The Potential Impacts of Biofouling on a Wave Energy Converter Using an Open Loop Seawater Power Take Off System

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Prepared for Aquamarine Power

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CONTENTS

FOREWORD

There are a great number of challenges to be overcome in the development of wave energy converting devices, many of which are down to exposure to the marine environment. Wave energy converters are placed in sites known to experience rough seas: In the British Isles, areas such as the Shetland Islands, Outer Hebrides or west coast of Ireland. Therefore, devices must survive the destructive forces of Atlantic storms, as well as rust and corrosion of metals and degradation of rubber and plastics in the saline environment. Another factor that must be considered is the part that the biotic environment will play in the function of such devices. No surface can be exposed to the sea and not interact with the organisms living there. In many cases, problems are caused when organisms in the sea settle and grow upon manmade structures in a process known as ‘biofouling’ (Stanczak, 2004).

Using information on the biology of biofouling organisms and drawing upon data showing how various industries worldwide are affected by and limit the impact of biofouling, this review shall:

- Explain biofouling and how it occurs.
- Provide an overview of the range of biofouling organisms and how they attach to various substrates.
- Explore factors that influence the development of biofouling including water velocity, pressure, temperature, depth, light and construction materials.
- Review the impacts of biofouling on industry.
- Detail commercially available antifouling technologies.
- Determine the extent to which a wave energy converter using an open loop seawater hydraulic system may suffer from biofouling.
- Outline measures that may be used to control or alleviate biofouling.

1. BIOFOULING

Regardless of the environment, biofouling is described as "the accumulation of unwanted material on a solid surface, which then becomes detrimental to the function of that surface" (Awad, 2011). The processes involved with biofouling are often highly complex; as exemplified by organisms biofouling surfaces in a marine environment. Marine biofouling has been generally described as the "undesirable accumulation of biological organisms such as bacteria, algae, plant and animal colonies on artificial surfaces immersed in seawater" (Hellio, 2009). A descriptive definition of biofouling is "a process of absorption, colonisation and development of living and non-living material on an immersed substratum" (Clare, 1996). In general, the complex process of biofouling follows an identifiable progression from a purely physical to mostly biological process in four main phases (Wahl, 1989);

- Biochemical Conditioning
- Bacterial Colonisation
- Unicellular Eukaryote Colonisation
- Multicellular Eukaryote Colonisation

The basic pattern followed in these processes generally remains the same for all marine biofouling, however the time taken and species present does vary slightly with changes in substrate, temperature, pH, water nutrient composition, depth, light availability and geographical location. These processes are outlined below.

1.1 Biochemical Conditioning

Biochemical conditioning is the term given to the adsorption of dissolved chemical compounds (macromolecules such as glycoproteins and polysaccharides) to any surface in contact with seawater (Wahl, 1989). Adsorption is "the adhesion of ions, atoms or molecules to a solid surface" (Dabrowski, 2001). The adhesion of organic molecules at the solid/liquid interface is a purely physical and spontaneous process (Baier, 1984) involving no biological processes. The process begins within seconds of a surface being immersed in seawater and depending on local conditions, reaches a dynamic equilibrium within a few hours, preparing the surface for bacterial colonisation (Wahl, 1989). This leaves the immersed substrate with a negatively charged macromolecular conditioning layer (MM; Fig. 1a).

1.2 Bacterial Colonisation

Bacterial colonisation involves both adsorption and adhesion phases. The adsorption phase begins when:

- A bacterial cell, under physical influences such as Brownian Motion, electrostatic interactions and van der Waals forces, approaches the substrate and first encounters a surface film of water molecules 40-100µm thick (V; Fig. 1a) over the substrate and macromolecular layer (Wahl, 1989).
- Slight water movements or micro turbulence at the edge of the surface film known as 'down sweeps' (DS; Fig. 1a) push the cell into this film and closer to the macromolecular layer (Wahl, 1989).

- Antagonistic physical forces of electrical repulsion and van der Waals forces hold the negatively charged cell 3-20nm from the surface of the macromolecular layer (Fletcher and McEldowney, 1984).
- Polysaccharide fibrils (F; Fig. 1a) produced by the cell penetrate the electrostatic barrier and anchor to the macromolecular layer. The cell shortens the fibrils through enzymatic processes, pulling itself close to the surface, assisted by van der Waal forces (Wahl, 1989).

The adsorption phase gives way to adhesion when the cell has pulled itself sufficiently close to the macromolecular layer that covalent bonds can form between the cell capsule and the macromolecules (Fletcher and McEldowney, 1984). This process begins within several hours of immersion, with the first bacteria attaching within a few hours (Chambers *et al.* 2006). The build up of both live (through colonisation and reproduction) and dead bacteria along with extracellular polymeric substances (EPS) they secrete in combination with the macromolecular conditioning layer form what is known as a slime layer or biofilm (Fig. 1a).

1.3 Unicellular Eukaryote Colonisation

The development of the biofilm is subsequently followed by colonisation by yeasts, protozoa (either sessile filter feeders or those which prey upon bacteria) and diatoms (single celled algae) (Callow and Callow 2002). Benthic diatoms attach themselves to the surface by mucus secretion and often densely cover wide areas of the substrate, contributing greatly to any chemical and biological changes in the substrate (Wahl, 1989). This phase of colonisation occurs several days after immersion and continues with species and population numbers constantly changing (Fletcher and McEldowney, 1984).

One to three weeks after immersion, the initial phases of macromolecular conditioning, bacterial and unicellular eukaryote colonisation have produced a complex highly developed three-dimensional community on the substrate. Together these organisms are known as a microfouling community. After one week, a microfouling community may cover 100% of a substrate up to several hundred micrometres thick but varies with site-specific conditions (Lefebvre, 1998).

1.4 Multicellular Eukaryote Colonisation

The fourth, final and longest phase of biofouling development occurs one to three weeks after immersion when algal spores and meroplanktonic larvae begin to settle on the surface (Wahl. 1989, Chambers *et al.* 2006). Algal spores develop into algal growth over the substrate where light is available. Meroplanktonic larvae are the offspring of larger biofouling organisms such as sponges (phylum Porifera), sea squirts/tunicates (subphylum Tunicata), anemones (order Actiniaria), tubeworms (class Polychaeta), barnacles (Crustacea, Cirripedia) and mussels (class Bivalvia) (Appendix 1). With the settlement and growth of these larger organisms, a macrofouling community is established on the substrate (Fig. 1b).

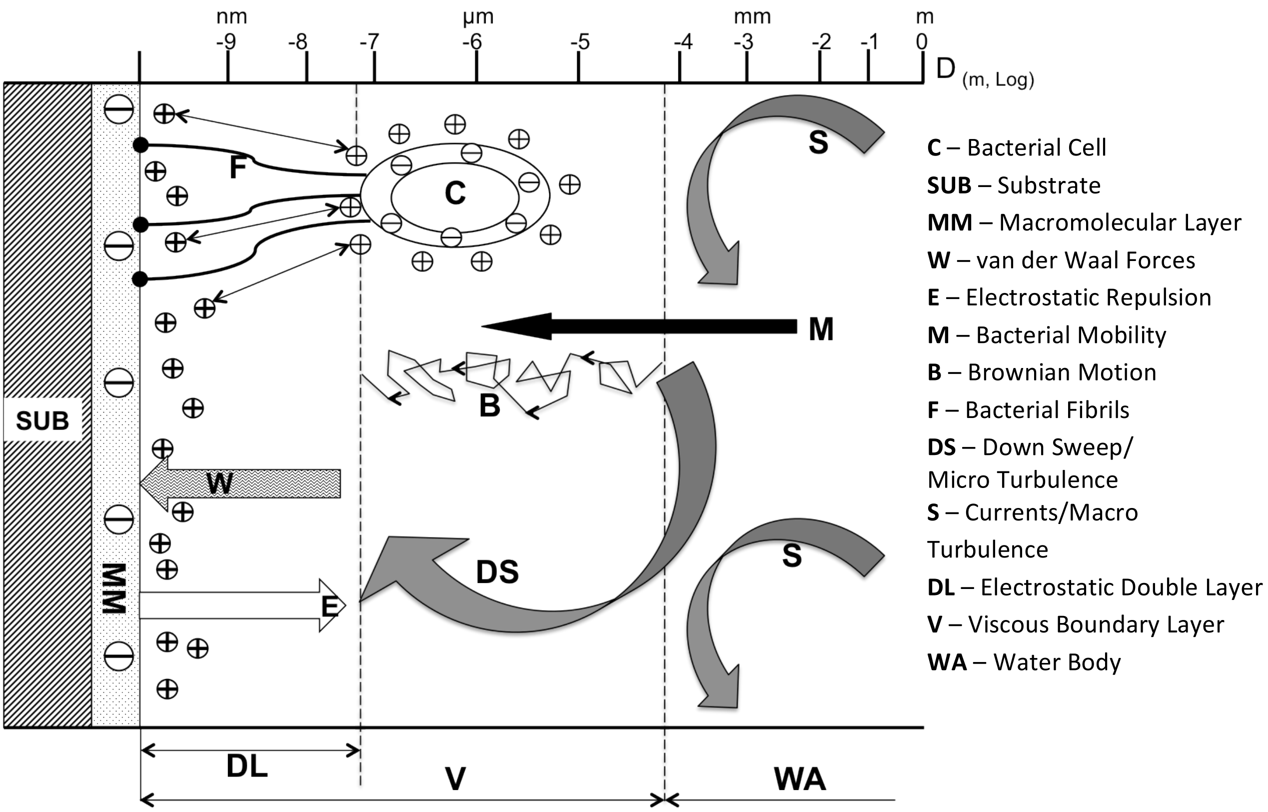
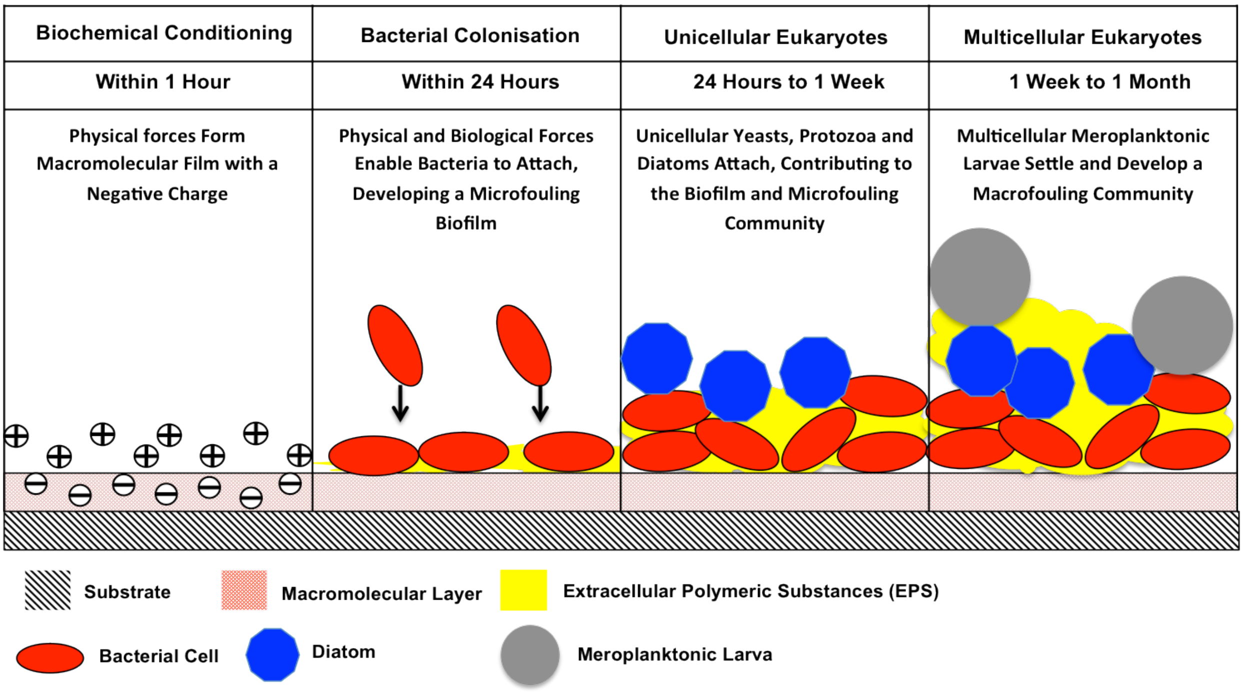


Figure. 1a. Schematic showing the highly complex physical and biological processes involved in bacterial colonisation of an immersed substrate following macromolecular absorption.

Adapted from Fletcher and McEldowney 1984.



Biochemical Conditioning	Bacterial Colonisation	Unicellular Eukaryotes	Multicellular Eukaryotes
Within 1 Hour	Within 24 Hours	24 Hours to 1 Week	1 Week to 1 Month
Physical forces Form Macromolecular Film with a Negative Charge	Physical and Biological Forces Enable Bacteria to Attach, Developing a Microfouling Biofilm	Unicellular Yeasts, Protozoa and Diatoms Attach, Contributing to the Biofilm and Microfouling Community	Multicellular Meroplanktonic Larvae Settle and Develop a Macrofouling Community

Figure. 1b. A highly simplified diagram and timescale of the four processes involved in the attachment of biofouling organisms to a substrate.

Adapted from Chambers *et al* 2006

2. BIOFOULING ORGANISMS

When studying biofouling, the lifecycles and characteristics of the organisms involved must be considered as variations in the size, body composition, spawning and settlement times all affect when and how they contribute to biofouling. These organisms do not just attach in isolation; a fouled substrate must always be thought of as a community which is a complex group of different species constantly interacting with each other, the substrate and surrounding environment (Nature Education, 2013).

With over 4000 biofouling species identified worldwide (Durr and Thomason, 2010), biofouling communities are often extremely diverse, making it impossible to describe a 'typical' biofouling community. The species composition of a biofouling community is also highly site specific and dependent on many aspects such as water depth, temperature, currents, light intensity and nutrient availability. However, it is common to divide these organisms into two main categories based on their general size and morphology. The smallest and simplest biofouling organisms such as single celled bacteria and multicellular algae are known as microfouling organisms whilst more complex animals such as barnacles and mussels are known as macrofouling organisms (Durr and Thomason, 2010).

