Institution: University of Oxford

Unit of Assessment: 8 Chemistry

Title of case study: UOA08-01: Oxford Catalysts Group – a successful company built on the development and application of highly-active catalysts for the conversion of natural gas to liquid hydrocarbons

1. Summary of the impact

Research carried out by Malcolm Green's group in the UOA led to the spin-out of Oxford Catalysts Ltd. A large part of the company's technology is based on Green's transition-metal catalysis research, which has enabled them to develop a highly efficient Fischer-Tropsch (FT) catalyst to convert natural gas to liquid hydrocarbons. In 2010, Oxford Catalysts Group (now Velocys) demonstrated the world's first smaller-scale, modular gas-to-liquids and biomass-to-liquids FT plants which made use of the catalyst for the efficient conversion of low-value or waste gas to liquid hydrocarbon fuels. Since then, orders worth £ 8M have been taken and the company has been selected to provide FT technology for 4 commercial projects. From 2008 – 2012, the company raised over £ 60M, achieved revenue of £ 30M and now employs around 90 people.

2. Underpinning research

The Fischer-Tropsch (FT) process is a collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen ('synthesis gas' or syngas) into synthetic crude that can be upgraded to high-quality motor fuel. Developed in Germany in the 1920s, the process was used in World War II to enable Germany to produce liquid fuels from coal when oil was not available, and again in South Africa where it was subject to sanctions during the apartheid era. The production of synthetic crude via the FT synthesis has not been adopted widely owing to the availability of cheap oil. However concern about diminishing oil supplies, combined with an increasing need to make use of 'wasted' resources, such as gas produced from waste biomass or the gas associated with oil production, is leading to a renewed and growing interest in FT catalysis.

The key technology behind the catalysts used by Oxford Catalysts is the result of nearly two decades of research at the Wolfson Catalysis Centre (part of the University of Oxford's Department of Chemistry). The focus has been on the use of transition-metal carbides as catalysts for the partial oxidation of methane to syngas, and as highly active, selective and stable FT catalysts for the conversion of syngas to synthetic crude. This work was led by Green, the co-founder of Oxford Catalysts Ltd. who was Head of Inorganic Chemistry at Oxford (to October 2003).

In 1993, Green reported a systematic investigation into the carbon deposition caused by a range of transition metals acting as catalysts for the partial oxidation of methane (POM). This built on his previous serendipitous finding that a lanthanide ruthenium oxide catalyst gave a remarkable 90% yield of syngas from methane via POM catalysis. Prior to this discovery, it had been considered impossible to convert methane to syngas in this way. Although only a thin film of carbon formed in the process, Green was aware that carbon deposition could potentially 'kill' a catalyst and render it useless for industrial exploitation. The 1993 study showed that nickel attracted the most carbon deposition and iridium the least, but the ruthenium and iridium catalysts, although effective, were too expensive for commercial use, and this prompted Green to look for alternatives [1]. He subsequently developed less expensive, non-precious metal, molybdenum and tungsten carbide catalysts [2, 3, 4], which, importantly, showed no macroscopic deposition of carbon.

In 2001, Green developed a non-carbide cobalt methane oxidation catalyst with activities comparable to noble-metal catalysts under comparable conditions [5]. Green's research continued to develop carbide catalysts towards industrial exploitation using micro-reactors and, in 2002, he reported catalysts that were stable at high temperatures and pressures using this technology [4]. The final critical development with regard to the commercial systems currently used by Oxford Catalysts Ltd. was described in a patent application filed in 2001 [6], in which cobalt salt precursors to the supported active catalysts are activated in a process involving hydrocarbon reductants. These catalysts have superior activity and are less susceptible to deactivation over time. This method of activation of the catalyst precursor forms a mixture of metallic cobalt and cobalt carbides. Critically, these catalysts are not only effective for POM, but also for FT catalysis that converts syngas into hydrocarbons [6]. Moreover, they do not promote carbon deposition and are selective to form hydrocarbons with five or more carbon atoms. A high selectivity is required for an economic commercial process.

In 2004, Green spun-out the company Oxford Catalysts Ltd. with the aim of developing a number of novel metal-carbide catalysts and catalysed processes that could lead to marketable products based in particular on the new FT catalyst technology.

3. References to the research

Asterisked outputs denote best indicators of quality; University of Oxford authors are underlined.

