Institution: University of Birmingham

Unit of Assessment: UoA 5 - Biological Sciences

Title of case study: Commercial development of novel environmentally-benign marine antifouling coatings

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

Marine biofouling is caused by the adhesion of macroalgae, microbial slimes and other marine organisms for instance barnacles to underwater surfaces, such as ships hulls. The research from the Bioadhesion and Biofouling Research Group (BBRG) that tackles this important problem has had a direct impact on commerce, with three new companies entering the marine coatings industry and a fourth achieving superior effectiveness from their existing product line. All have been able to develop novel products (with associated patents) positioned to address the requirements of an increasingly-stringent environmental legislative framework, seeking to reduce or eliminate the impact of toxic biocides on non-target species in the marine environment. In addition, some of these companies have enjoyed increased investments in their R&D programmes and proven market advantage over their competitors.

2. Underpinning research (indicative maximum 500 words)

The Bioadhesion and Biofouling Research Group (BBRG) is led by Professor J.A. Callow (Mason Chair of Botany to September 2012, subsequently Emeritus Professor of Plant Science) and Dr M.E. Callow (Senior Research Fellow). The other individuals in the UoA, contributing to the cited research, are two post-doctoral fellows, Drs J. Finlay and M. Pettitt. Work started in 1996 and has been continuously funded by several agencies and industry.

One of the strategic objectives of BBRG is to improve the understanding of structure/property/performance relationships for experimental antifouling coatings through interdisciplinary collaborations. The work contributes to an understanding of the 'design rules' for the rational development of novel, environmentally-benign, antifouling coatings that do not rely on toxic biocides for their activity. BBRG is one of a small number of laboratories providing expertise in the biological evaluation of the antifouling performance of novel coatings.

The purpose of such evaluations is to provide to beneficiary organisations engaged in novel coating design, rapid evaluations of the intrinsic performance of their coatings against a defined biological challenge, through hypothesis-driven experiments based on bioassays that BBRG has developed. These bioassays assess the antifouling performance (i.e. in preventing the initial adhesion of organisms) and the adhesion strength of organisms that colonise surfaces.

Based on their understanding and research track record in developing these types of evaluation, BBRG has collaborated with a large number of other laboratories, companies and researchers in order to deliver appropriate coating solutions to industry that meet legislation requirements and minimise environmental damage. Specifically, BBRG input to these collaborative experiments involved helping to develop the starting hypothesis; correct experimental design and analysis; conducting the experiments/bioassays; data interpretation and contributions to various outputs including the writing of papers in refereed journals. The design and provision of the test materials is mainly in the hands of the collaborating partners, but in some cases BBRG has suggested design modifications to enhance efficacy.

This input has been provided in a number of different ways. The Office of Naval Research (ONR) has a long term 'Marine Antifouling' programme involving over 30 laboratories with a wide range of expertise from polymer chemistry and nanotechnology, to hydrodynamics and marine biology. ONR has continuously funded BBRG from 1996 in recognition of the research understanding and expertise it brings to coatings evaluations; in this case, the precise context has been evaluations against marine algae, at laboratory scale.

The BBRG has also been funded by the EU: The 'AMBIO' ('Advanced Nanostructured Surfaces for the Control of Biofouling') project (2005-2010) was funded through the NMP 'Nanotechnology' Directorate in FP6. This 5 year Integrated Project (€12M total funding from the EU) was designed and coordinated by Professor James Callow and Dr Maureen E Callow and involved 31 partners,

of whom 15 were European companies. Apart from coordinating and ensuring scientific management of the whole project, BBRG also performed a research role similar to that described above for the ONR funding.

Finally, BBRG has been contracted directly by International Paint Ltd (a division of Akzo-Nobel), the leading global manufacturer of marine antifouling coatings, to provide a similar type and level of research evaluations on enhanced product ranges.

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

References 1 and 2 have been chosen to describe method development that underpins the bioassays conducted on test materials. References 4 to 6 illustrate the application of these methods to the evaluation of test materials at laboratory scale and relate to the impact described in Section 4. (Authors from the University of Birmingham are in bold)

