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Programme Area: Marine

Project: ReDAPT

Title: Reliable Data Acquisition Platform for Tidal (ReDAPT) project: Final Report

Abstract:

This report presents the conclusions of the ME8 Antifouling Systems for Tidal Energy Devices, focussing on 24 months of marine coating testing in the Fall of Warness, Orkney. It seeks to interpret the results of the coating testing presented elsewhere, attempts to contextualise and extrapolate the results with environmental data from the test site where available, and provides guidance on coating selection for marine tidal infrastructure. Attempts are made to predict the longevity of biocidal coating efficacy based on coating thickness measurements before and after testing. Advice to aid coating selection is based on the efficacy of the different coatings tested in terms of their ability to prevent the formation of biofouling and their ability to resist mechanical damage. A decision tree style diagram is presented to aid coating selection and the rationale behind the decision steps is discussed. This report also provides an update of developments in coating technologies that have arisen since the project started in 2010, together with an update of the legislation concerning the use of antifouling coatings in the marine environment. Finally, the current situation concerning marine renewable devices and marine alien non-native species is discussed together with predicted implications for the renewable energy industry in terms of monitoring and mitigation.

Context:

One of the key developments of the marine energy industry in the UK is the demonstration of near commercial scale devices in real sea conditions and the collection of performance and environmental data to inform permitting and licensing processes. The ETI's ReDAPT (Reliable Data Acquisition Platform for Tidal) project saw an innovative 1MW buoyant tidal generator installed at the European Marine Energy Centre (EMEC) in Orkney in January 2013. With an ETI investment of £12.6m, the project involved Alstom, E.ON, EDF, DNV GL, Plymouth Marine Laboratory (PML), EMEC and the University of Edinburgh. The project demonstrated the performance of the tidal generator in different operational conditions, aiming to increase public and industry confidence in tidal turbine technologies by providing a wide range of environmental impact and performance information, as well as demonstrating a new, reliable turbine design.

PML | Plymouth Marine Laboratory

Marine Matters

ETI MA1001 - Reliable Data Acquisition Platform for Tidal (ReDAPT) project:

ME8.5 'Final Report'

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Science for
Sustainable Seas

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Executive Summary

This report presents the conclusions of the ME8 'Antifouling Systems for Tidal Energy Devices' work package from the ETI's ReDAPT project. The scope for this work changed throughout the lifetime of the project and now focuses on 24 months of marine coating testing in the Fall of Warness, Orkney. The results of the tests are discussed in the previous ME8.4 Report.

In this report we interpret the results of the coating testing, attempt to contextualise and extrapolate the results with environmental data from the test site where available, and provide guidance on coating selection for marine tidal infrastructure. Attempts are made to predict the longevity of biocidal coating efficacy based on coating thickness measurements before and after testing.

Advice to aid coating selection is based on the efficacy of the different coatings tested in terms of their ability to prevent the formation of biofouling and their ability to resist mechanical damage. A decision tree style diagram is presented to aid coating selection and the rationale behind the decision steps is discussed.

This report also provides an update of developments in coating technologies that have arisen since the project started in 2010, together with an update of the legislation concerning the use of antifouling coatings in the marine environment. Finally, the current situation concerning marine renewable devices and marine alien non-native species is discussed together with predicted implications for the renewable energy industry in terms of monitoring and mitigation.

1   Introduction

The coating testing conducted for this section of the ReDAPT project has proved to be of considerable benefit to the renewables industry. We have been able to screen a range of marine protective and antifouling coatings in the harsh environmental conditions of the Fall of Warness in Orkney, for 24 months. The coatings have been assessed for suitability for offshore marine renewable energy infrastructure based of antifouling performance and resistance to mechanical damage. The full testing methods and results are presented in the preceding ME8.4 report.

The rates of biofouling and corrosion encountered at the test site were rapid, indicating that coating selection is likely to be a key consideration when attempting to ensure the long term and efficient operation of tidal devices.

If not managed adequately through coating selection and cleaning, the extent of biofouling we encountered is likely to have implications for energy conversion potential in terms of creating substantial hydrodynamic drag on key components. On a device scale, the level of biofouling encountered on unprotected surfaces could affect aspects such as the manoeuvrability and buoyancy of the turbine, potentially creating problems during deployment and retrieval.

The rate of biologically mediated corrosion we encountered on un-coated marine grade stainless steel without protection from anodes was in the region of 4 to 5 mm per year in some cases (see previous ME8.4 Report). These results suggest that suitable protection from biofouling is absolutely vital for long term deployments of marine infrastructure in high energy tidal races.

Our testing has shown that, as expected, the different coating technologies perform with varying levels of success in this environment. The results also indicate that some coating types are more suitable for particular roles that others. This information is used in this report to produce a coating selection guide that will assist device developers with the selection of a marine protective or antifouling coatings based on a number of criteria.

In addition to device efficiency and longevity, changes to legislation concerning the control of non-native marine species which often reside in biofouling assemblages present yet another reason to optimise biofouling control on marine renewable infrastructure, as discussed in Section 6 of this report.

The last section of this document presents the conclusions of this work together with recommendations for further work to characterise the performance of marine protective and antifouling coatings in high energy tidal streams.

2   Environment

2.1   Introduction

Please note that this section will be updated as more environmental data become available from the wider ReDAPT project.

Environmental parameters such as temperature, pH, salinity and water velocity can alter the performance of antifouling coatings considerably. This effect can be particularly marked on the performance of biocidal coatings where these parameters can alter the rate at which the biocidal component is released from the paint matrix. Consequently, by altering the release rate of biocides from coatings, environmental parameters can influence the efficacy and longevity of coating technologies.

It is a requirement therefore to characterise environmental parameters when investigating the efficacy of antifouling coatings to enable results to be extrapolated beyond the specific test site. For these reasons, the ReDAPT project initially aimed to characterise environmental parameters (temperature, pH, dissolved oxygen and salinity) of the seawater at the test site.

However, due to a series of technical and funding issues, this attempt was not successful and consequently the whole range of environmental data that it was hoped would be available to contextualise the coating performance we encountered was not available. Despite this, other instruments were deployed on and around the Turbine that captured environmental data during the coating trials that we will summarise and discuss in this section of the report.

2.2   Depth

In terms of understanding how the test coatings perform when applied to a tidal turbine, the most relevant test depth was that of the turbine itself, which is approximately 15 meters below the surface. However, as previously discussed in Section 2 of the ME8.4 report, the developmental delays with the turbine resulted in the coated test panels applied to the turbine only receiving a relatively short 56 day deployment. Consequently our main understanding of coating performance is provided by the coated test panels on the benthic pods. The benthic pods were situated on the seabed, close to the turbine, in approximately 42m of water. Depth was particularly important in this test as the water velocity varied with depth as described in Section 2.7.

2.3   Water Clarity

It was not possible to collect any data describing the light penetration at the test depth. However, the water in the Fall of Warness is generally very clear with underwater visibility in excess of 10 horizontal meters all year (See Figure 1).

Figure 1: Image showing example of good underwater visibility at 43 meters at the test site in April 2014, despite a period of unsettled weather

2.4 Salinity

The mean salinity at the test site was recorded as 34.75 PSU in 2011 based on data supplied by NASA (Aquarious – see References). This is well within the range of normal oceanic salinity conditions and within the design specifications for all of the marine coatings tested for this project. As salinity can affect the release rate of biocides from active antifouling technologies, it is advisable that if devices are to be used in fresh water, the design specification of any potential coatings is verified as being suitable for a fresh water application.

2.5 Temperature

The temperature of the water at the test site was recorded as a minimum of 6.1° C in March 2014 and a maximum temperature of 14.8°C in August 2014. This is well within the range of normal temperate oceanic temperature conditions and within the design specifications for all of the marine coatings tested for this project.

2.6 pH

The pH of the seawater at the test site was not recorded directly for the ReDAPT project, however, the mean surface pH South of Orkney was recorded as approximately 8.16 by Rérolle et al. (2011). This is well within the range or normal temperate oceanic pH conditions and within the design specifications for all of the marine coatings tested for this project.

2.7   Water Velocity

Water velocity is a crucial descriptor of the test site as the water speed will not only influence the rate of leaching and polishing of the coatings, the water velocity will also influence the settlement and growth of fouling organisms. Figure 2 describes the relationship between depth and mean water velocity during flood tides.
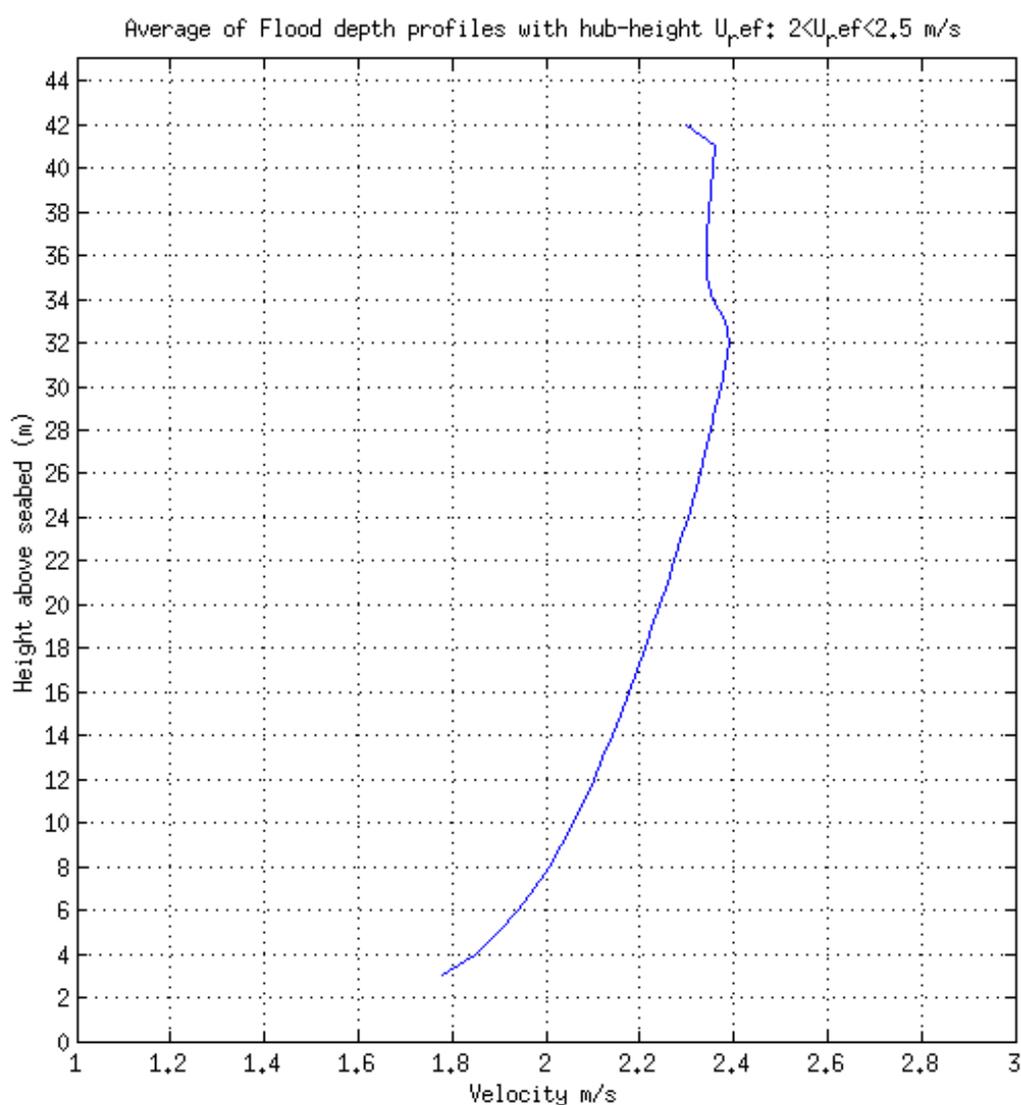
Figure 2: Plot showing the average velocity of water movement with height above the seabed at the tidal site.

