Institution: Imperial College London

Unit of Assessment: 8 Chemistry

Title of case study: C3 - Plaxica: Transformational Biopolymer Technology

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

Plaxica is a spin-out from, and based, at Imperial College London with economic, societal and environmental impacts. Launched in 2008, Plaxica is a process technology licensing business which is tackling the barriers that currently prevent a wider acceptance of bioplastics; specifically improving properties, decreasing cost and using non-food feedstocks to manufacture the biopolymer poly(lactic acid), PLA. Plaxica's technology uses sustainable feedstocks to produce PLA using more energy-efficient processes, to produce a strong, high-quality polymer, the result of which is a low-cost, environmentally-friendly biopolymer for use in applications including textiles, packaging, and automobile parts. In the REF period Plaxica has raised £10m from investors such as Imperial Innovations, Invesco Perpetual and NESTA Investments. The market pull for biorenewable materials from consumers is strong and the EU predicts that PLA will substitute >10% of the existing market for petrochemical polymers and forecasts a market >$15b [A].

2. Underpinning research (indicative maximum 500 words)

Plaxica's two academic founders, Prof Vernon Gibson and Dr Ed Marshall have a strong track record in the design and development of homogeneous catalysts for the production of polymers, with a particular focus on stereoselective polymerisations. Forging close industrial links in the past, they developed a range of polymerisation catalysts including examples for polyolefins, acrylics, styrenics and polyesters. Aspects of this work have been performed in collaboration with a number of multinational chemical companies including BP and BASF.

Gibson and Marshall started to examine polymers from renewable resources in the late 1990s and between 2000 and 2006 produced a number of academic publications and patents (e.g. [6]) in the field of stereoselective catalysts for the production of poly(lactic acid), PLA. Even from an early point in their research Gibson and Marshall realised the need to relate their research to real world commercial-type operations, and therefore published a number of reports exploring the use of well-defined molecular analogues of the industry standard catalyst, stannous octanoate [1]. Further stand out publications include the first detailed theoretical basis for stereoselectivity in lactide polymerisation catalysts (a computational study carried out in collaboration with Prof, Henry Rzepa at Imperial) [4], and a redox-active catalyst the activity of which can be attenuated by the oxidation state of the pendant ligand (work carried out with Prof. Nick Long at Imperial) [2]. PLA already had a significant profile aided by a number of desirable quantities, including biorenewability and biocompatibility and being compostable (according to EU and ASTM guidelines). The construction of a 140ktpa plant in Nebraska by a Cargill-Dow JV (NatureWorks) was seen as further evidence of the promise of PLA.

The team successfully applied for public funds [G1-G3], but industrial support for work on PLA was less straightforward to secure. In the early 2000's, it was thought that PLA suffered from a number of commercial deficiencies e.g. its relatively low thermal stability (it deforms at ca. 50-55°C), and hydrolytic instability. Its cost of manufacturing was also higher than that of the plastics it was predicted to compete most closely with e.g. PET, polyethylene terephathlate and PS, polystyrene.

Significantly, Gibson and Marshall's previous academic work had revealed that the properties of PLA could be improved by using catalysts to promote the formation of stereoregular PLA. With this advance, thermal stability, for example, could be increased to >100°C, greatly increasing the potential applications for PLA. Particular success was found with several families of aluminium catalysts, some of which led to PLA with melting points approaching 200°C [3, 5]. These important and commercially-relevant findings in the mid-2000s spawned the idea of Plaxica.