1. **Callow, ME, Callow, JA**, Pickett-Heaps, JD, & Wetherbee, R. (1997) Primary adhesion of *Enteromorpha* (Chlorophyta, Ulvales) propagules: quantitative settlement studies and video microscopy. *Journal of Phycology*, **33**, 938-947. doi: 10.1111/j.0022-3646.1997.00938.x
2. **Finlay, J. A., M. E. Callow,** M.P. Schultz, G.W. Swain and **J.A. Callow**. (2002). Adhesion Strength of Settled Spores of the Green Alga *Enteromorpha*. *Biofouling* **18**: 251-256. doi: 10.1080/08927010290029010
3. Schumacher, J.F., Carman, M.L., Estes,T.G., Feinberg, A.W., Wilson,L.H., **Callow, M.E., Callow, J.A., Finlay, J.A.,** Brennan, A.B. (2007) Engineered antifouling microtopographies – Effect of feature size, geometry, and roughness on settlement of zoospores of the green alga *Ulva*. *Biofouling*, **23**, 55-62. doi: 10.1080/08927010601136957
4. Beigbeder A, Degee P, Conlan SL, Mutton RJ, Clare AS, **Pettitt ME, Callow ME, Callow JA,** Dubois P. 2008. Preparation and characterisation of silicone-based coatings filled with carbon nanotubes and natural sepiolite, and their application as marine fouling-release coatings. Biofouling 24: 291-302. doi: 10.1080/08927010802162885
5. Akesso, L., **Pettitt, M.E., Callow, J.A., Callow, M.E.**, Stallard, J., Teer, D., Liu, C., Wang, S., Zhao, Q., D'Souza, F., Willemsen, PR., Donnelly, G.T., Donik. C., Kocijan, A., Jenko, M., Jones, L.A., Guinaldo, P.C. (2009) The potential of nanostructured silicon oxide type coatings deposited by PACVD for control of aquatic biofouling. Biofouling, 25: 55-67. doi: 10.1080/08927010802444275
6. Akesso, L. Navabpour, P., Teer, D., **Pettitt, M.E., Callow, M.E.,** Liu, C., Wang, S., Zhao, Q., Donik, C., Kocijan, A., Jenko, M., **Callow, J.A.** (2009) Deposition parameters to improve the fouling-release properties of thin siloxane coatings prepared by PACVD. Applied Surface Science. **255**, 6508-6514. doi: 10.1016/j.apsusc.2009.02.032

Quality Indicators

- Since 1996, to date (August 2012) a total of 107 papers have been published, 83% of which were in journals with Impact Factors >3.0.
- The quality of our work was acknowledged with an invitation by Nature Publishing Group to write a review for their new interdisciplinary journal 'Nature Communications' *(Callow JA, Callow ME. (2011). Trends in the development of environmentally friendly fouling-resistant marine coatings. Nature Communications **2**: 10.1038/ncomms1251*).
- Peer-reviewed research funding directly relating to the research underpinning the claimed impact has been obtained from 2 international agencies and industry. ONR has funded 8 grants (value, £2,722,394); the EU has funded 2 projects (value for the Birmingham components, £1,443,689).
- The EC invited Prof. Callow to 'showcase' the AMBIO project at the DG RTD Conference "Innovation in Practice, what we can learn for key enabling technologies? How to convert research into commercial success stories?" held in Brussels, 28/1/13.

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

The marine antifouling coatings industry has a global market ca. 1 billion Euros per year (Haras, D. *Mater. Tech. 2006, **93**, s27)*. The vast majority of current, commercial, marine antifouling coatings are based on the use of one or more toxic biocides that impede the growth of barnacles, tubeworms, algae etc. Such biocides are under increasing scrutiny because of their impacts on non-target species and an increasingly stringent legislative framework seeks to reduce their use, or

in certain cases, to remove them from the market. There has therefore been an increasing research focus on the development of novel coatings that rely on non-biocidal technologies based upon the physico-chemical properties of surfaces. This is to either reduce the initial attachment of marine organisms to surfaces or to reduce the adhesion strength of organisms that do attach so that they are readily removed by turbulent forces when the ship is underway. This is the area of research in which BBRG has made a significant impact in the last 15 years and below we describe how the outputs of this research have achieved an economic impact in the marine antifouling market since 2008.

Development of a new spin-out company

Sharklet Technologies Inc. (www.sharklet.com) (USA)

As part of the ONR-funded programme BBRG has collaborated extensively with the materials science group of Professor A. Brennan (University of Florida). This started out as a fundamental, hypothesis-driven study exploring whether 'bioinspired' microtextured silicone elastomer coatings, at an appropriate scale and pattern, will reduce the attachment of spores of marine algae. The systematic investigation of coating parameters and the elucidation of a general, quantitative model linking reduction in fouling to surface roughness is reported in ref. 3 (and 10 other refereed papers).