It is clear that the water velocity near the seabed at the depth of the pods (~42m) was not, on average, as fast as the water at the depth of the turbine (~15m). For context, most marine protective coatings tested here were designed for the commercial shipping industry. Commercial ships generally steam at around 17 – 23 knots or 8.74 - 11.83 m/s. The water near the pods was approximately 3.5 knots or 1.8 m/s.

When comparing coating longevity predictions between the shipping industry and high energy environments, it is important to consider that although the water velocity is generally slower at tidal sites, the wash out rate of any biocides and wear down rate of the coatings is also likely to be influenced by mechanical scouring of water borne debris. An assessment of the longevity of the biocidal coatings tested for this project is described in Section 3 of this report.

2.8   Biotic Factors

There are several key biotic factors that do not affect the chemical properties of the coatings as such, but do greatly influence biological aspects of the fouling organisms encountered at the site.

For example, the concentration and type of nutrients dissolved and suspended in the seawater will influence the growth rates of any settled organisms. Additionally, the larval supply at each site will vary spatially and temporally, with knock on effects on biofouling rates and community composition. These biotic factors are variable, challenging to quantify and as such are difficult to predict. The easiest way of characterising these parameters is not to measure them directly but measure growth rates and species composition of fouling assemblages, preferably over multiple years.

This information will aid coating selection and quantification of the bio-corrosion risk. For example, if the fouling assemblage is dominated by hydroids and non-calcareous fouling organisms, the risk of coating damage directly as a result of biological growth is reduced compared to an abundance of large calcareous organisms such as the barnacles encountered at the Fall of Warness.

2.9   Key Species

By far the most dominant fouling species on the test panels was a large operculate, or acorn, barnacle, *Chirona hameri*. Please note that this organism was referred to in previous reports as *Balanus crenatus*, but has since been reclassified. This species has a distribution within temperate regions of the North Atlantic Ocean, having been recorded around the British Isles (although it is now not found alive in the English Channel), off the coasts of the Netherlands, Sweden and France in European waters, as well as from Nova Scotia to Chesapeake Bay in North America (Southward 2008).

As with most barnacle species this organism is a sessile, benthic filter feeder, permanently attaching to hard surfaces where it uses its cirri (feeding appendage) to filter suspended particles out of the water column. This organism typically lives sub tidally, spanning the circalittoral zone and living at a depth ranging from approximately 20m to 200m.

Atypically for most barnacle species encountered around the British Isles, this organism can reach an average mature size of over 25mm in basal diameter and reach a height extent of approximately 30-40mm above the surface on which they are attached (Southward 2008). In particularly productive regions such as the Falls of Warness, where strong water currents supply water that is rich with oxygen and also has a high concentration of suspended particles (food), organisms have been noted with a basal diameter as high as 65mm. This

basal plate is of extra significance as even when the organism dies and the main body of the barnacle is removed, this basal plate remains (Figure 6).

Figure 3: Immature barnacles (3 months) from a tidal stream in Orkney showing basal plates remaining where adults have become dislodged (foreground).

The basal plate is particularly robust to mechanical abrasion and when a barnacle dies it provides novel space for other organisms to foul, forming a barrier between the underlying substrate and the newly settled individual, potentially reducing the efficiency of antifouling measures.

Additionally, this residue left by the previous generation of fouling organisms can act as a positive cue for settlement of subsequent larvae. The chemical and physical legacy left in the deposits from the previous organisms can persist to the extent that they can be detected by settling larvae even though the surface has been cleaned of all residue visible to the human eye, highlighting the importance of adequate cleaning procedures (Ralston *et al* 2014).

The size of this organism, the depth at which it occurs, the fact it forms a hard calcareous exoskeleton and the longevity of basal plates on surfaces long after the organism is deceased therefore make this species a particular concern for tidal energy infrastructure within temperate regions of the North Atlantic Ocean.

C. hameri has been proposed as a winter breeder (Southward 2008), benefiting from cold water distribution, meaning juvenile recruitment would typically occur between April and May. However, during field trials it was noted that multiple recruitment events of this species occurred throughout the year, highlighted by the presence of very young individuals on test infrastructure that was recovered on separate dates during June and September 2014.

In addition to *C. hameri*, the fouling community within the Falls of Warness consists of a number of sessile invertebrate organisms typical of the biotopes present within this region (Moore 2009). For example communities also contained two further barnacle species *Balanus crenatus* and *Semibalanus balanoides*. These species have a similar life style to that of *C. hameri*, being sessile filter feeders that form a hard calcareous exoskeleton, and thus have a similar potential impact on the operation and reliability of tidal devices; however individuals of these two species do not reach a size comparable to that of *C. hameri*, reaching a maximum basal diameter of 25mm and 15mm respectively.

Similarly to *C. hameri*, *B. crenatus* has a long recruitment period, with larvae being released between February and September. Similarly *S. balanoides* releases larvae between February and April, targeting the spring algal bloom, and thus avoiding leaving devise static at these times could help prevent settlement of this species. Within the Falls of Warness, however there were fewer individuals of these two species compared to *C. hameri*, and thus these smaller species likely pose slightly less of a threat to devices than their larger counterpart.

In addition to prolonged recruitment, larvae can survive for extended periods in the water column and thus can be transported great distances in tidal currents before settling. One recent study estimated temperate fouling species could be transported over 400-500 km during the larval stage, with a net dispersal of >70 km (Adams et al 2014). This suggests a high likelihood of connectivity of recruitment/settlement between separate tidal sites within the waters around the Western Isles, Pentland Firth and Orkney.

2.10 Extrapolation

In terms of extrapolation of data from this site to other test sites, caution must be exerted. If environmental conditions at another tidal site are very similar to the conditions encountered at the Fall of Warness, then it is reasonable to assume that the coatings will perform in a similar fashion.

However, a change even in one factor such as light penetration of the water caused by suspended sediments, is likely to result in a shift in the dominant species present in the fouling assemblages, and consequently different settlement and growth rates, together with hydrodynamic drag penalties.

Similarly, if factors such as salinity, temperature or pH vary considerably from the conditions encountered in Orkney, it is likely that biocide release rates will alter compared to those observed here, with the potential to change coating performance and longevity. Although the coating longevity predictions produced in this report are considered representative for the Falls of Warness, the variation in biological, physical and chemical conditions at alternative tidal sites should be examined when trying to extrapolate these findings.

2.11 References

Adams, T.P., Miller, R.C., Aleynik, D., Burrows, M.T. (2014). Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. Journal of Applied Ecology 51(2): 330-338.

Ralston, E. A., & Swain, G. W. (2014). The ghost of fouling communities past: the effect of original community on subsequent recruitment. *Biofouling*, *30*(4), 459-471.

Rérolle et al. Biogeosciences Discuss., 11, 943–974, 2014

http://aquarius.nasa.gov/

3 Forensic Coating Assessment

3.1 Introduction

The coatings tested for this project are described below.

Name in Report	Manufacturer	Brand	Technology Type	Anticorrosive (DFT info supplied by manufacturer)	Tie Coat	Top Coat (DFT info supplied by manufacturer)	Pre-test Total Dry Film Thickness	Notes
Hempel Red	Hempel	Hempasil	Fouling Release	Multi-strength 457751-12340 (DFT 250µm)	Nexus 27302-55001	Hempasil Topcoat	~1000µm	Manufacturer applied
Inter Grey	International	Not supplied	Fouling Release	Aluminium pure epoxy (150µm x 2 coatings)	Silicone Tie coat 100µm	Flouropolymer Antifouling 150µm	~550 µm	Manufacturer applied
Coppercoat	Coppercoat	Coppercoat	Biocidal copper filled epoxy resin	GP120 (DFT 250-300µm)	N/A	Coppercoat (DFT 250 – 300µm)	~350µm	Manufacturer applied
Jotun Red	Jotun	Seaquantum Ultra	Self polishing biocidal	Jotamastic 87	Safeguard Universal AS	Seaquantum Ultra	~600µm	Manufacturer applied
Inter Red	International	Not supplied	Not supplied	Not supplied	Not supplied	Not supplied	~550 µm	Manufacturer applied
Plastimo (Blue)	Plastimo	Plastimo Classic	Self polishing biocidal	Primocon (see below for details)	N/A	Plastimo Classic	~180µm	User Applied
GRP	International	Interzone 954	Epoxy	N/A	N/A	Interzone 954	N/A	User Applied
Jotun Yellow	Jotun	Baltoflake Ecolife	styrene free, glass flake reinforced polyester	Jotamastic 87	Safeguard Universal AS	Baltoflake Ecolife	~1200µm	Manufacturer applied
Ecospeed	Ecospeed	Ecospeed	Vinyl ester resin base, reinforced with glass platelets	N/A	N/A	Ecospeed (DFT 500µm x2 layers)	~1300µm	Manufacturer applied
Primocon	International	Primocon	Tar free quick drying primer	This product is an anticorrosive primer and was used as a control coating.	N/A	Primocon	~150µm	User Applied

Table 1:Coatings tested for ReDAPT project in order of technology type.

3.2   Results

After an inspection of the coatings following a 24 month deployment on the test pods, it became clear that in general, the biocidal coating technologies performed comparatively well. The main exception to this trend was the performance of the Plastimo coating, which was likely to be largely a result of the application procedures.