Key personnel:

- Dr E.L. Marshall, Lecturer in Green Chemistry, Imperial College London (2005-2009), then

Director of Research, Plaxica Ltd (2010-present)

- Prof V.C. Gibson, Chair of Polymer Chemistry and Catalysis then Chair of Inorganic Chemistry, Imperial College London (1995-10/2008), Visiting Professor, Department of Materials, Imperial College London, (11/2008-present)

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

[1] *A.P. Dove, V.C. Gibson, E.L. Marshall, H.S. Rzepa, A.J.P. White and D.J. Williams, "*Synthetic, structural, mechanistic and computational studies on single-site beta-diketiminate tin(II) initiators for the polymerization of rac-lactide",* J. Am. Chem. Soc.,128, 30, pp9834-9843 (2006). DOI, **81 citations (as at 5/9/13)**

[2] C.K.A. Gregson, V.C. Gibson, N.J. Long, E.L. Marshall, P.J. Oxford and A.J.P. White, "*Redox control within single-site polymerization catalysts",* J. Am. Chem. Soc., 128, 23, pp 741-7411 (2006). DOI, **74 citations (as at 5/9/13)**

[3] P. Hormnirun, E.L. Marshall, V.C. Gibson, R.I. Pugh and A.J.P. White, "*Study of ligand substituent effects on the rate and stereoselectivity of lactide polymerization using aluminium salen-type initiators",* PNAS, 103, 42, pp 15343-15348 (2006). DOI, **58 citations (as at 5/9/13)**

[4] *E.L. Marshall, V.C. Gibson and H.S. Rzepa, "*A computational analysis of the ring-opening polymerization of rac-lactide initiated by single-site beta-diketiminate metal complexes: defining the mechanistic pathway and the origin of stereocontrol",* J. Am. Chem. Soc., 127, 16, pp 6048-6051 (2005). DOI, **90 citations (as at 5/9/13)**

[5] *P. Hormnirun, E.L. Marshall, V.C. Gibson, A.J.P. White and D.J. Williams, "*Remarkable stereocontrol in the polymerization of racemic lactide using aluminium initiators supported by tetradentate aminophenoxide ligands",* J. Am. Chem. Soc ., 126, 9, pp 2688-2689 (2004). DOI, **231 citations (as at 5/9/13)**

[6] Patent WO2002038574 A1, "*Diamido alkoxide complexes as polymerization initiators of lactides*", Inventors: AP Dove, VC Gibson, EL Marshall, Applicant: AP Dove, VC Gibson, EL Marshall, Imperial Innovations, Publication date: 16/5/02

Grants:

[G1] EPSRC GR/N64892/01, *"New initiators for the controlled ring-opening polymerisation (ROP) of lactides and lactones"*, PI: V Gibson, 27/09/00-26/09/02, £121,867

[G2] EPSRC GR/N12084/01, "*P4:Polymers properties & polymerisation processes"*, PI: JS Higgins (Chem Eng, Imperial), co-I: V Gibson, 01/02/01-31/07/04, £1,089,242

[G3] EPSRC GR/R24838/01, *"Cationic metal alkoxides bearing weakly coordinating anions-new catalysts for small molecule and polymer synthesis"*, PI: V Gibson, 22/10/01-21/10/03, £126,061

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

The academic work of Gibson and Marshall revealed that the properties of PLA could be improved by using catalysts to promote the formation of stereoregular PLA, greatly increasing the potential applications for PLA. On this basis a business plan was constructed and funding secured leading to the formation of Plaxica in 2008 [B]. Marshall resigned his lectureship position in December 2009 to join the Company full-time (Gibson having previously taken a visiting professorship at Imperial when he joined BP as their Chief Chemist in 2008). The basis of Plaxica's technology is fully-owned by the Company. Nonetheless, the insight into the market and the understanding of the capabilities arose from academic work at Imperial over a number of years, and ultimately proved necessary when seeking funds for the launch of the spin-out company.

Plaxica is a process technology licensing company. It develops, demonstrates and designs process plants for the production of the key intermediates, especially L- and D- lactic acids and lactides, for stereocomplex polylactic acid (PLA) – a high performance biopolymer made from non-food renewable materials, such as cellulosic based materials. Plaxica's technology allows high performance PLA to replace traditional polymers produced from oil. It has a flexible approach to how it interacts with licensees, recognising that a successful biopolymers operation requires technology in the areas of feedstock production and conversion, intermediates production and polymerisation. Plaxica focuses on the ability to credibly scale up the chemical processes developed on a lab scale. Using a multidisciplinary team of chemists, process engineers and technical consultants the team works to deliver the correct balance of innovation, capital and operating costs. Before the launch of Plaxica, the UK had no commercial interest in the production of PLA, though several distributors could supply it.