[1] A study of carbon deposition on catalysts during the partial oxidation of methane to synthesis gas. Claridge, J. B.; Green, M. L. H.; Tsang, S. C.; York, A. P. E.; Ashcroft, A. T.; Battle, P. D. *Catalysis Letters 22* (4), 299-305, 1993. DOI: 10.1007/BF00807237

[2] Molybdenum and tungsten carbides as catalysts for the conversion of methane to synthesis gas using stoichiometric feedstocks. York, A. P. E.; Claridge, J. B.; Brungs, A. J.; Tsang, S. C.; Green, M. L. H. *Chemical Communications* 1, 39-40, 1997. DOI: 10.1039/A605693H

[3]* New catalysts for the conversion of methane to synthesis gas: Molybdenum and tungsten carbide. Claridge, J. B.; York, A. P. E.; Brungs, A. J.; Marquez-Alvarez, C.; Sloan, J.; Tsang, S. C.; Green, M. L. H. *Journal of Catalysis 180* (1), 85-100, 1998. DOI: 10.1006/jcat.1998.2260. *Paper illustrates the underpinning expertise in carbide catalyst technology of the Oxford Research Group.*

[4]* Study on the mechanism of partial oxidation of methane to synthesis gas over molybdenum carbide catalyst. Xiao, T. C.; Hanif, A.; York, A. P. E.; Nishizaka, Y.; Green, M. L. H. *Physical Chemistry Chemical Physics 4* (18), 4549-4554, 2002. DOI: 10.1039/b204347e. *Underpinning expertise in carbide catalyst technology of the Oxford research group in combination with a microreactor*.

[5] Methane combustion over supported cobalt catalysts. Xiao, T. C.; Ji, S. F.; Wang, H. T.; Coleman, K. S.; Green, M. L. H. *Journal of Molecular Catalysis A-Chemical 175* (1-2), 111-123, 2001. DOI: 10.1016/S1381-1169(01)00205-9

[6]* A supported cobalt-containing catalyst used in the partial oxidation of hydrocarbons or Fischer-Tropsch reaction. Green, M. L. H. and Xiao, T. C. Int. Appl. (2003), WO 2003002252. Assignee: Isis Innovation Limited, UK (a wholly-owned subsidiary of the University of Oxford, managing technology transfer). http://www.google.com/patents/WO2003002252A1?cl=en
One of the base patents underpinning Oxford Catalysts Ltd. FT technology.

4. Details of the impact

The research described above has underpinned the development of the first smaller-scale, modular gas-to-liquids (GTL) and biomass-to-liquids (BTL) Fischer-Tropsch (FT) reactors, launched by Oxford Catalysts Group in 2010. Several orders for reactors have been taken; the company has attracted very substantial investment as a result of the novel technology it offers, and has one of the world's largest patent portfolios in this area.

After its spin-out from the University of Oxford in 2004, Oxford Catalysts Ltd. concentrated on the creation of highly active and efficient cobalt-based FT catalysts based on Green's research. Such was the perceived potential of this new technology that the company's Initial Public Offering of 2006 raised £ 15M and was over-subscribed. Oxford Catalysts' patented technology, known as Organic Matrix Combustion (OMX), allows highly active cobalt-based catalysts to be produced with a reduced need for precious metal promoters, without any loss of performance and in fact with superior activity, selectivity and stability to conventional catalysts. In 2008, the company merged with Velocys, a US company specialising in microchannel chemical reactors (using channels with diameters in the range 0.1 - 10 mm, far smaller than those in conventional reactors). These small channels dissipate heat more quickly than conventional reactors so a more active catalyst can be used, and the mass and heat transfer limitations of conventional FT reactors are overcome. Importantly, this allowed Oxford Catalysts to take advantage of the highly active cobalt catalysts developed by Green [6]. The use of microchannel processing technology makes it possible to greatly intensify chemical reactions, enabling them to occur at rates significantly higher than conventional processes, thus enabling smaller-scale FT reactors for GTL and BTL. The merged company became known as Oxford Catalysts Group (re-named Velocys from September 2013) and is the only company working in this field to maintain in-house research in both catalyst and reactor development.

The company has capitalised on the potential of smaller and more versatile FT reactors. Existing FT plants are huge, designed for production levels of around 30,000 barrels of liquid fuel per day (BPD), and cannot be scaled down economically. They require vast sources of gas, and so are confined to a small number of locations (primarily in Qatar), and cost billions of dollars, putting them beyond the reach of all but the largest companies. Gas associated with oil production is usually wasted; it is frequently disposed of by flaring (burning) – an environmentally unfriendly process that is increasingly subject to regulation – or by re-injection back into the reservoir at considerable expense. According to the World Bank, 140 billion cubic meters of associated gas – enough to power Germany – was flared in 2011. An equivalent amount or more was re-injected simply to avoid flaring. Gas located at remote locations is often not developed; it is not economically viable to pipe the gas to where it is needed. Biomass resources such as agricultural and municipal solid waste are another important potential syngas for the FT process: the alternative being that they are disposed of as waste. Because biomass feedstock is not very dense, it is not economic to transport it over long distances to centralised production facilities. Therefore, BTL plants in particular need to be relatively small and located near the source of the feedstock. The technology developed by Oxford Catalysts Group makes it possible to take advantage of these ‘wasted resources’ to produce liquid fuels by using the biomass-to-liquids (BTL) or gas-to-liquids (GTL) processes. An added advantage is that the process creates synthetic clean fuels free from sulphur and aromatics (unlike those produced in conventional refinery processes), and can be tailored to produce high-value hydrocarbons such as jet fuel [7].