The positive performance of the biocidal coating systems is likely to be a result of its combination of active antifouling capability due to a toxic or biocidal component, together with a relatively hard and mechanically resistant surface. These coatings appear in general to resist settlement in some cases, kill and slough off newly settled organisms in other cases, whilst remaining intact and persisting without obvious damage due to scouring or collision with water borne debris.

Initially, the performance of the biocidal coatings indicates that they are the most suitable coating technology type for application on tidal turbine infrastructure. However, biocidal coatings fall into three coarse categories defined by the release mechanism of the biocide (see ME8.1 for a review). In either case, the amount of biocide and therefore the longevity of the coatings' active antifouling capability are finite. Consequently, despite the fact that biocidal technology types in general appear to be the most effective in this test environment, the critical question is how long is this effect likely to last?

In order to address this question, we analysed examples of the test coatings for roughness and thickness before and after the 24 month deployment to try and provide a measure of how much of the finite coating performance remained after 24 months. Depending on the mechanism of biocide release, different measures are required to evaluate coating longevity. Free association coatings and Self Polishing Coatings (SPCs) will reduce in thickness as the active element of the coating is exhausted. In contrast, Controlled Depletion coatings or Ablative/Erodible coatings will leave behind an insoluble matrix after the biocidal component has expired. Therefore the performance of the coatings needs to be evaluated in context of their mode of operation.

Please note: The epoxy coating systems were not included in this analysis as they were so heavily fouled that significant cleaning efforts would be required to remove the biofouling before the damage could be quantified. It was considered that this cleaning process itself would result in damage to the coatings that did not occur during the exposure.

Cleaning of epoxy coatings after short term deployments (8 weeks) appeared successful and did not result in visible damage to the coating, however this finding is based on qualitative observations only and was not directly assessed.

3.3   Methods

Surface rugosity (a measure of small-scale variations or amplitude in the height of a surface i.e. roughness) can impacts the propensity of a surface to foul and create hydrodynamic drag. Thus to assess coating performance it is key to understand the application continuity of different coating types. We measured coating thickness and roughness following initial application and following a 24 month deployment in a high energy tidal stream. Such measures will ultimately give an indication of likely coating performance, as well as an estimation of performance longevity. To test these different coating parameters a subset of experimental panels were analysed using laser surface profilometry.

Coating thickness was assessed using an Elcometer® magnetic digital thickness gauge, measuring thickness on a minimum of 10 points evenly distributed across each panel surface, ensuring no point was closer than 1cm to the edge. These measures were then used to generate an average surface thickness per panel. On post-deployment panels any areas that were either coated in barnacle plate or damaged were avoided. The thickness and roughness data were subsequently compared between coating types pre-deployment, as well as within coating type pre and post-deployment to assess possible life expectancy of field deployed coatings.

Contactless surface metrology was measured using an Alicona InfiniteFocus microscope. 3D surface roughness was selected due to the intended surface properties of antifouling coatings, being uniform and flat, with average roughness (Sa) and peak-to-trough roughness (Sz) being measured. A typical feature of antifouling paints is a pattern of waviness caused by the drying of the paints. Thus to decouple roughness from waviness, cut-off lengths (λc) were selected by visually assessing form in the Alicona software. Data were subsequently filtered to remove the impact of any waviness from the assessment of roughness. Three measures of Sa and Sz were assessed per panel, with these data being used to generate an average overall panel roughness (Sa and Sz).

As with coating thickness, areas of damage or residue fouling were actively avoided during roughness assessment. However, again as with thickness, this may skew the assessment of the performance of the coating, particularly with respect to hydrodynamicity of coatings, as damage and residual fouling are significant factors that should be considered when assessing coating performance. Data were analysed between panel type pre-exposure and within panel type pre- and post-exposure.

To assess coating performance prior to a field exposure a subset of 81 panels (9 replicates per coating type, 9 coating types) were analysed for panel thickness. It was not possible to magnetically determine thickness on coated GRP panels. A subset of 90 panels (9 replicates per coating type, 10 coating types) were analysed for coating roughness. Post exposure it was only possible to analyse 29 panels (divided between 6 coating types). This was due to the heavy fouling, corrosion product or coating damage encountered on some panels, thus meaning it was not possible to accurately determine thickness or roughness.

3.4   Results

3.4.1   Coating Thickness

3.4.1.1   Pre-field Exposure

Following initial application, coating thickness was assessed with coatings being ordered with respect to thickness (Figure 3A). International Primocon anticorrosive primer layer was the thinnest coating (mean 103.8 µm) with Ecospeed being the thickest (mean 1324 µm). However, as Plastimo was applied upon the anticorrosive layer it likely had a thickness in the order of just 80 µm. Jotun Red was the most consistent coating with respect to coating thickness between panels (2.3% Relative Standard Deviation), with the International Primocon anticorrosive layer being the most variable (27.1% RSD). Please note that both Primocon and Plastimo were applied by hand in accordance to the manufactures instructions prior to testing. The other coating systems were applied by their respective manufactures under controlled conditions relevant to each coating type.
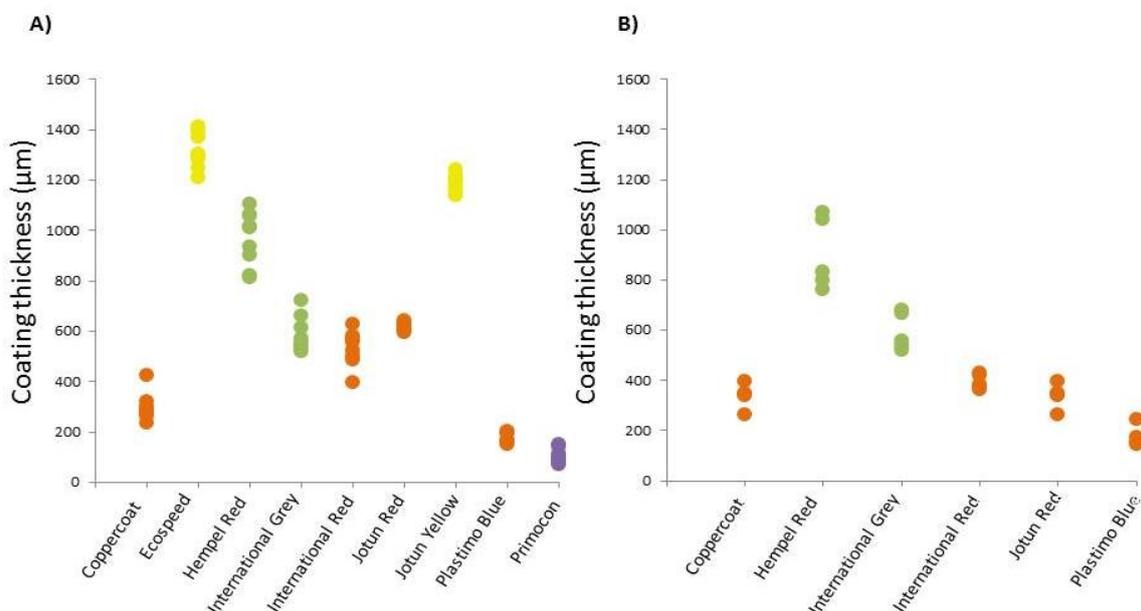
Figure 4: Mean coating thickness for each panel, separated by coating type. A) thickness pre-field exposure and B) after a 24 month field exposure. Epoxy coatings are represented by yellow symbols, biocidal coatings by orange symbols, FRCs by green symbols and the anticorrosive coating is represented by purple symbols. Each point is a mean of 10 measurements taken for each panel.

3.4.1.2   Post-field Exposure

Following a 24 month field exposure it was only possible to assess coating thickness on 29 panels, distributed between 6 coating types. This was due to the heavy fouling, corrosion product and damage encountered on some panels. Of the tested panels there was a significant difference in the change of coating thickness over time based on panel type (Figure 3B).

Despite being the thinnest coating initially, the thickness of Plastimo was not shown to change following a field exposure, as was also the case for International Grey and Coppercoat. The thickness of International Red, Hempel Red and Jotun Red were shown to reduce by 139 µm, 68 µm and 29 µm respectively.

3.4.2   Coating Roughness

3.4.2.1   Pre-field Exposure

As with thickness, there was a significant effect of coating type on coating roughness (Figure 4A). Following initial application Ecospeed was shown to demonstrate the greatest roughness (Sa = 5.16 µm), with International Grey the lowest (Sa = 410 nm). The Primocon anticorrosive layer was the most consistent coating with respect to roughness (RSD = 3.93%), with Hempel Red and International Red demonstrating the highest roughness variability (RSD = 43.9%, 26.6% respectively). The inconsistency of Hempel Red and International Red may have resulted from the way in which these two panel types were packaged in protective paper and foil respectively. These packaging methods resulted in a residue of glue on Hempel Red samples and small indentations on the Jotun Red samples. It should be noted, however, that despite the high variation of these two coatings, the overall roughness was still extremely low. Sz is shown to correlate well with the Sa values, with the exception being the case of both GRP and Jotun Yellow, where random inclusions and pores are quite commonly observed (see Figure 5E). These have the effect of slightly elevating Sz relative to Sa.
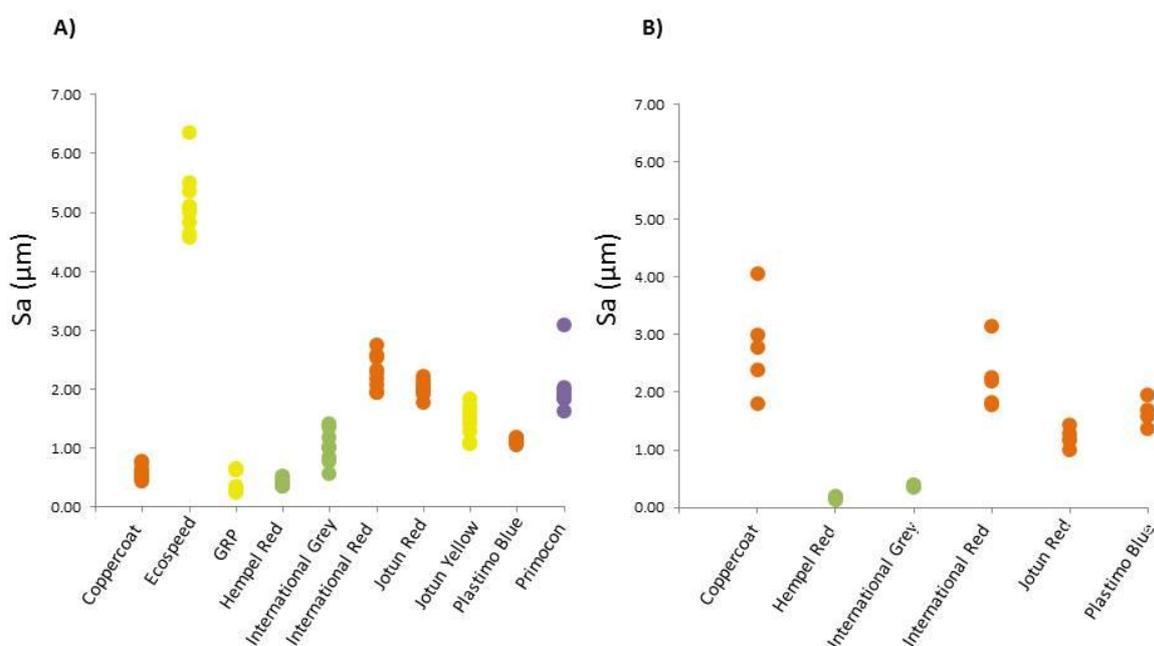
Figure 5: Areal roughness for each coating type. A) Roughness pre-field exposure and B) after a 24 month field exposure. Epoxy coatings are represented by yellow symbols, biocidal coatings by orange symbols, FRCs by green symbols and the anticorrosive coating is represented by purple symbols. Each point is a mean of 3 measurements taken for each panel.