Plaxica was formed to commercialise strong IP in low cost, high performance bioplastics. The product is a greener, cleaner and stronger form of plastic made from natural feedstock and can be used for a variety of applications including for example, fibres and packaging. It is "*developing next generation biopolymers that will be both cheaper to produce and have improved properties compared with first generation biopolymers. The novel chemistry underpinning this technology came from research by Professor Vernon Gibson FRS and Dr Ed Marshall at Imperial College London. Plaxica's technology uses sustainable feedstocks to produce a biopolymer known as polylactic acid (PLA) using more energy-efficient processes, to produce a stronger, higher-quality polymer. The result should be a low-cost, environmentally-friendly biopolymer for use in applications as diverse as packaging, textiles, electronics and automobile parts*" [C].

Since its formation in 2008 Plaxica has had several successful funding rounds and key milestones. Imperial Innovations funded the initial launch of the company in **2008.** A project involving Plaxica, Imperial and Holloid Plastics Ltd won funding for the High Value Manufacturing Technology Strategy Board in September **2009** [D], leading to conditions for the successful injection moulding of stereocomplex PLA. In October **2009** Plaxica received £1m in equity funding from Imperial Innovations, the Carbon Trust Investments Ltd and the National Endowment for Science, Technology and the Arts (NESTA) [C]. Commenting on the investment the CEO of Imperial Innovations Group plc, Susan Searle, said "*Existing plastics are no longer sustainable because of the oil they use and the waste they leave. This investment will help Plaxica develop a low-cost and environmentally friendly alternative for a wide range of industrial and consumer applications*" [C]. Rachael Nutter, Investment Manager at Carbon Trust Investment Partners LLP commented "*The rapidly growing market for bioplastics and Plaxica's position as a leader in this field have made it an exciting company to invest in. Plaxica has the potential to transform the cost and carbon footprint of PLAs and develop new applications for this polymer*" [C]. This equity investment allowed Plaxica to "*continue developing processes aimed at reducing PLA production costs to the point where it can compete with mass volume oil-based plastics*" [C]. In **2010** Plaxica announced that it raised a further £3 million in a Series A financing in which all existing institutional investors participated. The funds were used to accelerate development and scale up of the company's next generation PLA technology [E]. The funding consists of £1.2m Imperial Innovations) and £1.8m from other existing shareholders [E]. In **2011** Plaxica completed a £5m round in Series B financing with investment from Imperial Innovations, Invesco Perpetual and NESTA Investment [F]. In 2010, Plaxica began to rent space in the Wilton Research Centre on Teesside to focus on process development, scale-up and demonstration. By September **2012** the demonstration facility had entered the commissioning phase [20/9/12 announcement, G]. By May **2013** "*Plaxica [had] demonstrated the production of extremely high purity D-lactic acid from a racemic lactic acid feedstock, validating [their] Optipure enantiomer separation technology*" [30/5/13 announcement, G] and had attracted commercial interest from a number of clients and partners, especially in South East Asia and North America [H]. The product quality exceeded industry standards for polymer-grade lactic acid which was "*an important milestone in the validation of Plaxica's low cost technology for the production of lactic acid*" [30/5/13 announcement, G]. In total Plaxica has raised almost £10m in investment in the 2008-2013 REF period. It continues to attract investment as demonstrated by the recent £8M Series C financing round [10/9/13 announcement, G, H].

Plaxica currently employs 27 people covering R&D, engineering, plant operation and commercial functions. This includes 18 people in Wilton in the North East of England. Since 2008 Plaxica have employed 25 UK graduates in STEM subjects [H]. Further support is provided as required from a retained team of ca. 10 consultants (industry and academic experts).

