneh, B. E. Hayden, E. Furman, S. Perini, M. T. Lanagan, I. M. Reaney, Appl. Phys. Lett. 100 (2012) 082901. "High dielectric tunability in lead niobate pyrochlore films". https://doi.org/10.1063/1.3687722

3.7 S. Guerin, A. Guyomarc'h, B. E. Hayden, S. Yakvolev, J. Cotton, The Minerals, Metals & Materials Society (TMS2015) Supplemental Proceedings (2015) John Wiley & Sons, Inc., Hoboken, NJ, USA. "High-Throughput Synthesis and Characterization of Thin Film High Entropy Alloys Based on the Fe-Ni-Co-Cu-Ga System". https://doi.org/10.1002/9781119093466.ch138

Selected key grants

G1 EPSRC GR/M88365/01, GBP5.95m, JIF: Combinatorial Centre of Excellence, 2000-2004. PI: Prof. M. Bradley.

G2 Advanced Composite Materials Facility (ACMF), co-funded by EPSRC (GBP3.2m) and Ilika Technologies (GBP2.5m) and the UoS (GBP0.7m) in 2014.

4. Details of the impact

Research at Southampton's School of Chemistry that gave rise to a unique high-throughput solid-state synthesis methodology led directly to the creation of spinout company Ilika Technologies. This patented methodology provided Ilika with the capability to make, characterise and test functional materials up to 100 times faster than traditional techniques, enabling the company to establish a reputation as a leader in materials innovation. Over the impact period, collaborative research between UoS and Ilika within ACMF has driven technological advances for Ilika's next-generation applications for high-growth industries that include clean energy (solid-state batteries and low temperature fuel cells), electronics (memory and devices), and advanced alloys (aerospace and additive manufacturing).

During this period, using the ACMF production line that commenced in March 2015, Ilika has positioned itself as a pioneer in solid-state battery technology through the development of its new class of thin film solid state batteries, Stereax. The patented materials and processes that underpin these batteries have given them the following advantages over traditional lithium-ion batteries: non-flammable; six times faster to charge; double the energy density; 10 times longer storage without loss of charge [**5.1**]. Ilika '*expects*' the Stereax range to '*fit into or create end-markets worth in excess of $1 billion per year*' [**5.1**]. The company's revenue model involves four phases of activity: a) commercially funded and grant-funded development projects; b) manufacturing; c) IP licensing; d) receipt of royalties when products incorporating Ilika reach market. Throughout the REF 2021 period, Ilika has transitioned from the first to the second phase of activity. In the first phase, Ilika's portfolio of development programmes with industry partners generated a pipeline of commercial opportunities, which Ilika has begun to address through distribution of evaluation samples from the ACMF production line, creating a springboard for technology transfer to a 3rd party manufacturing facility. As production volumes exceed the capacity of that facility, Ilika expects to license its technology to larger scale production partners. [**5.1**].

Benefitting the UK economy and contributing to its global competitiveness

The sustained growth of Ilika Plc since 2014 has had a direct impact on the UK economy. Total turnover for this period is GBP11,500,000; annual turnover has risen from GBP1,000,000 in 2014 to GBP2,800,000 in 2020, increasing 95% from 2017 to 2018 and 38% from 2018 to 2020. As of 31 December 2020, Ilika Plc had a market capitalisation of GBP284,000,000 [**5.2**], up from GBP19,200,000 on 1 August 2013. With sales offices in the United States, China and Germany, Ilika attracts inward investment into the UK; around 90% of its commercial revenue is generated from companies headquartered overseas.

There has been a steady increase in employee numbers, from 34 in 2014 to 45 in 2020 [**5.3**]; 87% are high skilled roles in materials synthesis. In addition to Hayden as CSO, all four of the technical directors at Ilika were formerly researchers at UoS' School of Chemistry. This skills transfer has continued; 15 UoS students and researchers took up permanent employment positions at Ilika over the impact period.

Listed on the AIM in London, Ilika has attracted external investment totalling GBP25,000,000 between 2016 and March 2020. This sum was secured in three tranches. In October 2016 the company announced an equity investment of USD8m (reflected in their 2017 accounts as GBP5,800,000) following commercialisation progress made since the launch of its first class of solid-state thin film batteries earlier that year [**5.4**]. Ilika raised GBP4,100,00 at a price of 20p per share in July 2018 [**5.1**]. And in March 2020 it announced the completion of a GBP15,000,000 equity placing at a price of 40p per share to purchase manufacturing equipment and support its growth strategy [**5.5**].