2.1 Microfouling Organisms

The umbrella term of 'microfoulers' is generally sufficient to describe bacterial and unicellular eukaryotic biofouling organisms, with the process of their attachment to the substrate outlined above (Flemming *et al.* 2009). Their microscopic size does not mean that they do not have a significant impact on surfaces that they colonise; some microfoulers simply make the surface suitable for colonisation by macrofoulers whereas others can cause damage to the substrate:

Diatoms (microscopic single celled algae) often make up a large proportion of a microfouling community, and cause no damage to the substrate. These non-motile algae are amongst the most common types of phytoplankton, using sunlight to capture energy via photosynthesis. Most diatom species are pelagic in nature, remaining suspended in the water column, however some are benthic in nature, using mucus to attach to the substrate, increasing suitability for macrofouling attachment (Wahl, 1989).

Many species of bacteria are also present in biofilms, with most absorbing nutrients from the water column and utilising aerobic respiration. However certain species are anaerobic, notably sulphate-reducing bacteria (SRB), which thrive in environments low in oxygen. The development of anoxia on a fouled substrate e.g. The inside of a pipe can lead to death and putrefaction of many of the aerobic biofouling organisms. This prompts a rapid increase in the population of SRB that convert sulphate present in the water into hydrogen sulphide. The production of hydrogen sulphide can lead to serious issues with corrosion on metal and concrete surfaces; so-called 'souring'. Hydrogen sulphide is also harmful to humans above 10ppm and toxic above 300ppm, meaning that any pipework or enclosed space must be thoroughly vented to ensure dispersal of the gas before workers gain access (Health and Safety Executive, 2009).

2.2 Macrofouling Organisms

The larger, more complex multicellular organisms found in a biofouling community are known as macrofoulers. These marine invertebrates generally share common life history traits whereby adults spawn and release larvae or gametes into the water column for external fertilization. These larvae spend a certain length of time growing and feeding in the water column as part of the plankton community before settling and metamorphosing to adults (Hadfield and Strathmann, 1996). The adults feed either by using a specialised feeding apparatus to filter particulates from the water column or by grazing upon other organisms attached to the substrate. The organisms within a macrofouling community can be divided into two broad categories of ‘hard’ or ‘soft’ biofouling. Hard biofouling organisms either lay down a calcareous case or develop a hard shell e.g. tubeworms, barnacles, mussels and tube building amphipods (order amphipoda) (Fig. 2a). Soft biofouling organisms do not grow shells or build protective cases and often have a jelly like appearance e.g. sponges, anemones, hydroids (class hydrozoa), and sea squirts (Fig. 2b).

The lifecycles, geographical distribution and general biology of the main macrofouling organisms found in the waters around Western Europe and the British Isles are described in Appendix 1. It should be noted that each taxon may include different species, which show differing biological characteristics such as spawning and settlement temperatures.

Figure. 2a. Hard Biofouling Community Developed on steel plates over 1 year.
Bridger Scientific, 2005

Figure. 2b. Soft Biofouling Community Developed on a Polystyrene Sheet Submerged in a Scottish Marina for 8 Weeks.
Marine Scotland, 2014

2.3 Attachment of Macrofouling Organisms

In order for macrofouling organisms to remain in their specific habitat with access to nutrients and oxygen from the water column, it is vital that they remain securely attached to the substrate. For biofouling organisms, remaining attached is a potentially difficult task, with strong currents, wave action or even predators trying to remove them from the substrate. It is important to recognise that these organisms don't simply just 'hold on' to the surface, but that many have evolved a highly complex system of biological adhesives to ensure they remain attached (Callow and Callow, 2002). With such variation across biofouling species, it is impossible to provide detail on every attachment mechanism. However, to provide a general view on how these attachment mechanisms can vary between species, the mechanisms used by three common macrofoulers, barnacles, mussels and tubeworms are outlined below.

2.3.1 Barnacle Attachment

As detailed in the appendix, upon developing to cyprids (the development stage that leaves the plankton community to settle), barnacle larvae suspended in the water column seek out a suitable substrate for attachment. When in contact with a substrate, cyprid larvae use an adhesive organ, the antennular disc to remain temporarily attached whist moving and searching for a permanent attachment site (Khandeparker and Anil, 2007). Once a suitable site is found, secretory glands in the larva produce a complex mix of proteins, which form an insoluble underwater adhesive known as 'barnacle cement' (At this attachment phase, metamorphosis to an adult barnacle also occurs (Khandeparker and Anil, 2007). This mix of proteins varies with barnacle species and is so complex that its full composition is not known, however some of the proteins in barnacle cement are given in Fig. 3a (Smith and Callow, 2006). The protein complex is produced as a clear liquid filling any gaps between shell and substrate before turning to an opaque rubbery insoluble mass recognised as "the most durable and toughest connection in the aquatic world" (Cheung *et al.* 1977, Abbott, 1990). As the barnacle grows, more cement is secreted to ensure a secure attachment to the substrate; this attachment is so secure that attempting to remove a barnacle will often result in the shell breaking apart and the cement remaining attached (Khandeparker and Anil, 2007).

2.3.2 Mussel Attachment

Unlike barnacles which cement themselves to a substrate, marine mussels attach to the substrate using a structure known as a byssus, made of an adhesive pad or plaque and proteinaceous threads (Fig. 3b). Having settled on a suitable substrate, the mussel foot extends from the shell onto the substrate and secretes a protein rich material forming a plaque. After secreting the plaque, the foot disengages from the surface and pulls back into the shell leaving a protein thread (byssus thread) connecting the pad and shell (Waite 1987, Waite, 1992). Each mussel will create 10-40 byssal plaques with threads approximately 2-4cm long and 0.1mm in diameter.

There are three main protein types making up a byssal assembly; byssal thread polyphenolic proteins, collagen proteins and polyphenol oxidase enzyme (Bandara *et al.* 2012). These make an extremely strong thread, with a breaking energy of approximately 12.5 x 106 Jm-3 (versus vertebrate tendon 5 x 106 Jm-3) (Denny, 1988). The protein DOPA (peptidyl-3,4-dihydroxyphenylalanine) is common in mussel foot secretions (Rzepecki and Waite, 1995) but has never been found in barnacle cement (Naldrett, 1993).

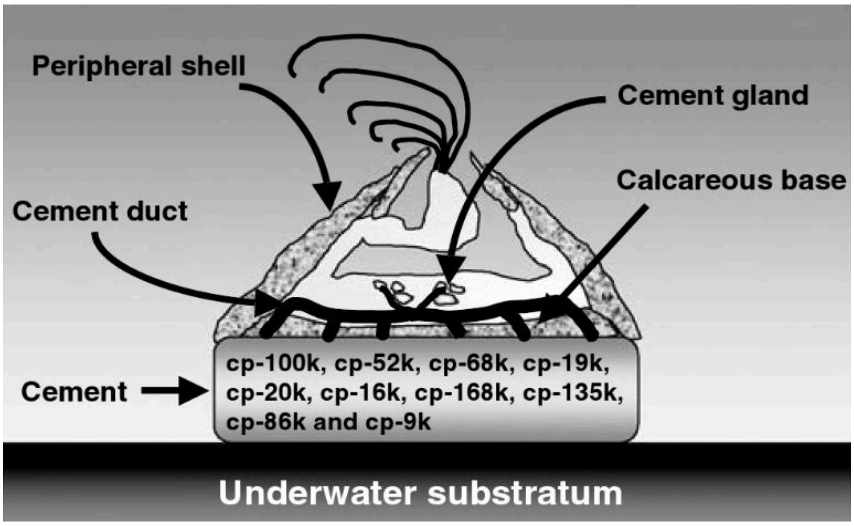


Figure 3a. Diagram showing anatomy of barnacle and protein composition of barnacle cement.
Smith and Callow, 2006

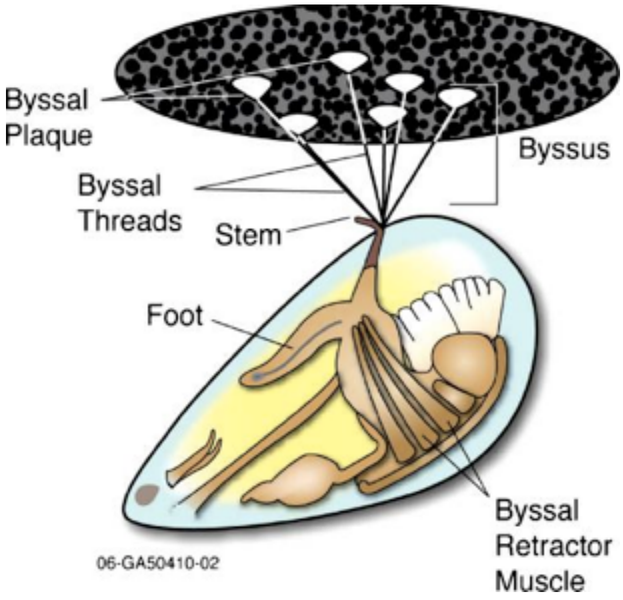


Figure 3b. Anatomy of *Mytilus edulis* mussel and byssus structures. Silverman, 2007

3. FACTORS INFLUENCING BIOFOULING

The sections one and two have shown how complex marine biofouling actually is in terms of:

- The physical and chemical processes occurring at the liquid/substrate interface.
- The vast range of lifecycles and lifestyles of biofouling organisms.
- The differing attachment mechanisms of macrofouling organisms.

However, other influences on the development of biofouling exist from molecular changes at a substrate through spawning times of biofouling organisms to the movement of larvae by wave action and global ocean currents (Durr and Thomason, 2010). This section will highlight the most influential factors and give particular attention to those that influence the development of biofouling in marine industrial environments. The factors discussed include:

- The influence of substrate characteristics on the rate of biofouling.
- Factors influencing larval settlement.
- The impact of pressure and pressure change.
- The influence of substrate material.

3.1 Influence of Substrate on the Rate of biofouling

Not all substrates experience biofouling at the same rate or to the same degree in the marine environment. The intrinsic physical and chemical properties of a material affect the water chemistry at the seawater-substrate interface. This ‘boundary chemistry’, has a considerable influence on the formation of the macromolecular conditioning layer, the nutrient composition of the layer and therefore the bacteria present (Dexter *et al.* 1975). A study by (Marszalek *et al.* 1979) found a correlation between the physical and biological ‘inertness’ of a substrate and biofouling; the more inert the substrate, the quicker it fouled. They observed materials such as glass and titanium which are relatively physically and chemically inert in seawater and non toxic to microorganisms have a high degree of surface stability. This degree of stability allows rapid macromolecular conditioning followed closely by bacterial and unicellular colonisation in the form of a biofilm. Conversely, mild steel in seawater is relatively reactive, with corrosion to iron oxide(s) forming products that are potentially toxic to marine life and leading to loss of surface stability. This results in slower macromolecular conditioning and slower development of a biofilm. In the case of toxic substrates such as copper, the lack of surface stability (caused by corrosion in seawater and ion release) slows macromolecular conditioning and in addition a thicker bacterial layer must form to offer eukaryote foulers some protection from toxic copper ions, slowing biofouling significantly (Marszalek *et al.* 1979).

In summary, biofouling species diversity is highest on physically and biologically inert substrates and lowest on physically and biologically active (corrosive or toxic) substrates.

3.2 Factors Influencing Larval Settlement

In addition to the surface conditions of a particular substrate, many other factors influence the rate of development of biofouling. A major influence on the development of macrofouling is the rate of settlement of larvae on a substrate, adding to the complexity of the biofouling process. These factors include but are not limited to:

3.2.1 The Number of Larvae in the Water Column - This is dependant upon geographical location, season, water flow, depth and currents and is highly site specific. A substrate close to a mussel bed will be exposed to high numbers of mussel larvae; therefore a high degree of biofouling may be expected. Study of an individual location across the seasons would be necessary to determine the numbers of larvae present at any given time.

3.2.2 Gravity – Many larvae of biofouling organisms have been found to react in a specific way to gravity; they tend to settle on the underside of surfaces. It is thought that the undersides of surfaces are likely to remain mud and silt free, allowing the organism better access to the substrate (Woods Hole, 1952). The larvae of the pacific coast oyster swim with their attachment surface upwards, making them more likely to adhere to the underside of a surface (Hopkins, 1931).

3.3.3 Light – The larvae of many biofouling organisms have been found to be negatively phototrophic, making them more likely to settle on dark surfaces e.g. the underside of ship hulls rather than the side of the hull (Woods Hole, 1952). It is known that larvae of barnacles are initially positively phototrophic when in the water column, ensuring that they remain in the plankton with an ample food supply. However, when they develop to cyprid larvae, they become negatively phototrophic, causing them to leave the brighter water column and move towards a substrate suitable for settlement (McDougall 1943, Woods Hole, 1952). The reduction in light with increasing depth ensures that settlement of photosynthetic algae does not occur below a certain level of light penetration, as they cannot survive without light.

3.3.4 Water Depth - In the section ‘Constructions in the Marine Environment’ below, a study by Bruijs, (2010) shows changes in a biofouling community with depth from 0-20m. There was a distinct shift in community structure with hard biofouling (mussels) dominating an ‘upper’ section, followed by a ‘middle’ section dominated by soft biofouling organisms and some mussels. Finally the ‘lower’ section biofouling community consisted of exclusively soft biofouling organisms.

3.3.5 Water Flow – Water currents and wave action can impact biofouling organisms in a number of ways. Water flow can direct larvae of biofouling organisms towards and even onto a suitable substrate. Once attached to a substrate, a suitable water flow is often essential for supplying nutrition and oxygen to the organisms.

Strong pressures and shear forces exerted by water flow may prevent settlement by moving organisms away from the substrate or may detach organisms already attached.

There are large variations in how water flow and currents impact upon the settlement of biofouling organisms, dependant upon the actual velocities and forces generated close to the substrate. It is generally accepted that if organisms can settle despite the pressures and shear forces caused by water flow, they will then benefit from the nutrition and oxygen provided (Woods Hole, 1952).