3.4.2.2   Post-field Exposure

As noted pre-exposure, coating type influences the average roughness of coatings post-exposure (Figure 4B). Of the sampled panels the greatest change in respective average roughness (Sa) was a 61% reduction noted in Hempel Red samples (a reduction of 431 nm to 167 nm). The Sa of International Grey and Jotun Red was also reduced by 6 % (410 nm to 381 nm) and 47 % (2.28 µm to 1.21 µm) respectively.

Whilst Sa was reduced in the above mentioned coatings, an increased Sa was noted in International Red, Coppercoat and Plastimo. The greatest respective increase in Sa was noted in International Red, increasing from 1.00 µm to 2.24 µm, a change of 122 %. Coppercoat and Plastimo became an average of 41 % (1.99 µm to 2.80 µm) and 18 % (1.39 µm to 1.64 µm) rougher, respectively. Unlike Sa, Sz was shown to reduce over time in all coatings following a field exposure, with one exception, International Red where peak-to-trough roughness increased by 69 %.
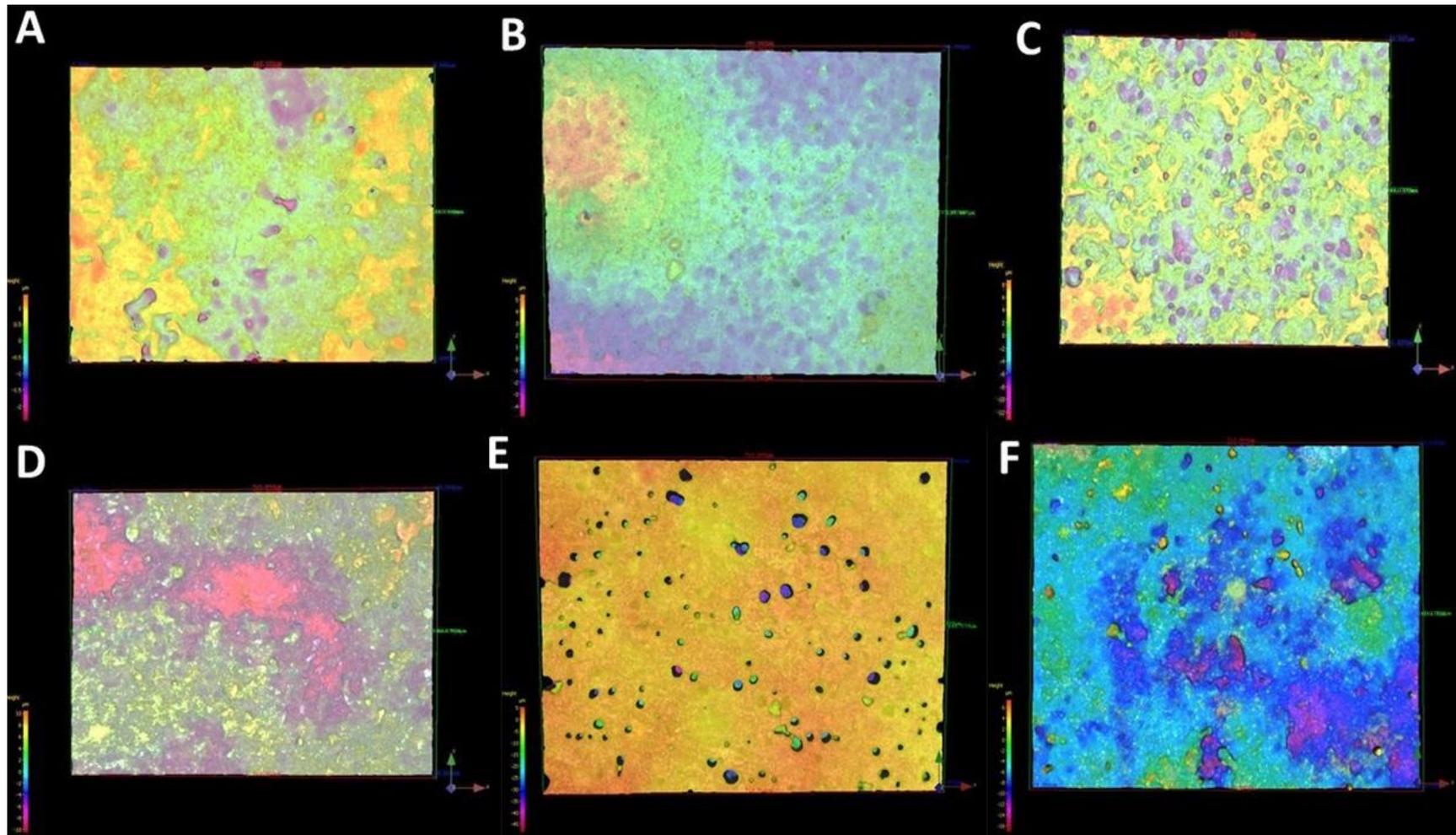
Figure 6: Texture map/optical images of each panel type post exposure from Alicona microscope. A) Hempel Red, B) International Grey, C) International Red, D) Jotun Red, E) Jotun Yellow and F) Plastimo Blue.

3.5   Conclusions

It was hoped that by measuring the coating thickness pre and post exposure, it would be possible to provide a predictive assessment of coating longevity. Although this was attempted, there are several aspects which severely limit the accuracy of these predictions.

Firstly, when the thickness measurements were taken post exposure, only areas of the coating that were obviously not delaminated were selected. This step was taken because the damage encountered by the coatings was highly variable and uncontrolled. Therefore, the longevity of the coating cannot be assessed on thickness alone as in some cases the areas of coating damage not characterised by the thickness measurements may have resulted in coating failure.

Secondly, in the predicted longevity values, we have assumed a linear decrease in thickness over time, which is unlikely to be the case for all technology types. Thirdly, because forensic analysis was not possible for all coating types due the presence of hard fouling that would require removal before analysis, not all coating types are represented.

As a result of these considerations, the predicted longevity of the different coating types over time assuming a linear reduction in thickness is highly variable and requires further investigation to provide sufficient confidence in the results. Once more information is available describing the active mechanisms coating technologies tested for this study, this section will be updated.

Based on thickness measurements alone, the FRCs tested in this study were predicted to last between 28 years and an infinite time if not exposed to mechanical damage. This is to be expected from a coating not designed to deplete or erode. This study also predicts that most biocidal technologies examined here will last for up to 8 years. However, some biocidal technologies showed no measurable loss of thickness during the whole 24 month deployment, which is surprising given the hydrodynamic activity and the potential for abrasion at the site.

4   Coating Selection

4.1   Introduction

This section aims to learn from the coating testing work conducted for the ReDAPT project to produce a protocol to aid the selection of marine protective coatings for use in high energy environments. Coating selection can be guided by many different factors from economic to environmental considerations. The following sub-sections describe different coating selection criteria and provide advice on each aspect gained from experience gained during coating testing for the ReDAPT project to aid decision making.

4.2   Cost

The first consideration should be the potential costs involved with correctly specifying and applying coatings. Our experience has demonstrated that despite coating performance being critical in terms of operational efficiency and asset longevity, coatings and biofouling are often overlooked and not considered until a relatively late design stage. This can lead to a situation where there is not enough resource available to properly research and specify coatings for different components, or secure suitable application procedures resulting in premature coating failure or sub-optimum performance.

Costs associated with coatings can be substantial. Our findings suggest that it makes good economic sense to characterise the working environment of a device and then specify coatings accordingly to provide the best chance of efficient operations, and to avoid premature coating failure.

4.3   Material Type

The material type of the component that is to be coated is generally prescribed by the mechanical requirements of the components role, and as such the choice of material type is likely to be either limited or fixed. Consequently, one of the first considerations should be the compatibility of the selected component material type and candidate coating technologies. For example, aluminium has long been considered as incompatible with copper based antifouling technologies as this combination has been recorded as creating severe corrosion issues. However, recent evidence in this area suggests that for some applications this is not so critical (Bagley , 2014). Further work is required in this area.

Other materials such as stainless or mild steel require particular steps to be taken in the application process and in most cases will require the application of an anticorrosive or tie coat layer. We suggest consulting the coating manufacturer for advice on compatible coating technology types that are suitable for the material type in question and then use the following decision criteria to select the final coating system to use. For reference, all the base materials used in this study were mild steel with the exception of one type of glass reinforced polymer panel in an attempt to get as close as possible to the actual materials used in the construction of tidal devices.

4.4   Regulation

Another key consideration is whether or not the proposed coating is legal for use at the proposed site. Antifouling coatings and their constituents are regulated and these regulations change/evolve over time. Please see Section 6 for a review on this area. The key considerations from a legal standpoint are the type and concentration of any active ingredients (biocides) in the antifouling coating.

4.5   Specific Requirements

The next step in coating selection should be consideration of the particular use of the component to be coated. Different coatings are more suitable for particular applications than others. For example, there are coatings specifically designed for optical use such as ClearSignal™ technology (a clear, non-toxic, rubber-like coating for marine instruments), which although not tested as part of this project, show potential for use on small but critical areas such as lenses and sensors.

Components that are likely to endure friction or mechanical impacts should not be coated in the foul release coatings (FRCs) tested here as these were prone to delamination resulting from mechanical impact. Many of the FRCs are also challenging to patch repair due to their inherently non-sticky nature meaning that if damage did occur, recoating the entire component might be the only option.