BBRG conducted studies which showed that the coatings retarded the settlement of marine algae and prompted further work into other marine organisms and bacteria. This work directly led Brennan to explore the effect of surface roughness on the attachment and growth of bacteria on biomedical devices. Brennan, as the inventor, patented the technology (patent US7650848 contains data from BBRG) and has commercialised it as a portfolio of related technologies through the start-up company 'Sharklet™ Technologies Inc.', which now offers products for both marine and biomedical applications. Brennan states "*Through studies at Birmingham we have shown that the design is unique in its ability to retard the settlement of spores of Ulva linza, a marine alga. The results from these studies led to the investigation of other marine organisms and a range of bacteria, including those of biomedical importance" (s1).* The company has now been established for approximately five years and is currently valued around $16 million (USD). It has attracted US government funding leading to industry collaborations (e.g. Cook Medical) and is actively pursuing further partnerships with global companies in the area of energy exploration.

Allowing existing companies to expand product range

Both Nanocyl and Teer Coatings Ltd directly benefited from collaborating with BBRG as it allowed them to develop and patent new products from their materials into marine coatings. As such, they have now entered a new market (marine antifouling) and generated additional investment into their R&D programmes.

Nanocyl (***www.nanocyl.com) (Belgium)***

In the AMBIO project BBRG worked with materials scientists from the University of Mons-Hainaut and the company Nanocyl to evaluate the hypothesis that silicone fouling-release coatings could be improved by the incorporation of small amounts of carbon nanotubes (CNTs). The results of the study are reported in ref.4 and demonstrate that improved fouling-release performance can be achieved by incorporation of CNTs, the effect being ascribed to the modulation of surface roughness at the nanoscale. Nanocyl patented the invention, including data from BBRG (US Patent Application 20100130665) and there is one product 'Biocyl™' currently in the market place *(s2).*

Teer Coatings Ltd. (***www.teercoatings.co.uk) (UK)***

In the AMBIO project BBRG worked with a SME, Teer Coatings Ltd, (now part of the MIBA Coating Group), a specialist in the production of hard, ultrathin, low surface energy coatings deposited on small objects by advanced physical vapour deposition methods. The company had no prior history of developing antifouling coatings but BBRG worked with them to evaluate the potential of a wide range of coating chemistries. *"Before participating in AMBIO TCL had no experience in the development of antifouling coatings and little experience in plasma assisted chemical vapour deposition (PACVD) but the University of Birmingham assisted us in the evaluation of the potential*

of a wide range of coatings chemistries" (s3).

A hydrophobic, nanostructured SiOx-like coating was shown to have good antifouling properties (ref. 5) and being optically transparent it was selected for field-testing on the optical windows of marine sensing devices. Further optimisation of the deposition process was conducted (ref. 6) which significantly improved the environmental resistance of the coating. The deposition technology and its application to antifouling was the subject of a patent application (US 2010/0247928) and the process is now commercially available within the Teer technology portfolio. This work has also attracted interest from new potential customers, who would not have approached the SME previously based on their existing product range.

Improved performance and independent assessment of current commercial products

International Paint Ltd (http://www.international-marine.com/aboutus/marine-coatings.aspx) (UK)

BBRG were funded by International Paint Ltd (£166K since 2005) primarily to conduct bioassays on novel anti-fouling coatings and fouling-release materials. Some of the research findings have directly underpinned the development of the next generation of fouling-release coatings 'Intersleek 1100SR' from the company. In addition, the independent analysis of the enhanced product performance by BBRG in comparison to market competitors is being used in the company's technical marketing literature. Reference to the University's bioassay results are viewed as providing a strengthened argument to customers as to why they should purchase these improved products over and above competitor products *(s4).*

In conclusion:

Between these four companies, the impact from research has been:

- the creation of a US spin-out company
- two companies have made additional investments in R&D
- two companies have discovered new business opportunities for their products and processes
- new products or services have been commercialised, and the associated intellectual property has been patented
- Birmingham data has been used in marketing material to demonstrate the effectiveness of an improved product

Further commercial information on sales and business performance is closely held by these companies and has not been made available for this case study. It is expected that environmental benefits will be realised in the future by the wider application of these coatings.

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

s1. Letter from Chief Technology Officer and Co-founder of Sharklet Technologies Inc. and University of Florida.
s2. Letter from Global Technical Services Associate Director for Nanocyl.
s3. Letter from R&D Technology Centre Manager for TEER Coatings Ltd.
s4. Letter from Manager, Marine & Protective Coatings Technology Centre for International Paint Ltd.