3.4 The Influence of Pressure Change on Biofouling

In most ‘natural’ circumstances, water pressure remains constant with few abrupt changes. For example, in regions with large tidal ranges, (10m in some locations) intertidal organisms are subject to a pressure change brought about by being submerged by the rising tide (1Bar per 10m depth); however this happens gradually and organisms are unharmed. In contrast, it is generally recognised that many marine organisms are vulnerable to rapid changes in pressure (Colt 2002, Inci 2004, Broens 2012). In industry, where seawater is pumped through a network of pipes and valves, larger pressure changes/pulses (which may have a negative impact on biofouling organisms) will be experienced due to the normal operation of systems such as valves opening/closing or pumps starting/stopping. Schaefer *et al.* (2010) tested the impact of pressure pulses generated by an electrical ‘sparker’ on freshwater zebra mussel fouling. They reported that pressures of 0.04MPa and pressure energy of 0.16Jm^{-2} were sufficient to prevent the settlement of mussel larvae 23m from the sparker whilst pressures of 0.23MPa and pressure energy of 5.8Jm^{-2} were sufficient to kill established adult zebra mussels 1.5m from the sparker. Further details of pressure change as an antifouling method are given in Section 5.6.

3.5 The Influence of Substrate Material

It is important to understand the susceptibility of a range of materials to biofouling. As before, this is dependant on several factors such as the substrate reactivity and toxicity. The target of any marine construction material is to strike a balance between cost, strength, resistance to corrosion and biofouling. Much data are available on the susceptibility of different materials to biofouling as large global industries such as power plants, shipping and military organisations all require research into antifouling in their designs. Studies by Marszalek *et al.*, (1979) (detailed in section 3.1) have shown that no material is biofouling proof; some materials are just relatively more resistant than others. This means the accumulation of biofouling is slower in some materials and the negative impacts are delayed. Several factors determine how resistant a surface is to the accumulation of biofouling. It is widely understood that the rate at which a material fouls is highly dependant upon the physical and chemical ‘interness’ i.e. surface stability and whether the material releases toxic products (Marszalek *et al.* 1979).

In addition, the material surface roughness affects the accumulation of biofouling (Lakshmi *et al.* 2012). It is accepted that roughness has a profound influence on the formation of a macromolecular conditioning layer in the initial hours after immersion, with rougher surfaces becoming macromolecularly conditioned sooner. However after this initial period it is the macromolecular conditioning layer itself that influences the development of further biofouling, meaning that the focus returns to surface stability and release of toxic products (Lakshmi *et al.* 2012).

The subsequent section will detail several studies that have examined the accumulation of biofouling on a range of materials exposed to natural seawater in differing geographical locations, depths, temperatures and immersion times. Information on the specific material grades, temperatures and immersion depths not detailed in the original sources cannot be provided here.

3.6 Biofouling Variation Between Materials

In order to provide an insight into the variation in biofouling experienced by different materials, Swami and Udhayakumar, (2008) immersed test panels in Mumbai Harbour for 30 days at 26.3-31.6°C. Upon recovery, panels were dried and the biofouling coverage, biomass and species present were recorded (Table 1).

Table 1. Settlement of Macrofouling Species on Different Materials Exposed for 30 Days at Mumbai Harbour
Adapted from Swami and Udhayakumar, 2008.

Material Panel 240cm2	Bryozoans Number m-2	Polychaetes Number m-2	Barnacles Number m-2	Area Covered %	Dry Weight Kgm-2
PTFE	1063	4210	607	90	0.33
Mild Steel	1514	1304	1304	45	1.30
Rubber	600	3465	646	35	1.75
Perspex	1230	12465	258	92	2.45
Fiberglass	1164	10664	6840	92	2.85
Timber	968	4085	508	85	3.20
Titanium	1128	10982	912	86	3.25
Glass	1013	11244	6746	80	4.61

Several differences in the biofouling potential of commonly available materials are noted; **Glass** experienced maximum growth; 4.61kgm-2 dry weight. Rapid biofouling observed was likely due to the physical and chemical stability of the surface allowing rapid macromolecular conditioning and further colonisation by macrofoulers giving the high biomass result (Marszalek *et al.* 1979).

PTFE (Polytetrafluoroethylene/Teflon®) experienced minimum growth; 0.33kgm-2 dry weight. This is unexpected as PTFE (like glass) has a low surface energy and is highly chemically and physically inert. However it is understood that the biofouling resistance of PTFE is due to its supple, soft polymer structure, with a high degree of mobility (Bonafede and Brady 1998). This means macrofouling organisms have great difficulty remaining attached, giving a relatively low biomass Fig..

Mild Steel appeared relatively resistant to biofouling with 45% coverage and 1.3kgm-2 of growth in the 30-day period. This is due to the relatively physically and chemically reactive surface (corrosion) slowing formation of a macromolecular conditioning layer and thereby slowing the formation of macrofouling (Marszalek *et al.* 1979).

The comparison of biofouling on these materials is interesting from a biological point of view and for illustrating the impact of surface stability on biofouling, however several of the materials tested may be less commonly used in modern marine construction. The following sections focus on biofouling of stainless steel, titanium and copper nickel alloys.

3.6.1 Titanium and Stainless Steel

Due to their structural strength and relative corrosion resistance, titanium and stainless steel are popular materials in marine installations such as tubing in heat exchangers and in general hardware. However, the data above in Table 1 and findings by Marszalek *et al.* (1979) show that the high surface stability of titanium makes it vulnerable to biofouling and therefore may reduce its attractiveness as a construction material. No data are provided above on the susceptibility of stainless steel to biofouling.

Szymlek and Kania, (2009) compared the accumulation of biofouling on stainless steel and titanium samples in the waters of Gdynia Shipyard, Poland on the South coast of the Baltic Sea. In Summary:

- 50 x 200mm plates of titanium and stainless steel were immersed in 8m of water at approximately 14°C for 224 days in 2007 (Fig. 4a and 4b).
- Upon recovery stainless steel plates had approximately 15-20% more barnacle growth (dry weight) than the titanium plates.
- Despite the difference in the level of biofouling observed, both materials have clearly suffered a great degree of biofouling in the relatively short time exposed.
- The same materials were immersed in 1m and 4m depth. These samples experienced more barnacle growth than the 8m samples. The authors attributed this to surface water temperatures being slightly higher, enabling faster growth (Szymlek and Kania 2009).

Both Szymlek and Kania, (2009) and Swami and Udhayakumar, (2008) show titanium and stainless steel to be highly vulnerable to biofouling in the marine environment.

Figure. 4a. Barnacle Growth on Grade 2 Pure Titanium Plate after 224 Days Immersion in Sea Water.
Adapted from Szymlek and Kania 2009.

Figure. 4b. Barnacle Growth on X2CrNi18-9 Stainless Steel Plate after 224 Days Immersion in Sea Water.
Adapted from Szymlek and Kania 2009.

3.6.2 Titanium, Stainless Steel, Galvanised Steel, Copper and Copper Nickel

The above studies show relatively corrosion resistant materials like stainless steel and titanium to be vulnerable to biofouling but corrosion prone materials like mild steel to be relatively biofouling resistant. This could present some difficulty in material choice when it comes to construction of marine systems. However, it is possible in some instances to replace or coat these materials (titanium, mild steel, stainless steel) with other metals that may provide a degree of biofouling resistance due to their ability to release toxic products into the water. An example of such a metal is pure copper or the 90-10 copper nickel alloy (90% copper 10% nickel, hereafter referred to as copper nickel) (Powell and Michels, 2000).

An illustration of the biofouling potential of copper and copper nickel as opposed to titanium, stainless steel and galvanised steel is provided by a study conducted by Vedaprakash *et al.* (2013).

The development of biofouling on five metals was examined in Ennore Port, approximately 24km North of Chennai, India from March 2007 to April 2008 (Vedaprakash *et al.* 2013). Metal plates, 100mm x 150mm were submerged in 3m of water at approximately 27°C for 185 and 390 days. They were removed from the water and the biological growth (biofouling) was examined (Table 2).

Table 2. Biofouling Observed on Metals Immersed in 3m of Seawater for 185 and 390 Days, Ennore Port.

Adapted from Vedaprakash *et al.* 2013

	Titanium	Stainless Steel	Galvanised Steel	Copper	Copper Nickel
Biofouling Mass 185 Days (g)	168.35	33.1	8.54	0.56	0.31
Coverage 185 Days (%)	90.75	73.75	19.43	0.00	0.25
Biofouling Mass 390 Days (g)	49.38	90.01	142.89	3.10	2.26
Coverage 390 Days (%)	87.20	93.20	88.40	45.00	25.10
No. Barnacles 390 Days	292.83	186.00	81.17	0.00	37.17
No. Tubeworms 390 Days	69.75	128.25	106.00	0.00	0.00
No. Oysters 390 Days	1.80	11.50	16.50	0.00	0.00
No. Mussels 390 Days	0.60	0.60	2.30	0.00	0.00
No. Sea Squirts 390 Days	141.00	127.67	16.75	0.00	0.60

Data displayed show mean values across four replicates of each metal.

In summary:

Titanium became heavily fouled, with 90.75% coverage and 168.35g biomass in 185 days. This was attributed to high surface stability leading to rapid macromolecular conditioning and higher biofouling. The mass of biofouling on the titanium decreased from 168.35g at 185 days to 49.38g at 390 days. Presumably the weight of growth present caused the mass of organisms to detach from the plate and colonisation to restart at some time between the two readings.

Stainless steel was colonised by both hard and soft biofouling organisms with a mean 186 barnacles, 128 tubeworms and 127 sea squirts being recovered from the 100mm x 150mm plates.

Galvanised Steel was relatively lightly fouled (8.54g) at 185 days and very highly fouled (142.89g) at 390 days. It is thought that the bio toxicity of the zinc coating prevented biofouling in the initial stage but then corroded to such an extent that toxicity decreased allowing biofouling organisms to rapidly colonise the surface.

Copper and Copper nickel met expectations having only 3.1g and 2.26g of biofouling after 390 days respectively. The small mass of biofouling recorded on the pure copper was due to surface oxide formation and algal microfouling; none of the macrofouling organisms were able to settle on the copper.

The results from this study show that copper and copper based alloys have great potential in antifouling applications. The specific antifouling properties of copper will be discussed in detail in Section 5 below.

3.6.3 Composite / Other Materials

Rather than reliance on exclusively metal constructions, composite materials are also used in the marine environment. Polagye and Thomson, (2010) assed the extent of biofouling on various materials to be used on tidal energy devices. Material samples were deployed at a depth 55-75m for 90 days in Admiralty Inlet, Puget Sound, Washington, USA and recovered for examination, with results shown in Table 3. The authors concluded that the lack of biofouling observed was due to the smooth surfaces and lack of crevices on the materials tested, with only one barnacle being able to attach to the relatively rough edge of a glass fibre panel (Polagye and Thomson, 2010). The authors found limited biofouling on the two experimental bearing materials; Feroform T14 and Feroglide 700. The lack of biofouling on these materials was attributed to their extremely smooth surfaces and lack of any crevices or grooves for organisms to attach.

Table 3. The Extent of Biofouling on Materials Immersed in 55-75m of Seawater for 90 Days, Admiralty Inlet, Puget Sound, Washington .

Adapted from Polagye and Thomson, 2010

Material	Extent of Biofouling After 90 Days
Glass Fibre Composite	Minimal – One Barnacle Attached
Carbon Fibre Composite	Minimal – No macrofouling
HDPE (High density polyethylene)	Minimal – No Macrofouling
Feroform T14 (Bearing material; woven fibre bonded with resin)	None Visible
Feroglide 700 (Bearing material, PTFE)	None Visible

4. IMPACT OF BIOFOULING ON INDUSTRY: CASE STUDIES

In order to ascertain the extent of biofouling *in situ*, it is useful to examine historical cases of biofouling in marine industries. Biofouling is an ancient problem; Aristotle commented on biofouling causing problems with movement of ships in the 4th Century BC (Woods Hole, 1952). In 1559, one author stated that “shell-fish stick so fast that they will stop ships, and hinder their courses, therefore our men must rub them off with sharp brushes, and scrape them away with irons that are crooked for the purpose” (Woods Hole, 1952). As noted previously, the formation of a macromolecular conditioning layer and given time, colonisation by micro and macrofoulers can occur on almost any natural or synthetic construction material, making biofouling a major problem in a wide range of industries worldwide (Flemming *et al.* 2009). Many of the issues caused by marine biofouling involve the impairment of the flow of water over surfaces, for example the increased drag caused by barnacles on the hull of a ship or reduction in water flow through the pipes of an industrial cooling system (Chambers *et al.* 2006) (Satpathy *et al.* 2010). However a wide range of issues can be encountered depending on the particular industry and geographical location. This section does not seek to provide an exhaustive list of industries and installations affected by biofouling, instead it highlights some major issues that are known to occur, these include:

- The build up of biofouling communities on maritime constructions (Bruijs, 2010).
- The build up of biofouling communities on aquaculture installations (Fitridge *et al.* 2012).
- Increased drag on marine vessels (Schultz *et al.* 2011).
- The blockage of inlets and piping in cooling systems for energy production, industry and shipping (Satpathy *et al.* 2010).

4.1 Constructions in the Marine Environment

The accumulation of a biofouling community on any structure in the marine environment causes the surface to become rougher, increases drag in the water, and causes the structure to experience extra loading. This is a widely recognised problem, with maritime engineering guidelines generally forcing designers consider the extra loads that biofouling build up will place on a structure (Fevåg, 2012). For the purposes of this report, actual loads and forces attributed to biofouling are not discussed; this example merely seeks to show the extent of biofouling growth on a structure over time.

An example of biofouling accumulation (and vertical zonation in a biofouling community) on an artificial substrate can be seen on wind turbines bases in a North Sea windfarm (Bruijs, 2010). The Egmond aan Zee windfarm (OWZE) was built 10-18km off the coast of the Netherlands (52°36'N 4°25'E) and opened in 2007. Each year, from 2007-2009 several turbine bases were examined using a video equipped Remotely Operated Vehicle (ROV) with the analysis of still images taken allowing researchers to see the extent of biofouling coverage, estimate the thickness of growth and develop biofouling zonation diagrams (Fig. 5a and 5b). The examination of one turbine (WTG-07) in June 2009 found distinct differences in the species of marine fouling organisms present, the thickness of biofouling and coverage as depth increased towards the seabed at ~20m (Bruijs, 2010). They divided the biofouling into three distinct zones:

Upper Zone

- From 0-14m deep the substrate was dominated by the Blue Mussel in a 25-30cm tick layer with 100% coverage.
- From 0-6m deep there were barnacles, tubeworms and a small degree of soft biofouling on top of the mussel layer.
- Also, at a depth of 11m, anemones were observed in patches over the mussel layer.