Conversely, the flexible nature of FRCs means that they are able to withstand a certain degree of flexing of the underlying substrate. This movement can cause other more brittle coatings such as many biocidal and epoxy based technologies, to crack and detach on components that flex and bend such as blades.

Although we did not assess the mechanical resistance of the coatings directly, the results from this study show a clear trend in the percentage cover of damaged coating after the 24 month deployment. The results of this assessment can be seen in Figure 7 and indicate that, based on our findings, if mechanical damage is anticipated, hard biocidal technologies are more robust that the FRC technology types in this application.

The severe surface corrosion encountered on the Primacon panels (Figure 9) is likely to result from poor or inadequate application of this anticorrosive layer, despite the manufactures guidelines being followed. This finding highlights the importance of application procedures in terms of achieving the optimal performance of marine protective coatings. See Section 4.1.
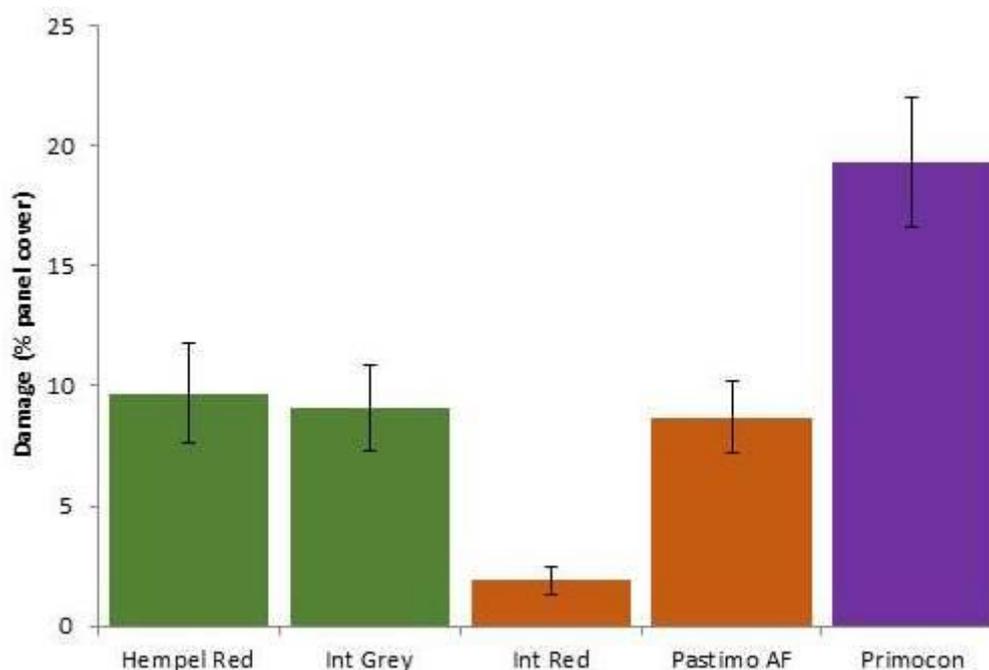
Figure 7: Relative differences between percentages of coating damage encountered on the different coating systems after a 24 month deployment. Values are means (± SEM). Green bars represent FRCs, Orange bars represent biocidal coatings and the anticorrosive coating is represented by the purple bar. N=10

4.6   Objective – Anticorrosive or Antifouling?

The next step in coating selection should be consideration of what the objective of the protective coating is. Does the component require active antifouling protection to protect it from hydrodynamic drag produce by biofouling, or is it simply enough to protect the component from corrosive seawater?

4.7   Corrosion and Mechanical Damage

If the component simply requires protection from corrosion and biofouling related drag is not a concern, a suitable anticorrosive coating followed by hard epoxy based protective coating system is likely to be sufficient. The advantage of an epoxy coating systems is that because there is no finite biocide being consumed, if correctly applied, the coating system should have a much greater longevity in the marine environment than a biocidal system.

The other advantage is that when biofouling becomes problematic, most hard epoxy coating systems can be mechanically cleaned. Crucially, with the exception of flexing of the underlying substrate, epoxy coatings are also able to withstand mechanical stresses that might occur near moving parts such as connectors, mooring lines and power cables etc.

4.8   Biologically Mediated Coating Damage

Coating damage can also occur as a result of biological factors such as the growth of a barnacle in a small indentation or imperfection on a coatings surface, see Figure 8. When a fouling organism such as a barnacle grows and expands in a confined area such as pit on the

surface of the coating, the pressure applied to the coating can be such that the coating is delaminated from the underlying coating layer, or even the substrate itself.

Figure 8: Coating damage caused by growth of a barnacle

This situation is of particular concern as a small area of substrate that is left unprotected by the coating can become a focus for very rapid rates of crevice or pit corrosion, leading to rapid failure of a component.

Coating damage caused by barnacles and other fouling organisms is known to occur on a variety of coating technology types. However, this form of damage was only recorded on the FRC technologies examined for this test suggesting that the hard biocidal coatings and epoxy based coating systems tested here were able to withstand this kind of biologically mediated coating damage.

4.9   Antifouling

If the component will suffer as a result of hydrodynamic drag or blockage from marine growth then both protection against corrosion and biofouling are design criteria. Thus a coating with an inherent antifouling capability will be required.

There are several main types of antifouling technology on the market, for reviews see ME8.1 and the update of ME8.1 in Section 7 of this report. The antifouling technologies tested for this project were either biocidal coatings or FRCs. The FRCs contain no biocides and rely on their low surface energy to prevent firm adhesion of fouling organisms to the surface and any fouling that does manage to attach is sloughed off as water velocities create shear force across the coating.

4.9.1   Flow vs Static

When selecting an antifouling coating it is important to consider the hydrodynamic conditions that a particular surface or component will encounter during its operation. For example, it is unlikely that in flooded internal areas of a device that hydrodynamic activity

will be sufficient to allow FRCs to function properly, although this aspect has not been directly tested in this study.

Results from this study however indicate that static components that are exposed to 2m/s tidal streams experience sufficient hydrodynamic shear to allow FRCs to operate satisfactorily see Figure 9.

Figure 9: FRC technology following a 24 month immersion trial

It is therefore reasonable to assume that the shear force created by moving parts such as blades will also experience sufficient hydrodynamic velocity in the tidal flow to allow FRCs to operate correctly. However, the lack of resistance to mechanical damage demonstrated by FRCs (Figure 6) may present problems for long term operation on components such as blades. Longer term (in excess of 8 weeks continuously) testing of FRCs on moving parts such as blades is required before this aspect can described with more certainty.

4.9.2 Cleaning

To achieve optimum longevity from a coating system, proposed cleaning procedures should be matched to the coating type in order that premature damage to the coating is prevented. Most mechanical cleaning will serve to roughen the coating system to some degree, with the likelihood of increasing hydrodynamic drag over the surface. Consequently it is important to schedule cleaning procedures appropriately so that they are conducted regularly enough to remove significant fouling but not so frequently as to damage the coating system. As the most appropriate cleaning approaches vary considerably between coating systems, we suggest consulting with the coating manufacture on this aspect.

4.10 Other Considerations

4.10.1 Application Procedures

Environmental conditions such as humidity, temperature, presence of loose particles and the surface finish of the material can have a dramatic influence on the adhesion of protective and antifouling coatings systems and their long term performance. If these conditions are not adequately controlled during the application process, it is very likely that the coating system will underperform or possibly fail entirely.

Figure 10: Corrosion and biofouling on a mild steel panel protected with a "user applied" anticorrosive coating.

Based on the performance of the coatings tested for this project, we suggest that particular attention be paid to application of the coating system, regardless of the technology type selected. Simply following manufactures guidelines for application may not be sufficient to ensure optimum coating performance. The severe surface corrosion encountered on the Primacon panels (Figure 10) is likely to result from poor or inadequate application of this anticorrosive layer, despite the manufactures guidelines being followed.

We suggest that to ensure the best chance of achieving the optimum performance of the coating, a specialist coatings applicator is contracted who is endorsed by the manufacture of the coating.

4.10.2 Coating Guarantees

In some instances, coating manufacturers may issue a coating performance guarantee. This is very unlikely unless an approved applicator is used. As most of the antifouling and protective coating systems on the market are actually designed for use on ship hulls, as opposed to renewable energy devices, it is not yet known whether manufactures will extend their guarantees to this alternative use of the technology. However, in order to achieve even partial insurance against an expensive coating failure, we suggest this subject is worth investigating with the manufacturer at the negotiation stage.

5   Decision Tree

5.1   Introduction

This section aims to present a generic framework to help guide device developers and operators through a coating selection process based on the testing conducted during this project. The order in which these decision steps should be addressed will vary between situations. However, it is hoped that consideration of these steps will help ensure that the most suitable coating systems are selected to help protect assets in these harsh, high energy environments.

5.2   Diagram 1 – Simplified Coating Selection Process

The diagram below provides guidance for specification of a coating system for components of tidal devices based on testing conducted for the ReDAPT project (Figure 11). The first step referring to cost is intended to aid consideration of the likely costs involved in the entire coating specification and application process, which should be considered at the outset (see Section 4.2). The subsequent steps are based on engineering aspects of the materials to be coated and the capabilities of the coatings themselves.

We suggest that coating specification decisions should be carried out in consultation with the coating manufacturer to ensure compatibility between brands and materials. We also suggest accessing independent coating selection advice for marine systems such as that provided by The International Paint and Printing Ink Council (IPPIC). For particular steps such as regulation, Section 7 of this report provides a current review to assist in the decision making process.
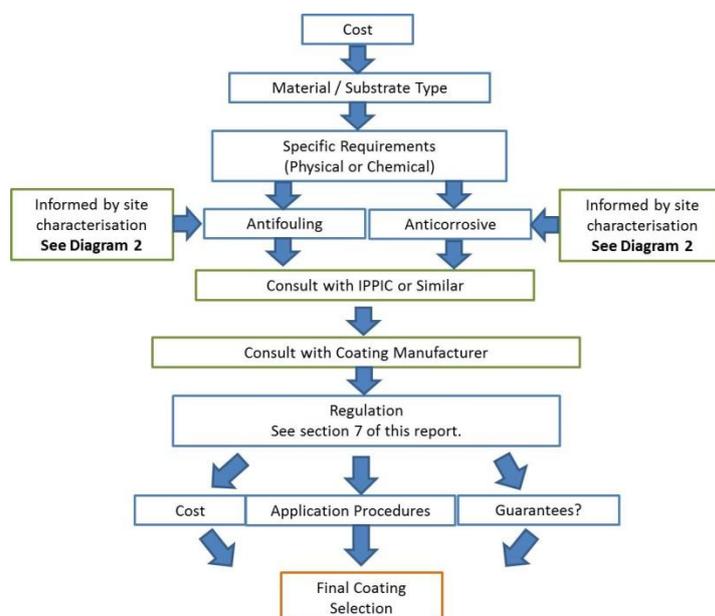

Figure 11: Decision Diagram 1 - Simplified coating selection process.