Oxford Catalysts Group has demonstrated that its reactors operate economically when producing as little as 1,000 BPD of FT products. The reactors are small enough that modules incorporating the reactors can be transported in standard-size shipping containers and easily delivered to where they are needed. This has opened up the market to smaller companies, smaller gas fields and more remote locations, enabling the distributed production (production at or near the source of the feedstock) of clean liquid fuels from stranded and associated gas, both on- and off-shore, and from biomass. For example, Oxford Catalysts Group has established a partnership with offshore-facility developers MODEC and the global engineering firm Toyo Engineering to develop small-scale GTL facilities based on microchannel reactors and designed for use offshore [14].

The huge potential of the reactors has generated a high level of investment in the company. Between 2008 and the end of 2012, the group achieved revenue of £ 30M and received over £ 60M in investment. £ 30.6M of the investment was raised in January 2013, at which time Roman Abramovich invested £ 4.3M in the company, generating press and television news coverage. Oxford Catalysts’ stock increased by around 200% between June 2012 and June 2013. Throughout this period, the company has been able to maintain its levels of employment (80 - 90 staff) in the UK and the US [8], and has offices in the UK near Oxford and in the USA in Texas and Ohio.

In May 2012, Oxford Catalysts announced the sale and start-up of a commercial scale FT reactor at an integrated energy company facility [9]. The Group’s technology has been selected for 4 commercial-scale projects including:

- A 1,000 BPD commercial GTL plant for Calumet Specialty Product Partners, L.P., a major US-based producer of speciality petroleum products, for use in the expansion of Calumet’s Karns City, Pennsylvania facility [10].
- GreenSky London waste-biomass to jet fuel commercial plant, in partnership with BA. Like many airlines, BA is concerned about carbon taxes and is, therefore, interested in securing

a low-carbon-footprint fuel based on biomass. The plant will provide enough fuel for BA at City Airport [11] – reportedly 50,000 tonnes of jet fuel annually over 10 years equating to $ 500M at today's prices.
- A 2,800 BPD GTL plant being developed by Pinto Energy in Ohio, USA, to convert low-cost natural gas into high value specialty products (solvents, lubricants and waxes), as well as ultra clean transportation fuels [12].

In November 2012, Oxford Catalysts Group was named as the preferred supplier of FT technology for Ventech Engineers LLC, a global leader in the design and construction of modular refineries. The deal raised £ 1.2M for the Group, and in April 2013, Ventech placed an order worth $ 8M for FT reactors for a plant of sufficient capacity to produce approximately 1,400 BPD. This gives an indication of the expected income from the projects listed above. Kevin Stanley, CEO of Ventech Engineers commented, 'After an extensive search of available technologies we identified Oxford Catalysts' FT product as the leading offering in the industry for modular GTL plants' [13].

Oxford Catalysts Group has established collaborations for the engineering, manufacturing and deployment of its technology with companies such as MODEC, Toyo Engineering, Haldor Topose and Ventech. The range of partnerships reflects the fact that Oxford Catalysts group is regarded as a leading player in the field of FT technology [14].

5. Sources to corroborate the impact

[7] http://www.velocys.com/our_business_overview.php
Oxford Catalyst Group (now Velocys) Business webpage, corroborating details of the technology offered by the company and its performance.

[8] *Details of investment/employment can be corroborated by Oxford Catalysts Group (Velocys).*

[9] http://www.oxfordcatalysts.com/financial/fa/ocgfa20120524.php
May 2012 press release from Oxford Catalysts, confirming sale and successful start-up of a commercial scale FT Reactor with an anonymous integrated energy company.

[10] http://calumetspecialty.investorroom.com/2012-09-06-Calumet-Specialty-Products-Partners-L-P-Announces-Plan-to-Expand-its-Karns-City-PA-Specialty-Products-Facility
September 2012 press release from Calumet, confirming that it has commissioned Oxford Catalysts/Velocys to supply FT technology for 1,000 BPD commercial GTL plant for Calumet at its Karns City, Pennsylvania site.

[11] http://www.solenafuels.com/index.php/in-the-news/10-solena-makes-the-news-items/10-british-airways-pledges-10-year-offtake-agreement-as-greensky-project-with-solena-gathers-momentum-on-greenair-online
November 2012 press release from Solena, confirming the selection of Oxford Catalysts to provide FT technology to GreenSky London, Europe's first commercial scale sustainable jet fuel facility, being developed in partnership with British Airways.

[12] http://pintogtl.com/partner/
Pinto Energy webpage confirming details of the joint project with Oxford Catalysts (Velocys).

[13] http://www2.ventech-eng.com/2012/11/oxford-catalysts-secures-1-3m-from-ventech/
November 2012 press release on the Ventech website confirming the Ventech/Oxford Catalysts collaboration and the fact that Ventech regards Oxford Catalysts' FT technology as at the forefront of the GTL industry.

[14] http://www.velocys.com/our_business_partners.php
Oxford Catalyst Group (now Velocys) Partners webpage, corroborating details of the companies with whom the group has active partnerships.