Key to the company's ability to attract this level of external investment is its IP portfolio, based on UoS fundamental research. Twenty-five patents filed since 2014 named UoS and Ilika researchers as co-inventors. According to the company's 2020 annual report, Ilika '*believes its patents ring fence and protect critical IP to avoid competitors working around a single patent*' [**5.3**]. As of 2020, Ilika maintained a portfolio of 15 patent families in solid state batteries, of which 20 were granted patents. As an example, on 8 October 2019, the company announced it had been granted eight of its Stereax solid-state battery patent filings in five patent jurisdictions,

with Graeme Purdy, Ilika's CEO, saying: '*Protecting Ilika's know-how relating to solid-state batteries is key to our ability to grow our business*.' Ilika's shares traded 2.2% higher in response to the announcement [**5.6**].

In the course of discussing this REF submission, Graeme Purdy stated that "Ilika continues to have a strong synergistic relationship with UoS. We access the ACMF facility for pilot-scale battery deposition and we also use the UoS cleanrooms for wafer processing. The intellectual support, provision of highly-qualified employees and access to state-of-the-art facilities are fundamental to the continued ability of Ilika to generate value for its shareholders." [**5.7**]

Influencing investment priorities and supporting technological innovation in the clean energy, medtech and transport sectors

Ilika secured five key development and deployment projects with Original Equipment Manufacturers (OEMs) for its thin film solid-state Stereax microbatteries. In December 2016, Ilika commenced a project with Sharp Laboratories of Europe (now Lightricity) to create an autonomous energy harvesting power source by integrating a Stereax battery with Sharp's photovoltaic technology [**5.1**]. This was worth GBP320,000 to Ilika over two years [**5.8**]. A follow-up project in January 2019, in which the integrated Stereax and PV technology was deployed to power an autonomous wireless sensor for environmental sensing and asset tracking, was worth GBP227,000 to Ilika, and provided Lightricity with a further opportunity to advance the technology [**5.1**].

In March 2017, Ilika announced a collaboration with Galvani Bioelectronics (joint venture between GSK and Verily) to develop a battery for miniature medical implants to provide treatments for serious health conditions through the body's own nervous system. This was worth GBP700,000 to Ilika over an 18-month period and Galvani itself benefitted from access to GBP700,000 of grants from Innovate UK and the Medical Research Council [**5.8**].

In November 2017, the company signed a partnership worth GBP400,000 over two years with the world's fourth largest manufacturer of wind turbines, Titan Wind Energy (China), to deploy Stereax powered devices for the condition monitoring of its turbine blades [**5.1**]. Following on from this, but in a separate project, on 4 February 2020 Ilika announced that a field trial of its Stereax M250 solid-state battery on a wind turbine blade at the offshore renewable Energy Catapult facility in Blyth had been successful. The news that sufficient energy had been harvested from the blade's vibration to charge a Stereax battery, which in turn powered sensors to monitor the condition of blades that can each cost up to USD30,000 to repair, caused Ilika's shares to rise 6.3% [**5.9**].

In March 2019 Ilika commenced a trial deployment of wireless sensors powered by Stereax batteries for monitoring the condition of rail infrastructure with Network Rail. The sensors were deployed to measure track strain at high temperatures. Ilika received GBP115,000 and Network Rail, benefitting from Innovate UK funding, said that the project was '*a great example of how Network Rail would like to work with our supply chain to assist in the deployment of technology that is closely aligned with our priority challenges in order to deliver significant business benefits*' [**5.10**].

Advancing green technology for the automotive industry

Before and throughout the impact period, Ilika has worked with Toyota to develop stable oxide core, platinum shell catalyst structures for low temperature fuel cells, as part of the company's development of hydrogen fuel cell electric vehicles for the consumer market. Toyota previously described (in the related REF 2014 impact case study) '*Ilika's fuel cell catalyst formulation*' as '*key to Toyota's strategy for cost reduction*' and Ilika's high throughput technology as '*essential to overcome some of the technological barriers*'. Toyota launched its first hydrogen-powered Mirai car to the European and US markets in autumn 2015.