5.3   Diagram 2 - Technology Selection

The diagram below (Figure 12) is designed to aid coating technology selection. The final coating technology types are deliberately over simplified as there are many variations within each technology type and new technology types are continuously emerging.
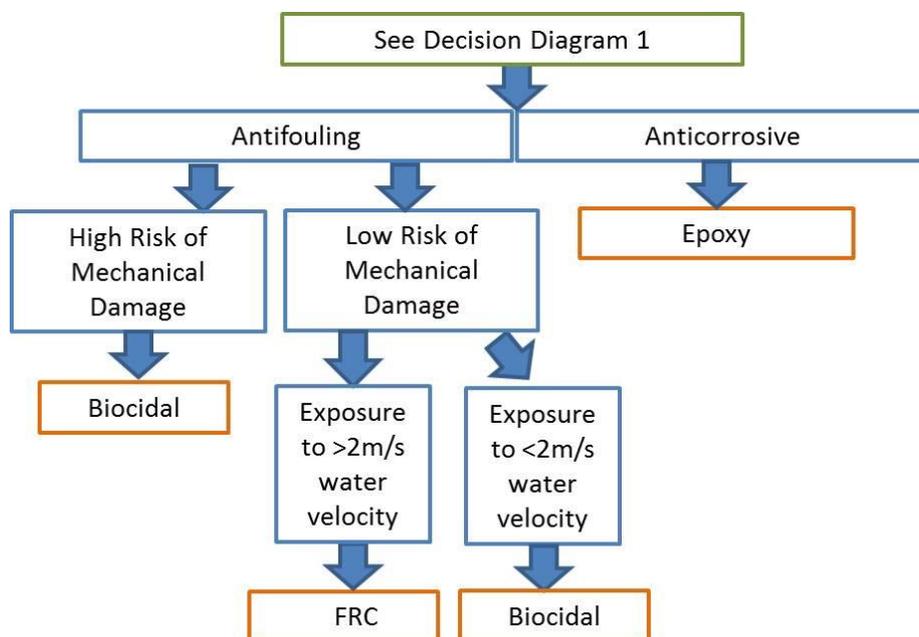
Figure 12: Diagram 2 - Coating technology type selection process.

In summary, if the only requirement of the coating technology is protection against saltwater corrosion and mechanical damage an epoxy based coating system is likely to provide sufficient protection. One exception to this could be if the underlying substrate is subject to flexing which could cause hard and inflexible coatings to crack and become detached, although this was not specifically tested in the current study. If the coating is required to have an antifouling capability and the material is likely to encounter mechanical damage, results from this test suggest that biocidal coatings are likely to produce the most effective results. Again there are question marks over the longevity of this effect that requires further investigation.

Based on the results of this test programme, if the coating system is not likely to encounter significant mechanical damage, then an FRC system is likely to be very effective if the water velocity exceed approximately 2m/s. However, water velocity and risk of mechanical damage are normally linked so the likelihood of these operational conditions arising is considered minimal.

If protection against biofouling is required in conjunction with water velocities of less than 2 m/s, it is likely that a coating system with an active antifouling mechanism such as the biocidal technologies will be most suitable. Examples of this situation would be inside flooded internal chambers of the device with restricted water exchange.

5.4   References

Arbuzova, K.S. The Effect of Macrofouling on Steel Corrosion in the Black Sea,. Transactions of the Institute of Oceanology, Vol XLIX, pp 266-273

Bagley, F. The use of Copper Based Antifoulings on Aluminium hulls. Proceedings of the ICMCF (International Congress of Marine Corrosion and Fouling) 2014. ICMCFsg0116a0001

6 Marine Alien Non-Native Species

6.1 Introduction

Please note that while every effort has been made to ensure this section is up to date and current, this text is for guidance only. We suggest that frequent reviews of this area are conducted before strategies for monitoring and mitigating marine alien non-native species are finalised to ensure that relevant legislation is complied with in this rapidly evolving area.

The UK government anticipates that over 33 Giga Watts of renewable energy projects will be created by 2020, the majority of which will be located in off-shore waters. 2020 is also a key deadline for national and European governments implementing regulation concerning the environmental issues affecting our coastal and off-shore regions.

The Joint Nature Conservation Committee (JNCC) is the lead government agency tasked with providing environmental advice to renewable energy regulators and individual companies. There has already been a lengthy process of consultation with stakeholders to determine issues of concern, and among those raised is the potential for infestation and/or association of structures and related equipment with alien invasive species (AIS).

6.2 European Stance

In a wider context, the European Union (EU) has been developing a strategy to control AIS since 2008, with the aim of protecting and improving the state of the EUs biodiversity, again by 2020. This EU Regulation was finally approved on September 29th 2014 and contained the following mandate: *Target 5- To control invasive alien species: By 2020, Invasive Alien Species and their pathways are identified and prioritised, priority species controlled or eradicated, and pathways are managed to prevent the introduction and establishment of new AIS.*

The European Commission's 2014 report on the prevention and management of the introduction and spread of AIS clearly describes the 'crucial' need to manage pathways of introduction, but does recognise that a large proportion of these pathways are unintentional. While no reference is made to any specific introductory pathway, off-shore renewable energy structures such as wind turbines will inevitably be fouled and have the potential to harbour AIS aiding their spread by acting as stepping stones from one environment to another. It does, however, concede that '*action in this area would need to be gradual, given the limited experience'* (Article 20).

The majority of all the actions in the report focus around terrestrial issues, so it is of note that the sole examples used to illustrate the issue of pathways are the voluntary guidelines of the 'International Maritime's (IMO) Guideline for the Control and Management of Ships' Biofouling' and the mandatory regulations of International Convention for the Control and Management of Ships' Ballast Water and Sediments', suggesting that marine pathways or introduction are very much in the forethought.

It is expected that the regulations, for all habitats, will enter into force on 1st January 2015, but it is likely that at that point in time, primary focus will be on a yet-to-be-established list of '*Union species of concern'*. Within 18 months of the adoption of the Union list, Member states must establish a surveillance system to detect the arrival of listed species (Article 14)

and specifically within three years must adopt priority pathway action plans to minimize new introductions (Article 13). If, by then, off-shore wind turbines, for example, are perceived as a pathway for introductions during initial assessments of current environmental status of Member State's marine waters, they will undoubtedly be required to undergo regular inspections and possibly be required to employ biosecurity measures.

6.2.1 "Good Environmental Status"

Specific to off-shore waters (with an overlap of jurisdiction between the Water Framework Directive on the boundary of coastal and offshore waters) is the Marine Strategy Framework Directive (MSFD) which hinges around the need to establish Good Environmental Status (GES), again by 2020. This states that by 2014 monitoring programs will actually be established, by 2016 programmes of measures will be implemented with the view that GES of UK waters will be met by 2020.

The MSFD does not state a specific programme of measures that Member States should adopt to achieve GES, except for the establishment of Marine Protected Areas (MPAs). However, the MSFD does outline 11 high level descriptors of GES in Annex 1, and importantly AIS are ranked as the second of these descriptors. This descriptor requires that *'non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystem'*. Again, if off-shore anthropogenic structures are perceived as having the potential of harbouring AIS at disruptive levels, mitigation will undoubtedly be required.

Within all consultation processes (whether UK or EU) is the acknowledgement that prevention is preferable to eradication. The financial cost of regular monitoring and surveillance, and the treatment of early stage introductions is considerably less, and far more effective than the cost of a late stage eradication and habitat restoration.

At the time of writing, it appears that monitoring efforts will be the responsibility of Member States, rather than the individual renewable energy companies, however it is likely that the use of specialist contractors will be employed to carry out the work and companies will be expected to comply if concerns are raised. This opinion is based on the fact that the monitoring programmes discussed in 'Monitoring for the Marine Strategy Framework Directive: Requirements and Options', 2012, are programmes which require considerable scientific resources such as remote sensing, population occurrence and abundance studies of a large range of taxa, oceanographic and genetic studies.

The report also states that Article 6 of the MSFD recommends Member States to *'use existing regional institutional cooperation structures, such as those under United Nations Environment Program (UNEP) Regional Sea Conventions (RSC), in order to achieve coherence and coordination of their marine strategies and build upon relevant existing programmes and activities'*.

The RSCs have already developed monitoring guidance and environmental assessment schemes and recommend the use of these schemes by any third party contractor carrying out monitoring and assessment. According to UNEP's Regional Seas Program offshore installations *are* classified as a threat to the north-east Atlantic alongside pollution, shipping, over fishing, coastal development and exploitation of the seabed for sand and gravel. So it seems highly unlikely that offshore developments will escape the net of regulation regarding

AIS. Although perhaps not a priority subject at the moment, as 2020 approaches, attention will undoubtedly focus on these installations in the near future.

6.3   Regional Stance

Whether the financial burden of AIS regulation will be borne solely by government has not yet been made clear, although changes to Scottish law perhaps serve as an indicator of future laws for the rest of the UK. In Scotland amendments to the Wildlife and Countryside Act make it illegal for the 'accidental transfer and spread of AIS (also referred to as non-native species or NNS) due to lack of/inadequate Bio-Security procedures'. Individuals and companies can be liable for the cost of eradication/control, as well as for the restoration of environment. These are 'strict liability offences' meaning ignorance is no defence and prosecutions can be made under any circumstances.

The Scottish regulation's need to prove that 'reasonable steps' have been made to prevent NNS entering Scotland's waters is vital. Good Practice Guidelines will need to be created and implemented by managers, and Bio-Security Action Plans are viewed as evidence that good practice is being followed. The new legislation also includes powers that compel managers to take action in relation to specified invasive species and also gives power to access land and water to carry out control work and the ability to recover costs when appropriate. While this is mainly focused on targeting the intentional or unintentional release of NNS into the wild, (e.g. plants, animals such as deer, or Killer Shrimp) it is thought that inshore anthropogenic structures such as marinas are vulnerable to prosecution if high risk AIS are present and thought to be spreading with no biosecurity measures in place.

The short step to regulation on offshore structures is easy to envisage and development of the EU and UK frameworks should be carefully monitored in order to stay compliant as 2020 approaches.