Mid Zone

- From 14-16m deep the substrate was dominated by soft fouling organisms in a 1-5cm tick patchy layer. The substrate was still visible through this layer.
- A relatively small number of mussels were present at this depth. Those present were being extensively grazed by large numbers of starfish.
- The rest of the fouling community was mixed hard and soft fouling organisms consisting of barnacles, bryozoans, hydroids and tubeworms.

Lower Zone

- From 16-20m deep the substrate was dominated by large numbers of soft biofouling. Anemones dominated, covering 100% of the substrate in a 1-5cm layer.
- No clusters of mussels were found in this lower zone.

In summary, the observed change in community structure with depth was seen to reflect the natural habits of the biofouling organisms. Mussels are naturally found in tidal zones and shallow waters, therefore they would not be expected at depths of 20m. Whereas soft biofouling bryozoans and hydroids are perfectly suited to deeper waters. Samples taken by divers in 2008 and 2009 were combined with data from the ROV to calculate densities of the main species seen on the turbine base. The study estimated there to be 3263 mussels per m^2, 828 anemones per m^2 and 535 tubeworm tubes per m^2 (4). These data show just how quickly an artificial structure such as a wind turbine base can be colonised; with up to 15cm of marine biofouling organisms within a year and up to 30cm growth within three years (Fig. 5b). Details of these fouling organisms are given in Appendix 1.

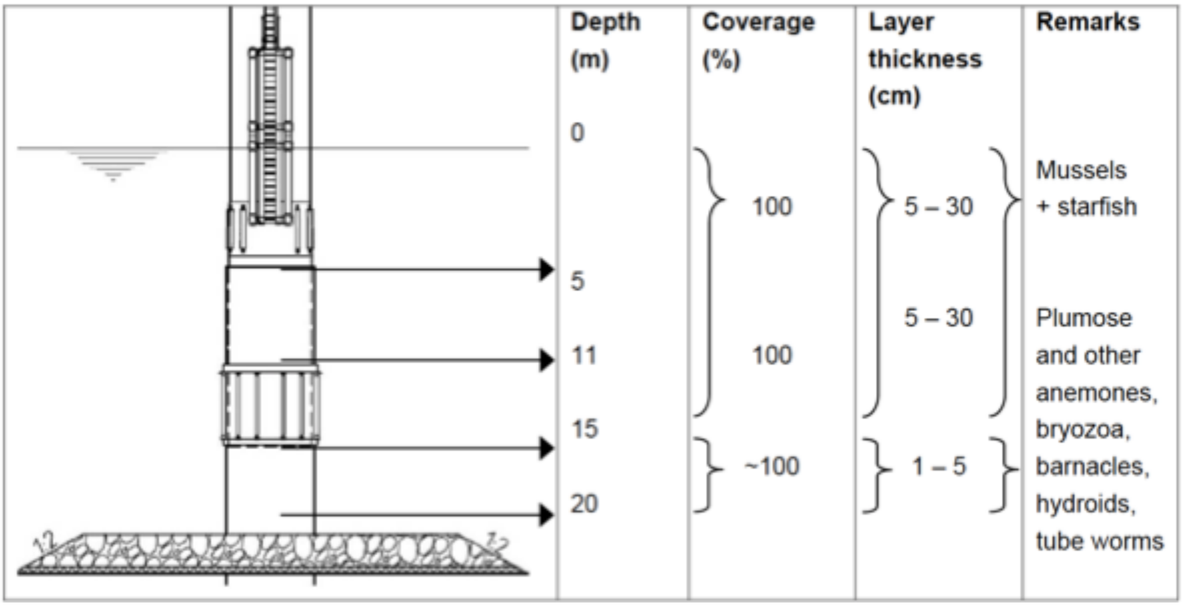


Figure 5a. Summary of Marine Growth at the WTG-07 Turbine June 2009.

Adapted from Bruijs 2010.

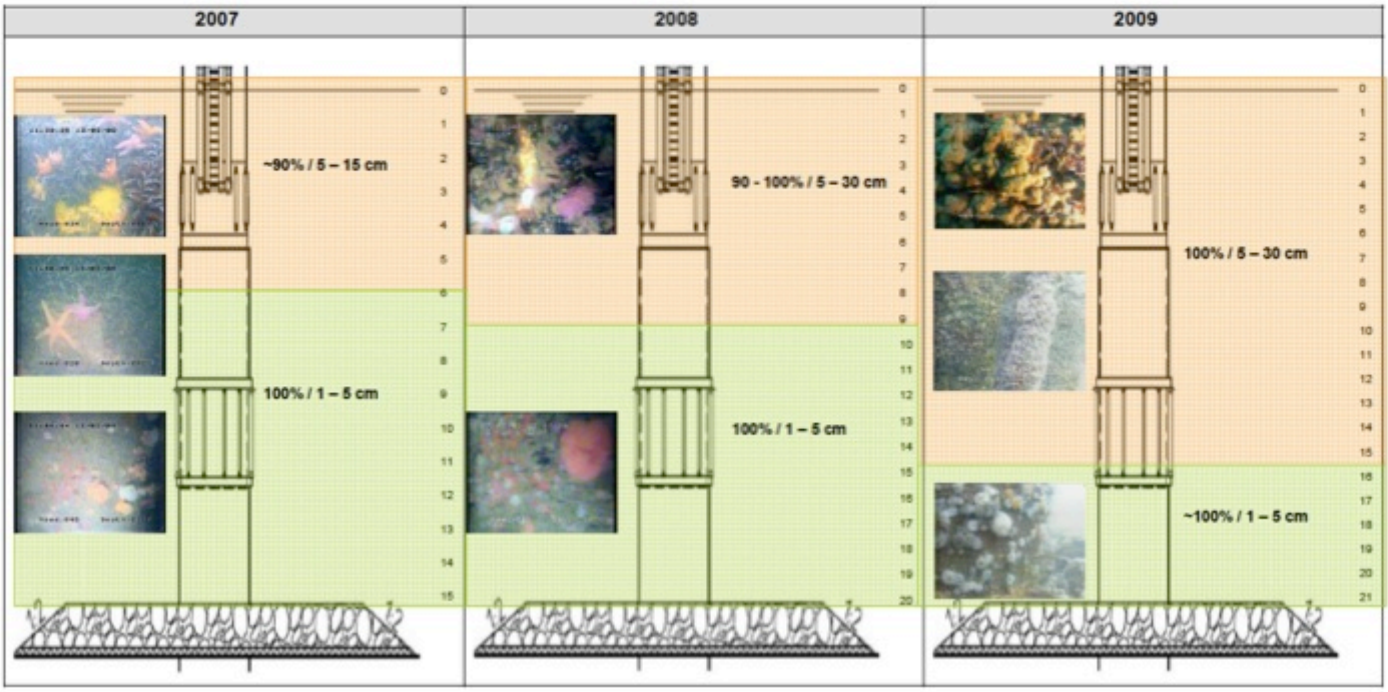


Figure 5b. The coverage and thickness of hard (orange) and soft (green) biofouling communities on the base of turbine WTG-07 from 2007 to 2009.

Adapted from Bruijs 2010.

4.2 Aquaculture Installations

With increasing global demand for low-cost protein, the global fish farming industry has experienced rapid growth over recent decades (De Silva, 2000). Many aquaculture installations are freshwater or land-based, however culture of salmon, cod and bivalve shellfish take place in marine environments thus making them susceptible to marine biofouling (Willemsen, 2005). Marine species are cultured in several different ways; finfish are held in large cages or sea pens generally suspended from floats and anchored to the seabed. Bivalve shellfish may be cultured in bags on trestles (e.g. oysters), on the bottom (e.g. mussels and scallops) or suspended in the water column (e.g. mussels and scallops). The impacts of biofouling on these industries vary according to the culture method and fish type (shellfish/finfish).

4.2.1 Shellfish Culture - It is estimated that the aesthetic damage due to the presence of biofouling such as barnacles and tubeworms on the surface of mussel and scallop shells can be responsible for a 20-30% drop in market value (Fitridge *et al.* 2012, Hartl *et al.* 2006). All cultivation systems are subject to colonisation by biofouling organisms, which cause economic losses to producers. For example mussels grown suspended in the water column on ropes are unprotected from biofouling. In one example, mussel shells attached to culture ropes became heavily fouled by sea squirts (Fig. 6a), adding approximately 10kg m-1 of extra weight to the lines. The result was that the mussels byssal threads were stressed to breaking point and 50-60% of mussels were lost from the lines (Hartl *et al.* 2006).

4.2.2 Finfish Culture – In this system, biofouling organisms tend to settle on the cages or sea pens. Fouled cages come under heavy strain, with up to 200 times the static load of a clean net due to the weight of biofouling organisms (Fig. 6c) and increased drag they cause (Hartl *et al.* 2006). This extra loading can stress cages to the extent that they have either broken free from moorings or broken apart, causing the escape of fish. As well as the physical stress on the net, biofouling organisms effectively clog the mesh structure (Fig. 6b), reducing water flow through the cage resulting in; reduced nutrient exchange, decreased oxygen in the cage and less waste being flushed out. In 2005, biofouling on cages at a salmon farm in Maine, USA caused the loss of USD $40,000 of stock due to lack of oxygen in the cages (Fitridge *et al.* 2012).

Figure. 8.
A – Sea Squirt Biofouling on a Mussel Culture Rope. B – Blue Mussel Biofouling on a Salmon Cage C – Extensive Hydroid Biofouling on a Salmon Cage Adapted From Fitridge *et al*. 2012.

4.3 Ship Hulls

Biofouling on the hulls of ships has most likely troubled humans since we began using the oceans for transport. The issue of hull biofouling is a prime example of how, at its most basic, biofouling simply interferes with the movement of water across a surface, or movement of that surface through water. The accumulation of biofouling on a hull serves to increase the roughness of the hull (Fig. 9a and 9b), reducing hydrodynamic efficiency and increasing drag, thereby forcing the ship to either reduce speed or burn more fuel (Schultz *et al.* 2011). Biofouling of any sort has the ability to impact severely on the efficiency of a ship:

- A biofilm 25µm thick can increase drag by 8% on a commercial ship (Flemming *et al.* 2009).
- The larger macrofouling organisms such as barnacles and mussels that are easily seen (Fig. 9b) have a larger financial and aesthetic impact.

A study by Schultz *et al.* (2011) examined the costs of hull biofouling on the United States Navy DDG-51 Type Destroyers; their most common mid sized surface ship, representing 30% of the entire surface fleet. The report estimated that;

- A non-fouled DDG-51 class ship would cost USD $11.1 Million per year to fuel.
- A ship with a typical level of both soft and hard biofouling organisms would use 10.3% more fuel, adding USD $1.15 Million to the fuel bill per year (Dec 2008 Fuel Prices) (Schultz *et al.* 2011).
- With costs of USD $26,000-34,000 each time a ship is cleaned and inspected, the combined cost of fuel, antifoul coatings, inspection and cleaning is estimated at USD $56 Million per year for the entire DDG-51 fleet or over USD $1 billion over 15 years (Schultz *et al.* 2011).

Figure 9a. Algal Biofouling on the 'Wet' Portion of the Hull
European Coatings, 2012.

Figure 9b. Barnacle Biofouling on the 'Wet' Portion of the Hull.
Hardsonic Marine, 2014.

4.4 Inlets and Piping

The accumulation of both micro and macrofouling in culverts and pipes ranging from a few centimetres to a few meters in diameter can have serious impacts on industry. These impacts can range from reductions in water flow and pipe blockages to lengthy shutdowns while pipes are cleaned or replaced (Satpathy *et al.* 2010). Seawater PTO systems are commonly used in cooling where excess heat generated by industrial processes must be dispersed. Two global industries that commonly use large volumes of seawater in their cooling systems are power generating plants and commercial ships.

4.4.1 Power Plant Cooling

The cooling systems of modern power plants require large volumes of seawater to condense steam (generated from freshwater) used in generating turbines; for example, a 500 MW nuclear power plant uses approximately 30m3 sec-1 of cooling water (Satpathy *et al.* 2010). With such volumes being drawn from the sea, it is clear that the potential for biofouling of intake screens, culverts, seawater pipes and heat exchanger tubes is extensive. An issue with this growth is that water flow becomes restricted, reducing the volume of water able to reach the heat exchange condenser tubes, and reducing cooling efficiency (Satpathy *et al.* 2010). A general estimate is that biofouling of tubes within seawater heat exchangers reduces cooling efficiency by 20-50%, with control costing an estimated USD $15 Billion per year worldwide (AMBIO, 2010).

Within these circumstances, mussels are a major cause of severe in power plant intake pipes worldwide. Examples include:

- **Madras nuclear power plant India** uses 35m^3 sec^{-1} of seawater for cooling of all its systems. The culverts and pipes used to carry this seawater suffer mussel biofouling on a regular basis. Fig. 10a shows a pipe from the plant with a 'typical' amount of mussel growth.
- **Poole Power Station, England** suffered severe mussel biofouling in the 1950's. A 'short' 2m-diameter inlet culvert was used to carry water from the sea into the power plant. This culvert experienced severe mussel growth to the extent that each year it was drained and cleared approximately 130 tonnes of mussels by men with shovels and scrapers (RWE Npower, 2005).
- **Pilgrim Nuclear Power Plant, Massachusetts**. A large volume of hot water from the cooling system was accidentally diverted to the cold-water inlet line, resulting in a mass kill of blue mussels. The byssal threads holding the mussels to the pipes degraded and over the subsequent period of 3 months the shells detached and were 'flushed' into the main reactor heat exchanger. The shells were of a size that effectively 'plugged' the tubes of the heat condenser (Fig. 10b). Due to the decreased efficiency of the exchanger, the plant was forced to reduce its power output by 30% for the entire 3-month period (Satpathy *et al.* 2010).

4.4.2 Ship Cooling

Cooling systems for the engines of ships and reactors of nuclear submarines function in a similar way to those in power plants, albeit on a smaller scale, using less water, narrower pipes and narrower heat exchanger tubes. The issues suffered with reduced water flow and heat exchange efficiency as a result of biofouling are shared between the two. Due to the movement of ships in the open ocean, they are less likely to encounter mussel larvae, meaning that barnacle biofouling is often more of an issue than mussel biofouling. However ships spending longer periods of time in either costal wasters or in port are vulnerable to mussel biofouling. Within heat exchanger tubes (both power plants and ships), microbial biofilms are problematic (Fig. 10c). The build-up of a microfilm inside an exchanger tube will decrease heat transfer from tube to seawater due to an increase in thickness of the liquid layer on the tube wall (Majka, 2005); essentially the biofilm acts as an insulating blanket on the inside of the tube. The presence of a biofilm on the inside of heat exchanger tubes can also increase the probability of silt particles settling and establishing conditions suitable for macrofouling growth.