In March 2017, the Toyota Research Institute announced a four-year, USD35,000,000 investment programme in materials science research. The initial focus of the programme was on identifying new advanced battery materials and fuel cell catalysts that can power future zero-emissions and carbon-neutral vehicles. At the time, Toyota said: '*Ilika brings unique technical capability and will be a critical partner in our effort to develop new methodologies for catalyst*

design as well as discover new materials.' [**5.11**] Over the impact period, Toyota has invested GBP1,000,000 in Ilika's materials development platform; three of Ilika's patent families in solid state batteries are jointly owned with Toyota [**5.3**] as a result of the work undertaken. Toyota's technological advances in this area have continued. It unveiled the second generation of its Mirai fuel-cell vehicle in November 2019, and in July 2017, Reuters reported that Toyota was planning to launch an electric vehicle powered by solid-state battery technology by the early 2020s, in an effort to market a car with a significantly longer range and a shorter recharge time [**5.12**].

The longstanding collaboration with Toyota has positioned Ilika as a leader in the development of chemistries and production methods for both electric hybrid and electric vehicles. In June 2018 Ilika announced that it had been awarded GBP4,100,000 in grant funding from the Faraday Battery Challenge, part of the Industrial Strategy Challenge Fund (ISCF), to participate in two automotive-related projects [**5.1**]. The first, with Honda and Ricardo, was focused on the development of rapid charging battery packs. The second, with McLaren and A123 Batteries, was developing battery pack technology for high performance vehicles. The projects were selected as an ISCF case study on the UK Government's gov.uk website [**5.13**]. A third project was announced in September 2019, with Jaguar Land Rover, in which Ilika is supported by a further GBP800,000 of grant funding to study manufacturing processes and costs for solid state batteries. In September 2020, Ilika signed a framework agreement with the UK Battery Industrialisation Centre in support of scale-up of its Goliath solid state cells [**5.14**] for electric vehicles, cordless consumer electronics and aeronautics.

5. Sources to corroborate the impact

5.1 Ilika Plc 2019 Annual Report (published 2 Sept 2019) https://www.ilika.com/images/uploads/general/Annual-Report-2019.pdf

5.2 Ilika share price closed at 205p on 31 December 2020, with 139m shares in issue https://www.londonstockexchange.com/stock/IKA/ilika-plc

5.3 Ilika Plc 2020 Annual Report (published 24 Aug 2020) https://www.ilika.com/images/uploads/general/Annual-Report-2020.pdf

5.4 Announcement on 18 October 2016 on Ilika.com website: https://www.ilika.com/latest-news/ilika-secures-us8-million-investment-for-stereaxtm-commercialization

5.5 Announcement on 27 March 2020 on Ilika.com website: https://www.ilika.com/latest-news/15m-growth-placing-to-support-solid-state-battery-commercialisation

5.6 Announcement on 08 October 2019 on Investis platform: https://otp.investis.com/clients/uk/ilika_plc/rns/regulatory-story.aspx?cid=870&newsid=1335083

5.7 Corroborating letter, Graeme Purdy, Ilika CEO, 19 Jan 2021.

5.8 Announcement from Ilika Plc of its half-year report that ended 31 October 2017: https://parkwalkadvisors.com/2018/01/ilika-half-year/

5.9 Announcement on 04 February 2020 on Ilika.com website: https://www.ilika.com/latest-news/successful-stereax-field-trial

5.10 Announcement on 07 March 2019 on Ilika.com website: https://www.ilika.com/latest-news/deployment-of-wireless-sensors-with-network-rail

5.11 Announcement on 30 March 2017 on Ilika.com website: https://www.ilika.com/latest-news/toyota-research-institute-brings-artificial-intelligence-to-the-hunt-for-ne

5.12 Article published on 25 July 2017 on the Autoweek news website: https://www.autoweek.com/news/technology/a1826616/toyota-promises-solid-state-longer-range-batteries-evs-early-2020s/

5.13 Industrial Strategy Challenge Fund https://www.gov.uk/government/case-studies/ilika-technologies-recharging-the-electric-vehicle-market

5.14 Announcement on 10 November 2020 on Ilika.com website: https://www.ilika.com/latest-news/framework-agreement-with-the-uk-battery-industrialisation-centre