6.4   Useful Links:

JNCC
http://jncc.defra.gov.uk/default.aspx?page=1532

DEFRA/Non-native Species Secretariat:
http://www.nonnativespecies.org

COWRIE:
http://energy.nstl.gov.cn

Regional Seas Convention (United Nations Environment Program)
http://www.unep.org/regionalseas/

Regulation (EU) No 1143/2014 of the European Parliament and of Council

of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species
http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1143&from=EN

European Commission/Alien species website:
http://ec.europa.eu/environment/nature/invasivealien/index_en.htm

The Invasive Non-Native Species Framework Strategy for Great Britain
www.**nonnativespecies**.org/downloadDocument.cfm?id=99

IUCN Guidelines for the Prevention of Biodiversity Loss caused by Alien Species. A guide to Designing Legal and Institutional Frameworks on Alien Invasive Species".
http://www.iucn.org/

Monitoring for the Marine Strategy Framework Directive: Requirements and Options
http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/23169/1/lbna25187enn.pdf

International Maritime Organisation (IMO).
http://www.imo.org/

International Council for the Exploration of the Sea (ICES).
http://www.ices.dk/

Commission for the protection of the marine environment of the North-East Atlantic (OSPAR).http://www.ospar.org/

Scottish Government, Alien species and legislation
http://www.scotland.gov.uk/Topics/Environment/Wildlife-Habitats/InvasiveSpecies/legislation

7 Current and Predicted Regulatory Position and Implications for Renewable Energy Sector

7.1 UK & EU Regulation

Please note that while every effort has been made to ensure this section is up to date and current, this text is for guidance only. We suggest that frequent reviews of this area are conducted before marine protective coating specification is finalised to ensure that relevant legislation is complied with in this swiftly changing area.

In the UK the Health and Safety Executive (HSE) is the competent authority for biocides. The HSE regulation is based upon the following (http://www.hse.gov.uk/biocides/basics.htm):

1. A biocidal product is defined as one that controls harmful or unwanted organisms through chemical or biological means.
2. The regulations state that products that contain biocides must be able to be used without causing harm to people, the environment or animals.

The HSE runs two regulatory schemes to assess product safety and the active substances (biocides) that they contain for use in the UK and it places conditions on their use. The schemes are:

- The EU Biocides Regulation (Regulation 528/2012) (EU BPR) covers a very diverse group of products, including disinfectants, pest control products and preservatives. It repeals and updates the Biocidal Products Directive 98/8/EEC (the BPD) and the supporting UK Biocidal Products Regulations (BPR) from 1 September 2013.

- The Control of Pesticides Regulations (COPR) is an older, UK national scheme which covers various pest control products that contain active substances. Some of the products covered under the EU BPR also fall within the scope of the Control of Pesticides Regulations (COPR). COPR also covers various pest control products, which contain active substances that are not yet fully regulated under the EU BPR.

Antifouling paints that contain biocides are classified as Biocidal Products or Pesticides. These products are regulated and the active substances they contain must be approved for that product type. Once this is done a product must be authorised before it can be placed on the UK market. Approval and authorisation of antifouling paints requires the evaluation of information and data on both the antifouling paint and the biocide as the active ingredient.

7.1.1 Antifouling Systems for Use on Ships

The major market for antifouling coatings is shipping and it is these coatings that are being considered for use on marine renewables. The International Maritime Organisation (IMO) Convention (the AFS Convention of 2001) prohibits the use of coatings that contain organotin compounds. TBT (Tributyltin) was the predominant organotin compound used and it was found to be extremely harmful to the environment. For shipping and marine structures the 2001 IMO-AFS Convention is now in force and TBT antifoulings are banned

by all countries that have ratified it. The Convention has been transposed into Community legislation by Regulation (EC) No 782/2003 on the prohibition of organotin compounds on ships and the related Commission Regulation 536/2008/EC.

In Britain the use of antifouling systems for ships are regulated by the Maritime and Coastguard Agency (MCA) under the Merchant Shipping (Anti-Fouling Systems) Regulations 2009, developed to provide for offences and penalties in relation to EC Regulation 782/2003, which was introduced to ratify the IMO-AFS Convention on the Control of Harmful Anti-Fouling Systems on Ships. The 2010 guidelines (RESOLUTION MEPC.195(61), Adopted on 1 October 2010) provide procedures for surveying to ensure that a ship's anti-fouling system complies with the 2001 IMO-AFS Convention and for issuance and endorsement of an International Anti-fouling System Certificate.

Organotin compounds (sometimes called organostannic compounds) are also subject to restrictions under EU REACH regulations (Registration, Evaluation, Authorisation and restriction of Chemicals). Under REACH, organostannic compounds (and many others) are restricted and banned from sale or use in antifouling products. The UK Environment Agency is one of the enforcing authorities under the REACH Enforcement Regulations 2008.

7.2   Future Impact of Regulation on Biocide Development

The burden of registration costs to comply with new regulations may restrict biocide development and limit the number of new biocides and new products containing them. This may result in fewer products and higher product costs. Also the restraints imposed by regulation on a wider international scale could result in fewer options for paint producers to use in developing new biocidal antifouling technologies.

7.3   Summary

The use of biocidal anti-fouling paints (including those containing copper) is under constant review both in the scientific literature and by regulators. There is little doubt that their use will become more regulated, especially in sensitive environments. Currently, biocidal antifouling products that are approved for sale have already been through regulatory approvals for sale and usage.

Some facts on usage of antifouling products:

- Boats whose hulls have been treated with TBT are forbidden to drop anchor in European ports.

- TBT antifoulings cannot be applied to any boat registered in the European Union and cannot be used in a worksite within the European community.

- In Sweden boats that only sail in the Baltic and North Seas must have a leaching rate of copper inferior to 55µg of copper/cm2 /day.

- In the UK Irgarol 1051 and Diuron are forbidden for pleasure boats. Copper and its derivatives are currently allowed.

- In the Netherlands the use of copper is now allowed but Diuron as a co-biocide is forbidden.

- In Denmark Irgarol 1051 and Diuron are forbidden for use on on vessels shorter than 25 metres while copper and its derivatives have a new authorisation. It is not permitted to import, sell or use anti-fouling paint on pleasure boats of 200 kilos and more and which sail mainly in salt water and on which the release of copper to the aquatic environment exceeds 200 μg Cu/cm2 after the first 14 days and 350 μg Cu/cm2 after the first 30 days (calculated from the time of application).

Whilst there are currently a few restrictions on the use of copper in antifouling paints (e.g. Canada, some US states, Denmark and Sweden) there remains a debate on its future use. In 2009 the European Union's (EU) Scientific Committee on Health and Environmental Risks (SCHER) challenged the Netherlands government saying that it "does not provide sufficient sound scientific evidence to show that the use of copper-based antifouling paints in leisure boats presents significant environmental risk". While currently more than 90 per cent of ships still use copper based products, it is still widely expected that copper may eventually be banned for use in antifouling coatings. Manufacturers are already developing alternative biocide free coatings (e.g. FRC and epoxy).

FRC and epoxy coatings which do not rely on or contain biocides (or active substances) to work do not require registration under the pesticides or biocidal products regulations.

7.4   Useful Links

http://www.emsa.europa.eu/implementation-tasks/environment/anti-fouling-systems.html

http://www.imo.org/OurWork/Environment/Anti-foulingSystems/Pages/Default.aspx

http://www.imo.org/blast/blastDataHelper.asp?data_id=29924&filename=195(61).pdf

http://www.hse.gov.uk/biocides/bpd/index.htm

2013 European Environment Agency Report -
http://www.eea.europa.eu/publications/late-lessons-2/late-lessons-chapters/late-lessons-ii-chapter-12/view
http://www.copperantifouling.com/map/europe.html

http://eng.mst.dk/topics/biocides/legislation/fact-sheet---anti-fouling-paint/

http://www.oceoprotec.com/en/environment_legislation.html

http://www.onboardonline.com/industry-article-index/features/cleaning-up-antifoulings-dirty-image
http://www.thefreelibrary.com/EU+expert+committee+challenges+Dutch+copper-paint+restrictions.-a0226476007

8 Recent Advances in Antifouling Coating Technology

8.1 Introduction

Whilst an extensive review of the antifouling technology available, or under development, was provided as part of the ME8.1 report (*Technical Literature Review on Antifouling Systems and Consultation with Device Developers*), this field is under constant development.

It is therefore possible that in the intervening period since publication of this report that new technological developments may have emerged, offering alternative antifouling solutions for the marine renewables sector that were not covered as part of ME8.1.

This section therefore aims to update and build upon this original information, specifically Sections 4 and 5 which cover '*TBT Free Biocidal Antifouling Coatings*' and '*Alternatives to Biocidal Antifouling Coatings*' respectively. Any recent advances made within these fields will be highlighted, and the suitability of such technology for use within the marine renewable sector appraised.

8.2 TBT Free Biocidal Antifouling Coatings

Biocidal antifoulants continue to represent a significant majority of antifouling coatings in use globally, with over 90% usage on commercial shipping and greater than 99% usage in the yachting sector (Lejars et al. 2012). This remains the case despite a continued increase in the regulation of these coatings; a result of the pervasive nature, potential for bioaccumulation and toxicity of the active compounds used in these coatings on the marine environment (Cui et al. 2014).

The continued reliance on biocidal coatings, coupled with stringent regulation of permitted active compounds, is driving research into the discovery of novel, potentially less environmentally damaging alternatives.

8.3 Synthetic Biocides

On 1st September 2013 the Biocidal Products Regulation (BPR) and the Biocidal Products Directive 98/8/EEC were revoked and replaced by the EU Biocides Regulation (528/2012). This European regulation governs authorisation of the use of active biocidal substances within European member states (HSE 2014). As of 13th November 2014, just two synthetic biocidal antifouling compounds covered within ME8.1 remained authorised for use in antifouling paints within waters off European member states, namely Zineb and SeaNine211. However, in addition to these two substances, in 2014 an additional three compounds were approved for inclusion as biocides by the Biocidal Products Committee. Copper Pyrithione and Tolyfluanid (also known as Preventol A5S or Euparen M), were both originally registered in 2006 and, as existing active substances, have subsequently been appraised for inclusion on the authorised active substance list in October and June 2014 respectively. A third compound, Tralopyril, is a new active substance that has been developed by Janssen Pharmaceutica NV, under the trade name ECONEA®. This non-metallic compound is an

arylpyrrole, promoted by Janssen as an alternative compound for use in coatings globally, claimed to be around ten times more active than copper against marine hard fouling organisms.

Furthermore, this new compound has recently become commercially available as an antifoulant, having been incorporated within a coating by International Paint Ltd (INTERNATIONAL INTERSPEED® 5640), as well as being incorporated as a constituent of Interlux's Pacifica Plus. Despite being less environmentally damaging, recent research has still shown Tralopyril to pose a significant threat to marine ecosystems (Oliveira et al 2014). The true environmental impact and thus, the longevity of such coatings as an alternative to traditional metallic-based paints thus remain to be determined.