The construction of a pilot demonstration facility in Teesside demonstrates Plaxica's commitment to creating jobs and revenue within the UK. Examples of the local press include:

- "*The licensing company, which develops transformational biopolymer technology, only moved into the Wilton Centre 18 months ago but has already had to take another laboratory and a large open plan office, in addition to its existing lab and two small offices*." [I]
- "*A technology and licensing company is doubling the size of its Teesside operation with the*

launch of a pilot plant that will demonstrate the conversion of bio-renewables into polymers using break-through technology." [J]

- "*Steve Duffield, accommodation manager at The Wilton Centre, said: 'The speed of Plaxica's progress is very impressive. It is an ideal operation to have at the Centre, complementing other organisations also here.*'" [K]

Imperial Innovations, one of the major investors in Plaxica make the following statement about the company: "*Plaxica is developing a new generation of biopolymers derived from renewable resources. Plaxica's polymers are a range of polylactic acid based materials which have improved physical properties compared with first generation biopolymers. In addition, they have a smaller environmental footprint, and are fully recyclable and cost competitive with current oil-based alternatives. First generation PLA is by far the most successful biopolymer to date, with 25% of the biopolymer market. Plaxica's second generation PLA is expected to combine the advantages of biopolymers with the mechanical and thermal performance of petrochemical derived plastics and is expected to develop a market much larger than that of existing biopolymers. Given Plaxica's PLA's improved physical properties, its applications will expand beyond the currently limited range of applications for which first-generation PLAs can be used… Plaxica's second generation PLA polymers are likely to compete effectively with conventional oil-derived products such as PET, polypropylene and polystyrene in applications ranging from textiles to automotive, electronics, household goods and packaging. Plaxica's technology is particularly suited to the use of sugars derived from cellulosic feedstocks - which are normally waste products and do not, in general, take food out of the supply chain*" [L]. They make the following statement about the global polymers market: "*The global polymers market is worth more than $400 billion in annual sales and has grown at an average of 3.5% per year over the last two decades. The current biopolymers market is in excess of $2 billion per annum and is growing at more than 10% per year. PLA has 40% of this market, at some $800m, and this is forecast to grow to $1bn by 2012*" [L].

The impact offered by Plaxica is nicely summed up by the CEO: "*Economically Plaxica has grown quickly to employ a critical mass of scientist and engineers… The emphasis on biopolymers from non-food sources such as cellulose has clear societal and environmental impacts, and the focus on using bioplastics in durable applications such as automotive interiors demonstrates a sustainable advantage not offered by current PLA materials*" [H]. Unfortunately, due to "*commercial sensitivities in the highly competitive PLA marketplace*", Plaxica are "*unable to be more forthcoming with details of the impact already realised by the company*" [H].

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

[A] 'Product overview and market projections of emerging bio-based plastics', PRO-BIP 200, Final report, June 09 (archived here)
[B] http://www.plaxica.com/about/about-us/ (archived here on 16/9/13)
[C] http://www.nesta.org.uk/press_releases/assets/features/plaxica_secures_1m_funding_to_develop_next_generation_renewable_polymers (archived here on 16/9/13)
[D] http://www.prw.com/subscriber/newsmail2.html?id=1254997521 (archived here on 16/9/13)
[E] http://www.plasteurope.com/news/detail.asp?id=217107 (archived here on 16/9/13)
[F] http://www.imperialinnovations.co.uk/news-centre/news/imperial-innovations-leads-5m-investment-plaxica/ (archived here on 16/9/13)
[G] http://www.plaxica.com/news-2/ (archived here on 16/9/13)
[H] Letter from CEO Plaxica Ltd, 1/11/13 (available on request)
[I] http://www.wiltoncentre.com/news/2012/03/16/Plaxica-pilot-plant-plans-lead-to-expansion.html (archived here on 16/9/13)
[J] http://www.thejournal.co.uk/business/business-news/plaxica-set-double-size-teesside-4412986 (archived here on 16/9/13)
[K] http://www.thenorthernecho.co.uk/business_all/9581859.Plaxica_scheme_to_create_plastic_from_plants/ (archived here on 16/9/13)
[L] http://www.imperialinnovations.co.uk/ventures/portfolio/plaxica/# (archived at here on 16/9/13)