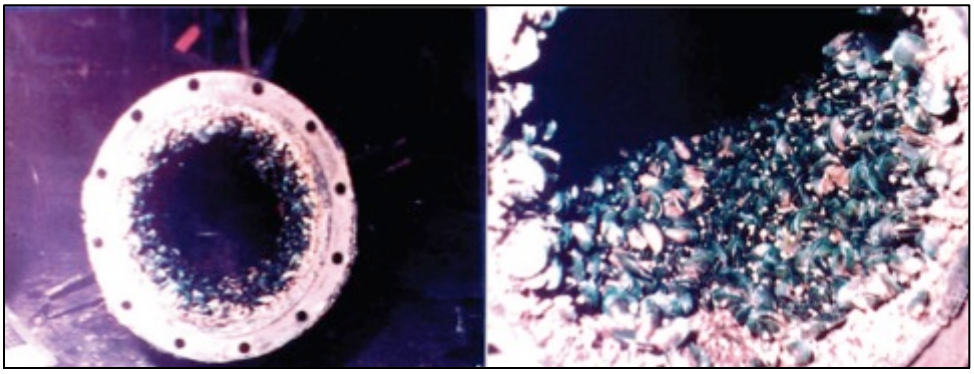


Figure 10a. Cooling Water Pipe from Madras Nuclear Power Station Fouled with Green Mussels. Adapted from Satpathy *et al*. 2010

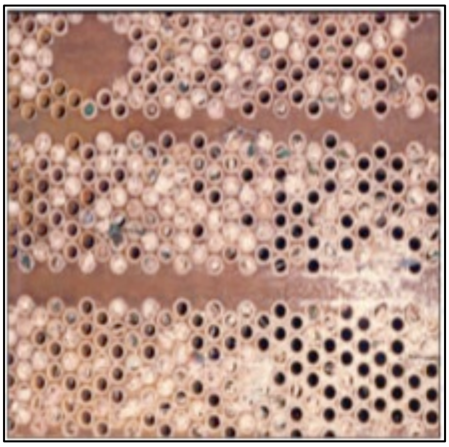


Figure 10b. Heat Exchange Condenser Tubes at Madras Nuclear Power Plant Blocked by Mussel Shells.
Adapted from Satpathy *et al*. 2010

Figure 10c. A Slime Layer/Biofilm on Heat Exchanger Tubes in a Commercial Ship.
AMSA, 2013.

5. ANTIFOULING

The above sections illustrate that biofouling is ubiquitous and inevitable on almost all surfaces within the marine environment. Therefore, every industry based in or handling seawater is vulnerable to biofouling. Large sums of money are directed into antifouling research, development and application. Most research seeks to understand how to prevent settlement of organisms onto equipment or at least slow the development of biofouling to an acceptable level; e.g. reducing the cleaning frequency of ships from annual to biennial. Antifouling techniques range from simple mechanical means such as pressure washing, to adding chemicals, to toxic metal coatings to the use of electrolysis to create a hostile environment unsuitable for colonisation by biofouling communities. Rather than providing an exhaustive list of all biofouling control methods currently available, this section will provide an overview of some commonly used antifouling techniques, namely:

- Mechanical antifouling.
- Antifouling paints.
- Copper and copper nickel coatings.
- Chemical dosing.
- Electrolysis.
- Pressure pulse.

5.1 Mechanical Antifouling

The term 'mechanical antifouling' means some form of scraping or scrubbing and covers a wide range of processes and methods for the prevention or removal of biofouling organisms from problem areas. Some of the simplest methods of mechanical antifouling include pressure washing, scraping and replacement of fouled surfaces. These procedures are generally carried out as required, with no specific cleaning routine due to the variations in the severity of biofouling and the rate of accumulation in different geographical areas.

5.1.1 Exterior surfaces

Exterior surfaces such as inlet screens and filter meshes in the marine environment are often vulnerable to biofouling and can become problematic relatively soon after immersion. Where accessible, these are often cleaned by scrubbing or are designed to be routinely replaced. Where large inlet culverts are used e.g. at power plant cooling systems, inlet screens may be positioned within rails or a frame such that they can be quickly lifted out when fouled and replaced by a biofouling free mesh.

Alternatively, water inlet screens for fish farming operations are often cylindrical, allowing them to be rotated such that half is under water, exposed to biofouling organisms and half exposed to allow cleaning or mesh replacement whilst still being fully operational. Another form of these cylindrical screens are constantly rotated by a motor, with the screen passing a brush or scraper with every rotation, meaning biofouling organisms are constantly removed (Fig. 11a). For structures difficult to remove from the water, i.e. the hulls of ships or oil platform legs, there are other mechanical scraping/abrasive cleaning methods. Divers may be used to clean the hull of a ship using a hydraulically driven machine, which sucks onto the hull and vigorously scrubs the surface using rotating brushes (Fig. 11b). Despite being a costly process, ships, submarines and other floating installations can also be brought to dry dock for periodic maintenance, providing an opportunity to scrub/pressure wash hulls and other surfaces in order to remove biofouling.

5.1.2 Interior Surfaces

In addition to biofouling on exterior surfaces such as inlet screens and ship hulls, biofouling on the inside of pipes and culverts is a major problem, causing restrictions in water volume and velocity (Satpathy *et al.* 2010). Many pipes carrying seawater are buried, small in diameter or are placed too deep to allow the above methods of using divers to pressure wash and machine scrub to remove biofouling. Despite these restrictions, there are mechanical methods for dealing with biofouling inside pipework; in certain circumstances, it may be cheaper to replace a heavily fouled pipe section than to clean it (Colt and Huguenin, 2002). It is possible to drain large diameter culverts, allowing workers access to manually remove biofouling, which is possible in certain industries and locations (RWE Npower, 2005). Pipes of all diameters may be cleaned by ‘pigging’ whereby a device is inserted into and pushed along the pipe to clean the interior surface. These ‘pigs’ can range from a simple ‘bung’ with wire brushes attached (Fig. 12a) to complex robots equipped with lights, cameras, sensors and brushes (Fig. 12b). Unfortunately this procedure is costly with a lot of system down time. Moreover, specialist pipe sections are required for insertion and recovery of the pig (Colt and Huguenin, 2002).

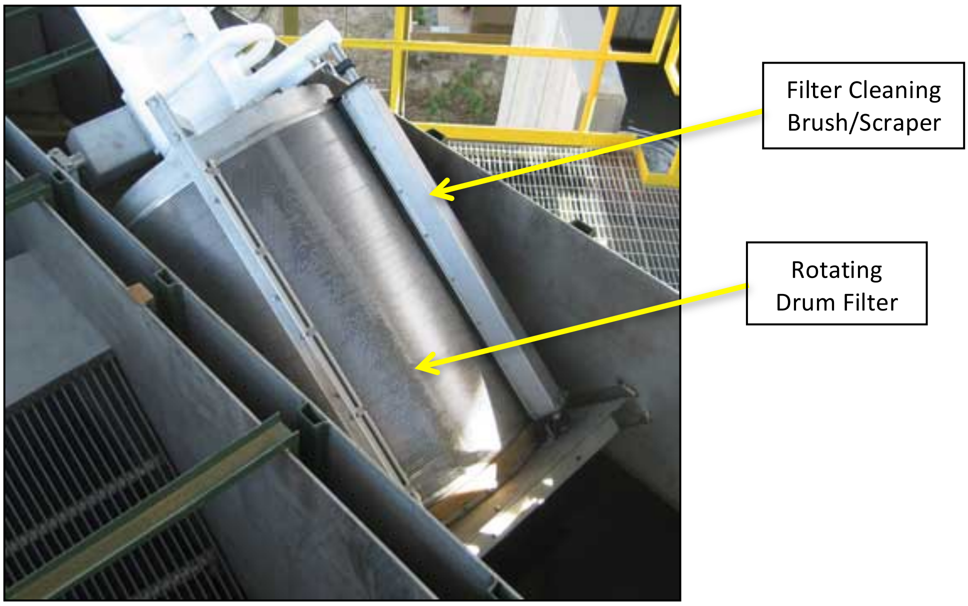


Figure 11a. A Self-Cleaning Rotating Drum Filter at a Fish Farm Water Inlet.
Waterworld, 2014

Figure 11b. A Diver Removing a Slime Layer from a Hull.
Hydrex, 2011

Figure 12a. A simple pig made of plastic with wire brushes.
PipeTech, 2010

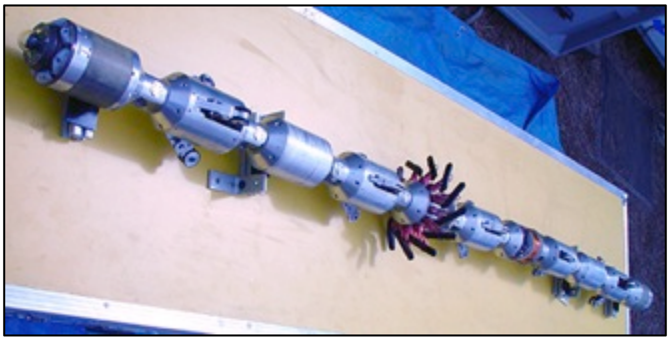


Figure 12b. A complex robotic pig equipped with sensors, lights and cameras.
NETL, 2007.

5.2 Antifouling Paints

The commercial shipping industry provides a great deal of information on antifouling coatings and paints. The costs of biofouling on ship hulls shown in Section 4.3 show how economically important an effective antifouling coating is to a company operating such a vessel. Again, these paints do not seek to completely prevent biofouling; their goal is to reduce the development of biofouling to an acceptable level, increasing fuel efficiency and reducing costs. Such paints are generally applied to exterior surfaces but can also be applied to the interior of pipes and culverts, which may be of use in a seawater pumping system. Table 4 compares the lifespan and costs associated with these coatings. Commercially available antifouling paints can be divided into three main categories based on their composition and mode of action:

- Fouling Release Coating (FRC)
- Controlled Depletion Polymer (CDP)
- Self-Polishing Copolymer (SPC).

5.2.1 Fouling Release Coating (FRC)

- These coatings are extremely smooth at the molecular level, the surface energy is so low that biofouling organisms find it difficult to attach and remain attached.
- When painted onto ships, biofouling organisms can attach to the hull when the ship is stationary. When the ship reaches a speed of 15-20 knots, the drag forces on biofouling organisms becomes greater than their adhesive strength and they are swept off (Chambers *et al.* 2006).
- Fast ships and those spending minimal time in dock benefit most from FRCs
- These have the highest initial retail cost of the three coatings but last the longest on the hull of a ship meaning they are the cheapest per unit area per year (Table 4).

The FRCs fall into two types; fluoropolymers and silicon-based FRCs. There have been environmental concerns over high concentrations of silicon oils leaching into waters at ports and the use of dibutyltin (DBT) as a curing agent for the coating (Chambers *et al.* 2006). The FRCs are also vulnerable to damage by mechanical cleaning such as brushing and have little resistance against biofilm formation (IMC, 2012).

A silicon based FRC was applied to the hull of the 380m Ultra Large Crude Carrier TI Asia, which travels between the Arabian Gulf and California. This reportedly saved 12 tons of fuel per day (USD $3,600) compared to her sister ship TI Europe which was treated with a tin-based antifouling coat (Thorlaksen *et al.* 2009)).

5.2.2 Controlled Depletion Polymer (CDP)

- This is the cheapest (retail cost) of the three antifouling coatings mentioned.
- It consists of rosin impregnated with a biocide. In seawater, the soluble component of the rosin dissolves and, the biocide leaches into the water to create a hostile environment for biofouling organisms close to the coated surface.
- Insoluble components of the rosin remain attached to the hull leaving a rough surface. The dissolving/leaching process continues until seawater no longer penetrates the coating deep enough to dissolve more material (Fig. 13a).

The CDP coatings will also react quickly with oxygen in the open air, so must be applied just before the ship is put into the water, unlike the FRC's which can be applied at any time during dry docking. The brittle nature of the rosin also means that coatings can crack and break off with even small knocks (IMC, 2012).

5.2.3 Self-Polishing Copolymer (SPC)

- These are often seen as the most effective antifouling coatings, combining the positive aspects of biocide release from CDP's and low surface energy of FRC's into one product.
- The SPC's consist of an acrylic polymer resin with silyl acrylate, copper acrylate or zinc acrylate mixed through as a biocide.
- When exposed to seawater, the biocide in the coating leaches into the water, creating a toxic environment for biofouling organisms. The polymer resin simultaneously erodes away, maintaining a smooth surface (Fig. 13b).
- For a copper based SPC, the leach rate required for effective biofouling prevention is 10μg cm^{-2} day^{-1} (IMC, 2012).
- In general, SPC coatings can be reapplied at any time without stripping the previous coat.

Table 4. The Costs Associated With Antifouling the Hull of a Commercial Ship. Adapted From Eliasson, 2003

Coating	Lifespan	Cost USD $\$m^{-2}$	Cost USD $\$m^{-2}$ $Year^{-1}$
FRC	Up to 10 Years	116	11.60
CDP	3 Years	50	16.66
SPC	5 years	75	15.00

The figures quoted take into account the cost of the ship being unavailable for hire, hull cleaning, surface preparation, paint, coating application and dry dock time.

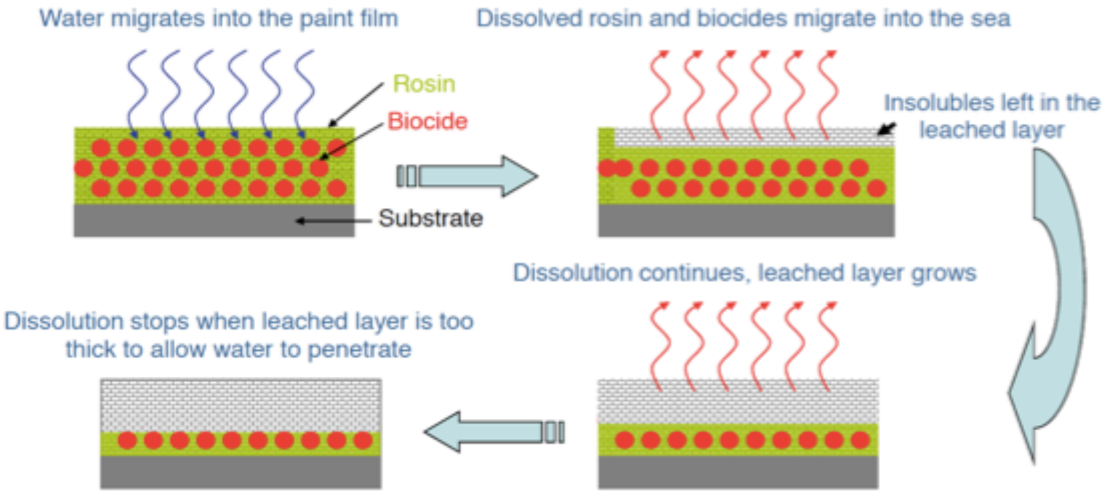


Figure 13a. Representation of how a CDP Coating Reacts in Seawater.