A further area of development in recent years with respect to synthetic biocides has come in the screening of pharmaceuticals and veterinary medicines for antifouling properties (Rittschoff et al 2006), with one pharmaceutical in particular, medetomidine, receiving particular attention (Ohlauson et al 2012). Medetomidine is an α_2-adrenoreceptor agonist used as a sedative and analgesic in human and veterinary medicine, yet it is also shown to inhibit barnacle settlement and metamorphosis (Ohlauson 2013). Interestingly however this settlement inhibition occurred at concentrations of the chemical 100,000 times lower than the lethal level for barnacle cyprids (Dahlström et al 2000). The mode of action is demonstrated as an induction of hyperactivity, disturbing settling behaviour and inducing larvae to swim away from the coated surface (Lind et al. 2010).

This recent research has led the UK HSE to recommend the approval of medetomidine (commercially referred to as Selektope) for inclusion within the EU Biocides Regulation, with this substance likely included on the new active substance list by late 2014 (i-tech, 2014). As with traditional biocides however, pharmaceuticals are by their very nature chemically and structurally stable to aid a long shelf life and to ensure drug delivery to target sites within a patient. Such stability may lead to persistence of these chemicals in the marine environment and possibly facilitate bioaccumulation and/or ecotoxicity within non-target marine organisms, albeit over much longer timescales than traditional biocides. This is due to the low concentrations needed in paints for an antifouling effect, reducing the potential non-target toxicity.

8.4   Enzyme Based Coatings

A possible alternative to synthetic biocides or pharmaceuticals are enyzmes which are ubiquitous within the marine environment. They occur naturally and being non-toxic, enzymes have been subject to antifouling research since the mid 1980's (Noel 1985). Interest in using these compounds as alternatives to synthetic biocides has significantly intensified in recent years (Lejars et al. 2012).

Enzyme based coatings act in one of two ways; either directly, breaking down the newly settled organism or the organisms adhesive compound, or indirectly, by catalysing the production of biocides from substrates available in seawater or bound within the coating (Lejars et al. 2012). Despite the potential to offer an alternative to traditional biocides, to date only a single enzyme based coating, Coatzyme©, is commercially available, having been developed by BioLocus A/S in Denmark.

One limitation for the use of enzymes as antifoulants is that, if shown to act directly by breaking down adhesives of the settling organisms the enzyme is now subject to the EU Biocides Regulation (528/2012). This means further development of similar enzyme based antifouling technology will require significant research under the regulations prior to becoming commercially available on a global market. This will ultimately result in a significant delay before such coatings are available for commercial shipping, or renewables infrastructure.

8.5   Naturally Occurring Compounds

As outlined in the ME8.1 report, isolating, characterising and utilising novel antifouling compounds from marine organisms remains an extensive area of research with investigations having taken place on bacteria, fungi, algae, sponges, corals and nudibranchs (Gao et al 2014). This has remained the case over the past 4 years.

Further research has been undertaken on compounds that had already been highlighted as natural antifoulants in ME8.1, such as capsaicin (Wang et al 2014), alongside research highlighting the discovery of novel antifouling compounds such as the myristic, palmitic and octadecanoic acids isolated from marine biofilms (Gao et al. 2014), as well as 49 secondary metabolites isolated from a variety of Chinese marine organisms (Yong-Xin et al 2013).

Yet as highlighted previously, whilst discovery of these novel compounds offers potential for the development of new coatings, in reality this process is incredibly complex. The isolated compound needs to be small, and structurally simple, making large scale production easier and cheaper (Cui et al 2014).

Compounds must also undergo rigorous testing and meet regulations before being considered for commercial application. The difficulty of incorporating the substances into coatings without altering their activity also impacts the process, meaning very few screened compounds have the potential for incorporation into commercially available paints. Consequently many of the recent developments using natural biocides have been research based only, with little recent progress made in fully commercialising a natural biocide based antifoulant.

8.6   Alternatives to Biocidal Antifouling Coatings

8.6.1   Hybrid FRCs

Currently on a global commercial scale the main alternative to traditional metallic biocidal paints is FRCs which represents around 10% of commercial shipping coatings by volume (Lejars et al 2012). However despite offering a nontoxic alternative to biocide based coatings, FRCs have a number of limitations which include their propensity for fouling during idol periods and under periods of low mechanical stress.

Furthermore, these coatings are particularly susceptible to the build-up of slime layers, with diatom slimes in particular posing a significant problem. This is due to the hydrophobic surfaces typically exhibited by FRCs favouring the adhesion of diatoms, with adhered diatoms subsequently able to withstand speeds exceeding 30 knots (Holland et al 2004).

This resultant fouling results in significantly increased drag of FRC coated vessels (Schultz and Swain 2000; Schultz 2007). There is therefore a need to increase the efficiency and performance of FRCs to overcome these issues.

In addition to the development of hydrogel based FRCs (as commercialised by Hempel through their coating Hempasil X3 87500), fluoro-silicone based coatings (as offered by International Paint with Intersleek 900) and nanofiller technology (as offered by Jotun with their SeaLion Repulse coating and Nanocyl, who incorporated nanotubes in Biocyl) developers have started to investigate the use of booster biocides bound in FRCs.

Three compound groups have been investigated for use in FRCs as booster biocides (Lejars et al 2012):
- Triclosan, a broad spectrum antimicrobial/antibiotic,
- Quaternary ammonium salt (QAS) moieties,
- Zwitterionic polymers.

Triclosan, bound in a silicon matrix has been shown to perform as well as both a copper based biocidal coating and Intersleek 425 over a period of 29 days. However, longer immersion in the study lead to an increase in fouling on this hybrid FRC compared the FRC controls (Choi et al 2007). QAS moieties have also been shown to improve the antifouling properties of FRCs. Majumdar et al 2011 demonstrated that a coating containing hexadecyl ammonium salt outperformed Intersleek 700 and 900, as well as Silastic T2. Webster et al 2010 also demonstrated that coatings containing zwitterionic polymers had better antifouling and fouling release properties, with better inhibition of bacteria, diatoms and pseudobarnacles, than commercial silicone FRCs. Hybrid biocidal FRCs are not yet widely available commercially.

8.7   UV Capability

The use of UV as a seawater treatment within the aquarium and aquaculture sector is long established. However, recent developments have led to the utilisation of UV systems for the prevention of fouling in a marine environment. Designed initially for niche applications, such as the requirement of keeping optical surfaces free from fouling, UV-C based systems to prevent fouling were patented by the Woods Hole Oceanographic Institute in 2014 (publication number - WO2014014779 A1). This system has subsequently been commercialised by AML Oceanographic, BC, Canada. By emitting light in the 200-280 nm range, these UV-C probes are able to target specific surfaces of an instrument and inhibit fouling by disturbing cellular division of the newly setting organisms. Whilst targeted at extending the deployment period of often sensitive scientific instrumentation such as conductivity sensors, pH probes, cameras or photo sensors, the early trials of this technology have highlighted the potential for more widespread utilisation as an antifoulant through incidental clearing of structures by UV-C radiation. This technology is unlikely to offer a fouling solution for an entire tidal energy device but it does offer realistic potential for the protection of cameras and other sensitive elements on tidal energy devices.

8.8 Biomimetic structures

Biomimetics or biomimicry is the imitation of elements that occur in nature for the purpose of solving complex human problems. Shark skin has long been proposed as a potential source of technological advancement (Carmen et al 2006), yet by virtue of their lifestyle sharks are active swimmers, moving through the ocean often at high speeds (shark skin could be said to be one of nature's FRCs).

Often the challenge of biofouling on vessels is in fact proportional to the time spent stationary (Brady 2000). Thus new avenues of research have begun to investigate the properties of stationary organisms that inhibit biofouling. Bai et al (2013) investigated the use of bivalve shells as a basis for biomimetic antifouling coatings. By accurately recreating the fine microstructure of *Dosinia japonica* shells using E44 epoxy resin, they were able to inhibit fouling of *Nitzschia closteriums* using this newly discovered antifouling microstructure.

Biomimetic structures from a wider field than shark structures may therefore offer a sustainable, environmentally friendly antifouling alternative in the future.

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9   Conclusions

In conclusion, the rate and the severity of biofouling encountered at the EMEC test site should be taken seriously by operators in this environment. We suggest that, if not managed adequately with appropriate antifouling technologies and maintenance programs, the biofouling we encountered is on a scale that is very likely to cause operational problems and influence the life expectancy of any infrastructure deployed at the site.

As described in the previous report, ME8.4, the turbine nacelle sustained considerable settlement from barnacles in just 8 weeks. This fouling was removed effectively using power washing of the epoxy coating. However, based on evidence from the benthic landers, if left in place for 24 months we suggest that the fouling has the potential to cause severe corrosion issues and hydrodynamic drag, as well as obscuring cameras and instruments. Consideration of the above suggests that antifouling and protective coating performance is critical to ensure the efficient operation of tidal energy devices.

There is a strong link between biofouling from large barnacles and the corrosion of un-coated marine grade stainless steel without anodic protection (see previous ME8.4 Report). The rate of corrosion encountered during this study is sufficient to require further attention to fully understand the mechanisms taking place, and to understand if a link exists between the rates of corrosion encountered and high energy environments in general.

The different coatings examined here performed with clearly different levels of success. In general, hard epoxy coatings resisted damage, but were heavily fouled. The FRCs were variable in performance. Where they sustained no damage, they were highly effective in preventing biofouling. However, many FRC samples did not withstand damage which resulted in considerable biofouling on the damaged areas. Overall, the best resistance to biofouling and damage was provided by biocidal coatings, although the life span of this loose grouping of technology is not yet fully characterised and requires further tests and verification. Further testing of the many derivative types of biocidal coatings is also suggested.

As with other marine industries, it is unlikely that coatings alone will be sufficient to prevent the tidal energy industry from encountering all biofouling and corrosion problems. We suggest that to fully address biofouling issues on a turbine scale, especially in niche areas, a combination of active non-coating based antifouling approaches (such as electro-chlorination), should be considered, and where appropriate, matched with compatible coating systems and cleaning methods.

The requirement for a biofouling monitoring and control policy is likely to be increasingly important as described in Section 6. This is not only to avoid accelerated corrosion and hydrodynamic penalties, but also to avoid the requirement for mitigation measures in the event the detection of non-native marine species in biofouling assemblages.

This study has provided a first glimpse at how variable antifouling and protective coating performance can be at high energy tidal sites. It also suggests that informed coating selection based on field testing can prove cost effective, compared with dealing with operational issues once a device is commissioned and deployed.