International Marine Coatings, 2013.

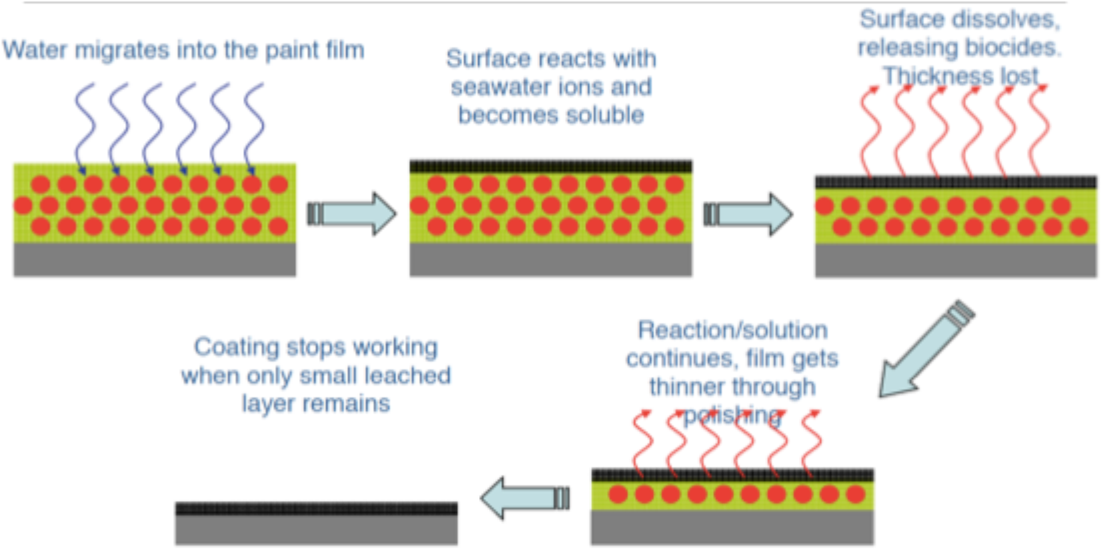


Figure 13b. Representation of how a SPC Coating Reacts in Seawater.

International Marine Coatings, 2013.

5.3 Copper and Copper Nickel

Copper is toxic to many marine organisms and therefore many anti-biofouling mechanisms involve the use of copper, such as copper based paints, copper sheets, copper alloys and plastics embedded with copper particles (CAEP, 2012). This section will focus mostly on the 90-10 copper nickel alloy rather than pure copper (unless otherwise stated); copper nickel is much more commonly used in antifouling applications due to its superior strength, and corrosion resistance (Powell, 2004)

5.3.1 Antifouling Properties of Copper

Copper has been described as one of the most toxic heavy metals in freshwater and marine organisms (Schroeder *et al.* 1966). However, sources promoting its antifouling abilities rarely provide details of why this is the case; many simply state that copper is an excellent antifoulant 'due to the release of toxic ions'. Studies examining why copper is toxic to marine invertebrates have been undertaken. Dissolved cupric ions (Cu^{2+}) and some hydroxyl complexes produced when copper is exposed to seawater are apparently responsible for the biologically toxic effects (Hall *et al.* 1988) (Hung *et al.* 1990). It is normal for marine invertebrates to absorb copper from the water as it is necessary for the synthesis of haemocyanin, a blood pigment (similar to human haemoglobin) (Eisler, 1997)). Therefore, when elevated levels of cupric ions are present, they are absorbed and may:

- Cause gill damage, interfere with oxygen transport and disrupt energy metabolism in biofouling organisms (Hansen *et al.* 1992).
- Bind to hydrophilic regions of the external membranes of epithelial cells, negatively altering their biochemical properties.
- Disrupt the normal functioning of the enzyme peroxidase and protein ferritin (Eisler, 1997)
- Increase production of peroxides, such as hydroperoxides and malondialdehyde within the cell. These are toxic to vital functions of membranes and cells. Bivalve mollusks exposed to copper show significant increases in these products (Chelomin and Belcheva, 1992)

In summary, the primary lethal effect of copper in marine biofouling organisms is due to disruption of normal biological processes, leading to the accumulation of toxic products in the organism (Eisler, 1997)

5.3.2 90-10 Copper Nickel

During the 1970's the La Que Corrosion Services Research Centre at Wrightsville Beach, North Carolina investigated the use of copper-nickel as an antifoulant. Their observations predicted that the copper oxide film developing on the metal was responsible for the antifouling properties, rather than the toxicity of cupric ions released. They hypothesised that cuprous oxide in the seawater gradually converting to cupric hydroxychloride caused the surface to become less adherent than cuprous oxide alone, causing any biofouling to slough off. However, their conclusions were that the excellent antifouling characteristics of the copper nickel were down to a combination of both properties; primarily the release of toxic cupric ions to the water and second, the unsuitable surface created by oxidation to cupric hydroxychloride (Powell and Michels, 2000)

A vulnerable surface can be protected from biofouling by applying copper nickel sheeting onto the surface as a protective jacket/sheath. This can be done in the form of relatively thick copper nickel sheets welded to a surface or adhesive backed foil (0.15mm thick) stuck onto the vulnerable surface. The foil method is popular for coating the hulls of small boats as it is easily cut and can be folded around the awkward curves and contours of a hull (Boulton *et al.* 1999)

A long-term study at La Que Corrosion Services (La Que) saw steel piles located in natural seawater at Wrightsville Beach and monitored for accumulation of biofouling after five and ten years with a copper nickel sheath or no protective coating. The results of the trial (Table 5) showed that the 90-10 copper nickel provided excellent biofouling protection, with 36.8% coverage and 4.43kg m^{-2} of biofouling compared to 100% coverage and 12kg m^{-2} biofouling on bare steel piles after ten years exposure.

An example of the use of copper nickel sheeting on large ships was on the Arco Texas, a 73,000 Ton crude tanker built in 1973. The ship was experimentally fitted with 3 'bands' of copper nickel sheets to determine the biofouling difference between steel hull and sheeted hull. After two years of service, during which time the ship was taken through the Panama Canal seven times, the copper nickel plates were reported to be biofouling free, whilst the steel hull was reported to be 'normally' fouled (Thorlaksen *et al.* 2009)

Table 5. Biofouling Accumulated on Steel Pilings at La Que Corrosion Services, Wrightsville Beach, North Carolina. Adapted From Powell and Michels, 2000.

Material	5 Years Exposure		10 Years Exposure	
	Coverage (%)	Biofouling (kgm^{-2})	Coverage (%)	Biofouling (kgm^{-2})
Bare Steel	100	18.0	100	12.0
90-10 Copper Nickel	44.3	7.95	36.8	4.43

5.3.3 Copper Composite Materials

In order to reduce the costs of coating large areas with copper/copper nickel, several composites have been developed incorporating copper in order to provide the same biofouling protection in a more practical manner. Two of the composites have been developed for use in the offshore oil and gas industries.

La Que tested a composite of 90-10 copper nickel fragments bonded to neoprene to make a strong, flexible antifouling sheet. Granules of copper nickel, 1mm^2 were bonded to the surface of 3mm thick neoprene sheet such that approximately 30% of the exposed surface was copper nickel (Powell and Michels, 2000). The composite material provided a strong, flexible coating that could be easily rolled, transported, unwound and attached to the legs of oil platforms to protect the 'splash zone' from biofouling. La Que reported that over 13,000m^2 of the neoprene coating has been successfully applied to oil platforms, mostly in the mid to late 1980's.

An alternative composite consists of copper nickel particles or mesh bound to a brightly coloured polyester gel to make a small 'jacket' that can be attached on or around subsea pipelines to identify specific points and ensure the marking remains biofouling free (Powell and Michels, 2000).

5.4 Chemical Dosing

5.4.1 Chlorine

Industrial systems such as power plants handling large volumes of seawater are vulnerable to severe biofouling (Satpathy *et al.* 2010) and as such normally treat their seawater intakes with some form of antifoulant. A common antifouling chemical used in such applications is chlorine; either as chlorine gas or as sodium hypochlorite (Majka, 2005). In terms of antifouling action, is not the chlorine which deters/kills biofouling organisms, but products of the reaction between seawater and chlorine. When chlorine is added to seawater, a rapid reaction occurs with bromine naturally present in the seawater (68 mgl^{-1}). Within ten seconds, 99% of hypochlorite is displaced, creating the biocide hypobromous acid, which reacts with nitrogen from organic material in the water creating biocidal bromamines (Polman *et al.* 2007) A method traditionally used in most power plant cooling systems was to add chlorine gas to cooling water in one of two ways:

- A continuous feed of 1-3ppm chlorine pumped into seawater pipes in order to prevent the settlement of biofouling organisms
- Shock chlorination, whereby larger volumes of gas (3-8ppm) are added every 4-8hrs for one full cycle period to ensure any settled organisms are killed.

This effectively controlled the settlement of biofouling organisms in cooling systems, however with the security and safety risks associated with the transport, storage and use of chlorine gas, the method has fallen out of favour (Majka, 2005).

Sodium hypochlorite dosing is another delivery method for chlorine to cooling systems, at approximately 0.05-0.3$mgml^{-1}$. A modern method for the application of 'aqueous' hypochlorite is Pulse-Chlorination®, whereby, hypochlorite injection is on a constant on-off cycle. Pulse-Chlorination® is intended to take advantage of the ability of mussels to close their shells to avoid toxins in the water. By cycling the dosing, mussels are forced to keep opening and closing, expending energy, to the extent that they essentially die from exhaustion (Jenner *et al.* 2008)(Fig. 14).

Chlorine is also used as an antifoulant in electrolysis, which is discussed below.

Figure 14. Pulse-Chlorination at the Maasvlakte Power Station, Rotterdam
Left - a Screen in the Cooling System fouled by mussels before Pulse-Chlorination.
Right - a Screen in the Cooling System free from biofouling following Pulse-Chlorination.
The treatment resulted in a significant reduction in mussel biofouling and is reportedly saving the plant €150,000 per year and using 50% less sodium hypochlorite than used before.
Jenner *et al.* 2008.

5.4.2 Ozone

As with chlorine and sodium hypochlorite, ozone can be injected into water carrying systems to prevent the accumulation of biofouling. Being an oxidising agent, ozone reacts with bromide naturally present in seawater to give hypobromite, hypobromous acid and hypobromite ions, which act as the biocide, killing fouling organisms (Shifler *et al.* 2000).

Ozone can be generated on site using specialised equipment and then piped along and injected into pipework systems. The (freshwater) cooling system of the Bruce Power Station, Canada uses 600ls^{-1} of water for which is treated with 2 kgday^{-1} ozone. The ozone is administered with 1kg injected over 5 minutes twice per day to keep the cooling system free from biofouling (Claudi, 2001). Ozone is more commonly used to treat freshwater systems than seawater systems due to its short half-life and therefore relatively short efficacy period in seawater (Cloete, 1998).

5.5 Electrolysis

This technique was developed as a cheaper, safer method of chemically dosing seawater systems. In this process an electrical current is passed through different metal electrodes to either release metal ions into the water or ‘split’ seawater to produce chlorine (Gefico, 2012). This is common in industries where biofouling of pipes is an issue, with many companies producing seawater electrolysis machines and systems for use in shipping, power plant cooling and desalination plants (Fig. 15). Very often, the intention of electrolytic antifouling is not to kill already established biofouling organisms but to simply to create a hostile environment which prevents initial settling in vulnerable areas of a system (Knox-Holmes *et al.* 1994). This is an obvious benefit in terms of the environmental impact of electrolysis systems and reduces the potential for the accumulation of dead biofouling organisms, the development of putrefaction and potential production of hydrogen sulphide by SRB.

5.5.1 Electrochlorination

The use of chlorine/sodium hypochlorite as an antifoulant is mentioned above in Section 5.4. During electrochlorination, the use of hypochlorite is somewhat similar, however the source differs. This system uses an electrochlorination machine (Fig. 15) on site to generate hypochlorite, which is then injected into the seawater pipe system:

- Seawater is fed through a cell where DC current passing through oxide coated titanium anodes splits it to produce sodium hypochlorite and hydrogen gas.
- The hydrogen gas is separated, diluted with air and released as a by-product while the sodium hypochlorite solution is injected at one or a number of points along the protected seawater system.
- The electrochlorinator constantly generates a supply of sodium hypochlorite on site, rather than having to transport, store and apply either a liquid solution or more dangerously, chlorine gas.
- Typically, electrochlorinators are able to generate different concentrations of sodium hypochlorite and adjust their dosing strength and timing according to a set program.

Commercial systems, such as those produced by SANILEC® produce 500-2500ppm sodium hypochlorite which is then injected into the pipework system to be protected to give a concentration of 1-2ppm. A typical dosing schedule for a power plant cooling system may be a 2ppm constant dose with a shock dose of 6ppm for 15-20mins up to four times per day. A SANILEC® electrochlorinator with the capacity to treat a seawater intake of $56m^3h^{-1}$ with 2ppm chlorine weighs approximately 128kg and runs on AC 1.2 kVA (Severn Trent De Nora, 2012). This technique can be used to apply hypochlorite at low dose in order to create a hostile environment or at higher dose to kill biofouling organisms already attached. In many instances, the more modern methods of copper chlorine and copper aluminium dosing have replaced traditional chlorine electrolysis as the preferred method of biofouling control. However, electrochlorination is still commonplace in power plants where relatively large volumes of water are used for cooling.

Figure 15. A Small Electrochlorination Plant on Board a Ship.
Gulf Green Environmental, 2014

5.5.2 Copper-Aluminium Electrolysis

Another commercially available system which provides biofouling protection utilises copper and aluminium anodes to produce cupric ions and aluminium hydroxide. The copper anode functions in the same way as detailed above, by releasing toxic cupric ions to the water which deters settlement of biofouling organisms. The role of the aluminium anode is to produce aluminium hydroxide which forms small flocs (aggregations of suspended particles) in seawater; trapping copper ions in what is often described as a 'copper aluminium gel'. These copper aluminium flocs are relatively dense and tend to settle in areas of slower water movement which is conventionally where biofouling organisms are likely to settle, providing a higher copper concentration and an extra level of protection (Gefico, 2012)

Many commercial copper-aluminium systems use large anodes which have up to a five year serviceable lifespan; these are common place in sea chests (water inlet screen on hull and initial section of pipe) on large ships (Fig. 16a). Smaller self-contained, systems (which require more regular intervention) can be based in accessible areas of a ship. An example of a smaller system made involves a smaller volume of seawater being pumped through a stainless steel vessel where it is dosed with copper aluminium before being injected back to the main water flow (Fig. 16b). A system capable of treating 500m3h^{-1} of inlet water will have a 483 x 395 x 637mm vessel and 400 x 500 x 200mm control panel (mounted remotely) consuming 0.5Kw of electricity at 1.3Amps with an anode life of approximately 10 months (Gefico, 2012).

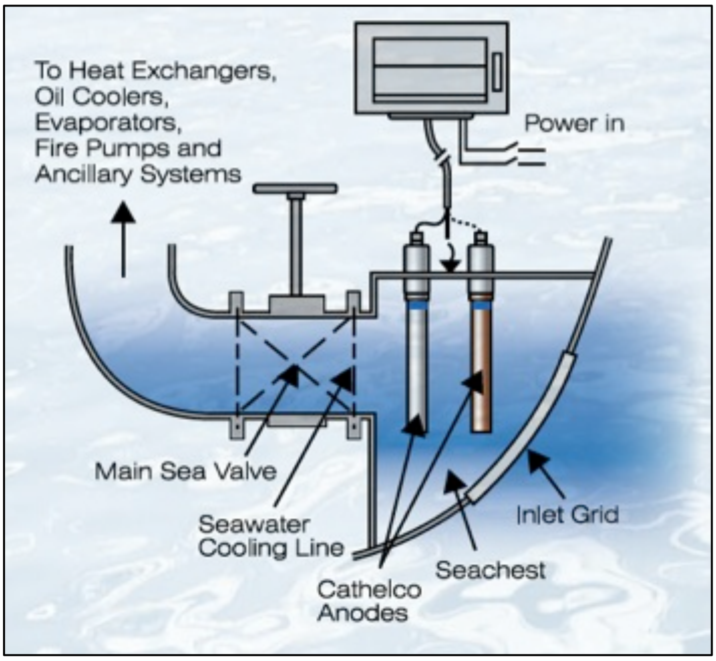


Figure 16a. Example Location of Copper Aluminium Anodes in a Sea Chest.
Cathelco, 2014

Figure 16b. A Copper Aluminium Seawater Dosing Vessel Produced by Gefico.
Gefico, 2012.

5.5.3 Copper-Chlorine Electrolysis

In the 1980's a method for antifouling using low levels of copper ions and chlorine dosing was developed by Brent Knox-Holmes in conjunction with Sheffield University and marketed under the company Biofouling and Corrosion Control Ltd (BFCC). The system uses a copper anode and mixed metal oxide (MMO) anode on a pulsed one minute on – one minute off cycle to produce low levels of copper and chlorine in the water, which work synergistically to produce a stronger antifouling effect that both constituents alone. It is thought that the presence of chlorine in the water increases the permeability of cell membranes, resulting in biofouling organisms absorbing more cupric ions and suffering metabolic damage more quickly (Knox-Holmes, 1994). The system produces approximately 50µgl^{-1} copper and 5µgl^{-1} chlorine in the water, and is not designed to kill biofouling organisms already attached to surfaces, but to create an environment hostile enough to prevent settlement. This method uses 5-10 times less chlorine than conventional systems, thereby reducing the environmental impact of residual chlorine, and reduces chlorine-associated corrosion on pipes. The UK Electricity Generating Board carried out an experiment into electrolytic antifouling in steel pipes, comparing chlorine, copper chlorine and copper aluminium producing electrolysis systems (Knox-Holmes *et al.* 1994). At the end of a 4 month experiment in which seawater was pumped through steel pipes, it was found that the BFCC copper chlorine method was most affective at preventing biofouling build-up with only 3g of biofouling per unit area as opposed to 28g per unit area on unprotected steel (Table 6).

Table 6. Biofouling Mass Accumulated on Steel Pipes over 4 Months When Treated With Different Antifouling. Adapted From Knox-Holmes et al. 1994.

Treatment	Mass of Biofouling (g per unit area)
Control	28
35 µgl^{-1} Copper 5 µgl^{-1} Aluminium	25
200µgl^{-1} Chlorine	9
BFCC 50µgl^{-1} Copper 5µgl^{-1} Chlorine	3

Table 6 compares the three methods of electrolysis discussed. It is clear that the synergistic effect of copper chlorine dosing is the most effective method of biofouling control; with the added bonus that it involves the release of a relatively small concentration of chemicals to the environment. In systems where anodes are placed directly in the main seawater flow, they are often inaccessible i.e. in the sea chest of a ship or power plant inlet culvert. This makes periodic replacement and maintenance difficult, potentially requiring expensive dive teams or dry-docking of ships. In cases where self-contained units (Fig. 16b) are used, there may be a requirement for a long system of pipes allowing ion-dosed water from the electrolysis device to be injected into the main seawater PTO system. This makes retrofitting of such systems difficult, emphasising the need for careful consideration of biofouling control at the design phase.

5.6 Pressure Change

Environmental impacts and the potential negative public image that come with the use of chemical dosing systems mean that 'chemical free' antifouling methods such as self cleaning screens and pressure washing are often more attractive than the use of chemical based systems. However, as seen above, many of these are either labour intensive or not effective enough to replace the convenience and reliability of controlled electrolysis or chemical application. Preventing the settlement of biofouling organisms or killing those already settled could potentially be achieved by rapid pressure change using either water hammer or electrical pressure pulse.

5.6.1 Water Hammer

The phenomenon of 'water hammer' causes rapid pressure change in pipe systems and may have an influence on the development of biofouling similar to that of electrical pressure pulses above. Water Hammer is caused by a rapid stopping of flow in a pipe e.g. by closing a valve;

- The rapid deceleration of the fluid when it hits a closed valve causes the kinetic energy of the moving water to be converted to pressure energy.
- This results in a pressure wave being propagated upstream where it is reflected and returned, creating a pressure pulse at the closed valve (Wylie and Streeter 1978, Colt and Huguenin, 2002).
- The pressure pulse created can be several orders of magnitude greater than the normal operating pressure of the pipe and is dependant on; water velocity, pipe length and the rate of valve closure;
- In general, a high water velocity in a long pipe with a short valve closure time will give a high pressure pulse (Colt and Huguenin, 2002).
- For example, water travelling at $3ms^{-1}$ through a 210m pipe is stopped by a valve with a closure time of 1 sec; the pressure pulse created by the stoppage will be approximately 34.5 Bar above normal operating pressure in the pipe (Colt and Huguenin, 2002).

Water hammer has been used to successfully control microfouling in ultrafiltration membranes (pore size of 0.3μm) experimentally (Broens *et al.* 2012), however there is little information available on its commercial application. (Inci *et al.* 2004) proposed that water hammer be used to control biofouling by the freshwater zebra mussel in pipes of hydro-electric power projects. They acknowledged that zebra mussels are susceptible to sustained pressure changes but that the water hammer of 1.5 times static pressure that would be created in the proposed hydro-electric plant would not be sufficient to eradicate zebra mussel biofouling. They recommended that water hammer be used in conjunction with another biofouling control method such as chemical dosing in order to effectively control the zebra mussel population.

5.6.2 Electrical Pressure Pulse

The desire for an automated non-toxic antifouling system has led to the development of the electrical pressure pulse antifouling system, which can be used in more ‘open’ systems such as culverts rather than closed pipes. The electrical pressure pulse system was tested in the water inlet culvert of the Georgia-Pacific paper mill on the shores of lake Champlain, Vermont, USA by (Schaefer *et al.* 2010).

The system uses a high power electrical arc discharging between two electrodes located in the water:

- An electrical charge is accumulated on capacitors before being discharged in an arc between two electrodes suspended in the water column.
- The pulsed discharge rapidly heats and vaporises the water between the electrodes, producing a shockwave and a steam bubble.
- The high pressure steam bubble rapidly expands before contracting and collapsing and producing another pressure pulse (Fig. 17a).
- This process of expansion and collapse repeats until all the energy in the bubble has dissipated into the water.
- Using a metal reflector plate, it is possible to direct the pulse along a pipe or towards a particular area requiring protection (Fig. 17b).

A pressure pulse system was tested experimentally in the inlet culvert (0.76m diameter x 115m long) of a paper mill on the freshwater Lake Champlain, USA as an antifouling mechanism against the freshwater hard fouling zebra mussel (*Dreissena polymorpha*) by Schaefer *et al.* (2010). The experimental setup used a pressure sparker driven by two capacitors with a combined 64µF capacity, charged to 5.5kV giving a 968J pulse every 45 seconds for 24hrs (with a power conversion of 80% efficiency, power drawn <30W). The results of the study showed:

- The maximum peak pressure measured 10cm from the sparker itself was 0.7MPa (100psi)(Fig. 17a), with lower pressures recorded further away along the culvert.
- Peak pressures of 0.04MPa and pressure energy of 0.16Jm^{-2} were sufficient to prevent the settlement of mussel larvae 23m from the sparker.
- Peak pressures of 0.23MPa and pressure energy of 5.8Jm^{-2} were sufficient to kill established adult zebra mussels 1.5m from the sparker.

The results of this trial show that pressure pulse is a viable option for the control of some types of biofouling in pipework systems. In order to evaluate the utility of such a system, the cost of installing a permanent sparker at the Lake Champlain site was estimated at USD $60,000 for installation and training with a further USD $5,000 per year running cost (Schaefer *et al.* 2010).

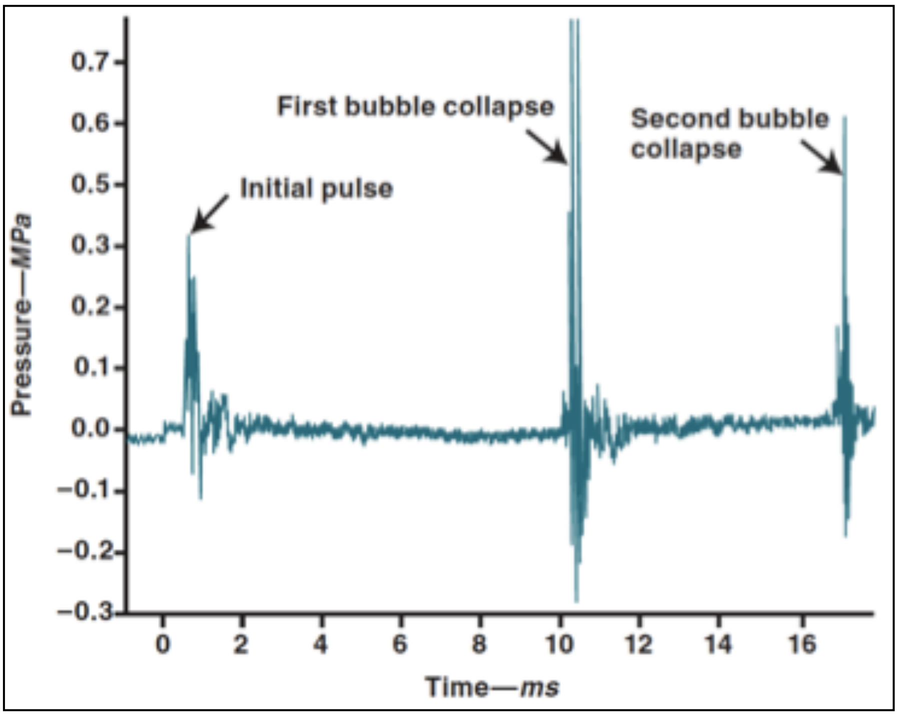


Figure 17a. Graph showing the pressures recorded 10cm from the sparker device with the bubble expand-collapse pattern identified

Schaefer *et al* 2010.

Figure 17b. Two electrodes of a pressure pulse device inside a directional reflector.

Schaefer *et al* 2010.

6. WAVE ENERGY CONVERTER USING AN OPEN LOOP SEAWATER POWER TAKE OFF (PTO) SYSTEM

Information gathered on biofouling can assist in understanding how wave energy converting devices in the marine environment are themselves susceptible to biofouling. Accumulation of a degree of biofouling on screens and in pipes handling seawater in industries such as power plants and shipping is inevitable (Aylott, *et al.*, Knox-Holmes *et al.* 1994, Majka 2005, RWE Npower 2005, Polman, *et al.* 2007, Jenner *et al.* 2008, Satpathy *et al.* 2010). The major unknowns for a wave energy converter are the potential extent of biofouling, how quickly it could accumulate, and where in the system it could occur. Due to the complex nature of biofouling and its dependency on many factors it is impossible to give an accurate assessment of these risks without site-specific testing. This section will outline:

- How a wave energy converter using an open loop seawater PTO system may function.
- The potential for biofouling within the system.

6.1 Layout and Function of a Wave Energy Converter Using an Open Loop Seawater PTO system.

As this review is intended to examine the potential for biofouling in a wave energy converter that uses an open loop seawater PTO system as the PTO, the potential layout of such a system is important. Although there may be variation in design, any system based on pumping seawater to a turbine and discharging it back to sea is likely to incorporate at least some of the sections outlined below. Both the diagram (Fig. 18) and explanation are intended to give a general idea of how an open loop system may function so that potential 'biofouling weaknesses' can be identified. Once such potential pitfalls have been identified, it should be possible to design suitable control mechanisms to reduce the chance of serious biofouling developing.

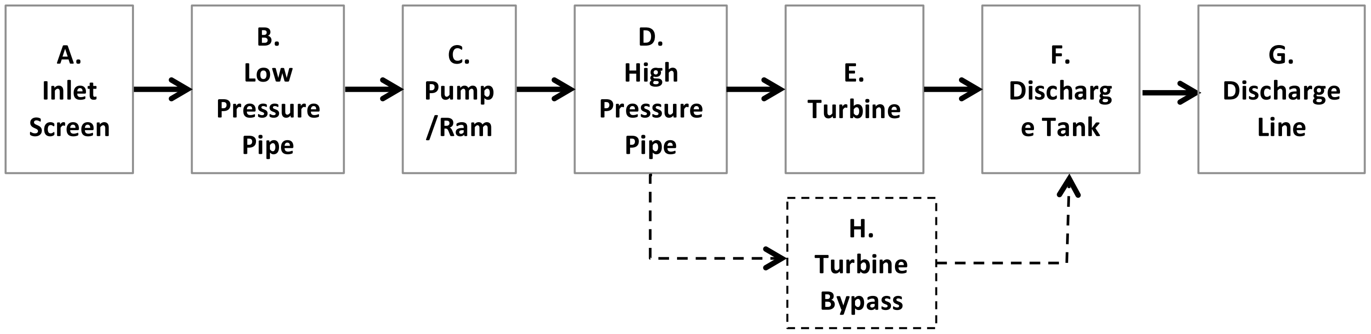


Figure 18. Box Diagram Showing Theoretical Layout of a Wave Power Device Using an Open Loop Seawater PTO system.

A. Seawater is drawn in through a mesh filter. Water flow through the filter is part driven by suction from the pump and part natural flow across the filter mesh.

B. Seawater travels from the inlet filter to the pump via a relatively short low pressure pipeline.

C. Wave action causes pump to draw seawater from the low pressure inlet pipeline and force it into the next pipeline at high pressure.

D. Pressurised raw seawater from the pump is carried through this relatively long (potentially offshore to onshore) high pressure pipeline towards a turbine.

E. Seawater from the high pressure line is forced through fine nozzles onto turbine blades.

F. Seawater draining from the turbine at low pressure is collected in the discharge tank awaiting return to the sea (in case of onshore generation).

G. The low pressure discharge pipeline carries seawater from the discharge tank to below the low water mark on the shore where it is released.

H. Turbine bypass exists to allow the system to be tested under operational conditions without involving the turbine and to allow pressure to be released from the system.

6.2 Potential for Biofouling in the System

Surfaces in contact with seawater, from ship hulls to power plant heat condensers will foul (Satpathy *et al.* 2010, Schultz *et al.* 2011). Biofouling will also occur within an open loop seawater PTO system, especially if mitigation methods are not employed. Given the wide range of conditions and materials, some areas may be more susceptible than others. The following section details the potential biofouling risks in all sections of the open loop seawater PTO system (Fig. 18) Detailed information on the flow rates, pipe diameters and pressures involved are not included as these details are specific to each system. Nevertheless, potential vulnerabilities and biofouling 'pinch points' are identified:

A – Inlet Screen

- Constant exposure to the open water means that this is perhaps the most vulnerable section of the system.
- All biofouling organisms and larvae passing in the current or drawn close by the action of the pump have the potential to settle and attach to the mesh screen.
- Seawater flowing past the screen will provide a steady supply of nutrients and oxygen, encouraging the growth of biofouling organisms that have settled (Woods Hole, 1952).
- The availability of light and relatively higher temperature if the screen is placed close to the surface of the water also provide conditions for algal growth.
- Depending on the mesh size, the screen will also be vulnerable to blockage by other natural and manmade material in the water column e.g. plastic bags or even jellyfish.
- The screen is likely to be highly vulnerable to larval settlement when the system is idle or with minimal water flow across the surface.

B – Low Pressure Pipeline

- The initial low pressure line is relatively open to the water column. The associated supply of fresh nutrients and oxygen in this section mean that larvae that have passed through the screen may attach here.
- Larval settlement could be an issue in this section during idle time, low wave conditions or when water velocity in the pipe is reduced.
- No light availability in this section means algal growth is highly unlikely.
- This pipe section is likely to have a constant oxygen supply, therefore anoxia and the development of SRB is unlikely.

C – Pump/Ram

- When in motion, the scraping action of the piston moving within the cylinder is likely to 'self clean' both piston and cylinder.
- The rapid pressure and flow changes within the cylinder as water is pumped into the high pressure line may serve to create a hostile environment, preventing settlement. Similar to the pressure pulse detailed above (Schaefer *et al.* 2010).
- The actual pressures generated will determine whether larvae are able to survive the pumping process or are killed outright. This will vary with each individual device.

D – High Pressure Pipeline

- When fully operational, high flow and pressures within the high pressure pipeline may prevent settlement and attachment of biofouling organisms. This is strongly dependant on actual pressures and flows generated in each device.
- During times of minimal water flow or idle periods, settlement and attachment of larvae within the pipe may occur.
- During idle times, closed valves at each end of the pipeline my cause water to be 'shut in'. This will force any aerobically respiring organisms in the line to consume the available oxygen, turning the system anoxic. This may serve to kill off biofouling organisms, however SRB may become problematic. SRB produce hydrogen sulphide, which can cause issues with corrosion on both metal and concrete surfaces as well as being toxic to humans.
- The time taken for anoxia to develop will depend on; volume of water, oxygen content, number and species of biofouling organisms and temperature. These factors will vary with each device, location and season.
- Any organisms that have settled and begun to grow in the pipeline during an idle period or those killed by anoxia may become detached by a sudden change in pressure/flow upon start-up. These could be swept towards turbine nozzles or valves, risking blockage.

E – Turbine

- Biofouling of the turbine itself is unlikely due to the water velocities and rapidly moving parts involved.
- Any organisms in the high pressure pipeline which may detach could enter the turbine much like 'grit', potentially causing wear.

F – Discharge Tank

- Spent water from the turbine will collect in the discharge tank, potentially allowing biofouling organisms to settle and grow in the tank itself. This may be a problem, especially if growth occurs around the turbine outlet and tank outlet vales, possibly restricting flow.
- A community of biofouling organisms in the discharge tank could produce larvae that are likely to settle in and contribute to biofouling in the discharge line.
- If not built with an airtight lid, the development of anoxia here is unlikely.

G – Discharge Line

- Water flow in this line will be at relatively low pressure and is likely to be at relatively low velocity. Both of these factors could lead to a high rate of settlement of biofouling organisms.
- An intermittent flow in the discharge line could replicate wave action on a rocky shore, creating a habitat suitable for mussels, barnacles and other shallow water biofouling species. Again this is highly dependant upon actual flow rates and would benefit from experimental investigation.
- If not capped with a valve, the sea based end of the discharge line could easily become fouled as seawater naturally washes in and out with wave action and tides, resembling a rocky shore environment. The constant supply of fresh seawater would provide oxygen and nutrients to a biofouling community.
- In an extreme case, the end section of the pipe may become severely restricted by the accumulation of biofouling organisms, causing water to back up towards the discharge tank.
- As with the high pressure line, anoxia could lead to an increase in the population of SRB and associated safety and corrosion risks.

H – Turbine Bypass Pipe

- To be used infrequently, the bypass line could become fouled when closed off and larval settlement occurs.
- When this line is closed off, anoxia could lead to an increase in the population of SRB and associated safety and corrosion risks.

7. BIOFOULING CONTROL IN AN OPEN LOOP SEAWATER POWER TAKEOFF (PTO) SYSTEM

If a wave energy converting device using an open loop seawater PTO system is to be built and deployed on a commercial scale, biofouling protection must be incorporated into its design. This should be based on the philosophy of '*Design in Discomfort*' i.e. the primary objective should be to make the system as 'unfriendly' or antagonistic to biofouling organisms as is possible without adverse impact on the surrounding environment. If this is achieved, the system should not only function more efficiently, but also require minimal maintenance and have a long service life ensuring maximum return on investment.

The aspects of the system that can be manipulated or modified in order to Design in Discomfort can be divided into four main categories (Fig. 19):

Physical – A change to any of the physical forces in the system, mostly associated with the forces influencing conditions on surfaces throughout the system e.g. pressure, velocity and volumetric flow rate. As a consequence of system shut-in (i.e. no flow), the development of anoxia in the system is included here.

Surface Chemistry – A change to the chemical properties of surfaces in the system that are in contact with the water e.g. applying a copper based coating such that the surface releases cupric ions to the water.

Bulk Chemistry – The addition of chemical doses to the water to change the environment within the system. Note that system shut-in could also be regarded as a bulk chemistry effect (i.e. the development of anoxia).

Mechanical – Scraping or other manual abrasive techniques to remove biofouling from a surface e.g. pigging or pressure washing.

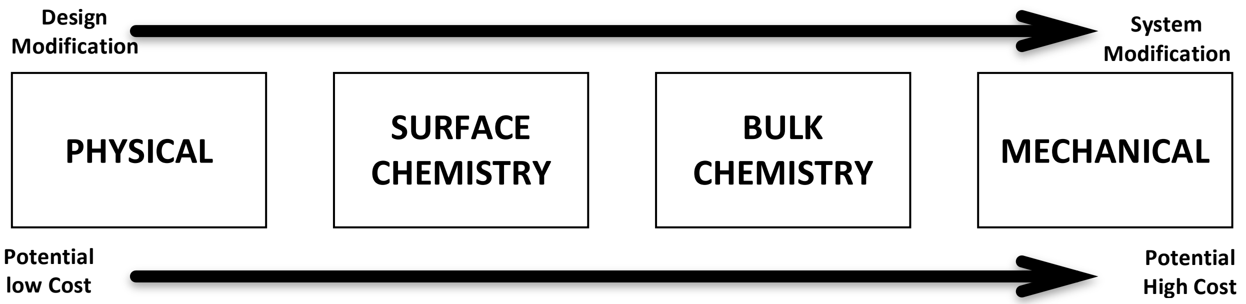


Figure 19. Diagram showing system design changes in terms of ease of implementation and cost.

The changes in these four aspects of the system range from subtle design modifications to significant system modifications, with associated impact on capital expenditure (CAPEX) and operational expenditure (OPEX) ranging from low to high cost. These terms are defined below:

Design Modification - The implementation of a design modification will discourage the establishment of biofouling organisms by changing the physical conditions at surfaces within the system. A low cost design modification, for example, would include the use of a smaller diameter high pressure pipeline. This would result in an, increase in velocity (physical), and make it more difficult for biofouling organisms to settle. However, such a change may reduce the overall generating efficiency of the system by increasing the resistance.

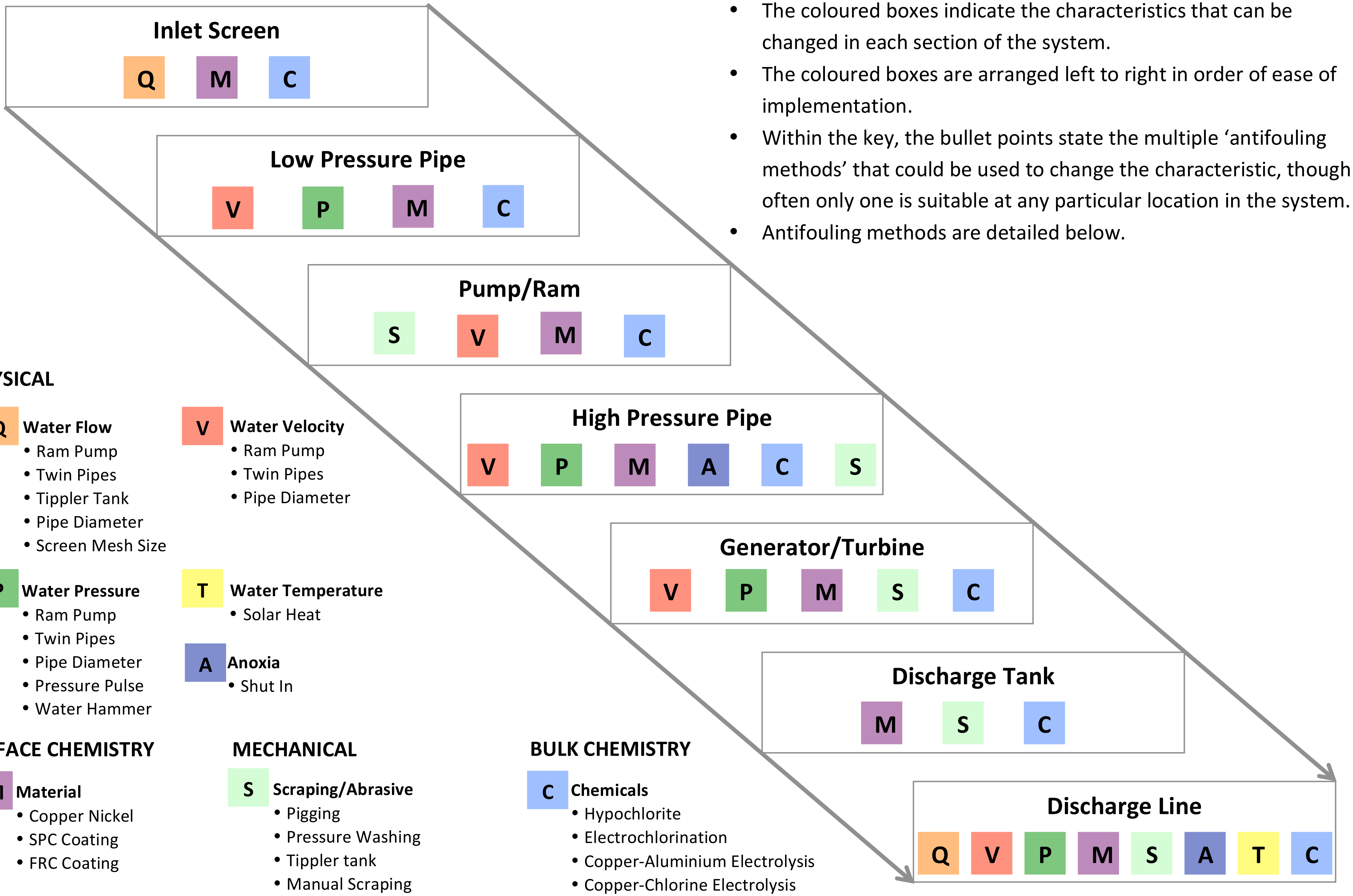
System Modification - The implementation of a system modification would require the likely expensive addition of specialised hardware for biofouling control. An example of high cost system modification would be the incorporation of a pig launcher and trap (mechanical) or a change to the system to incorporate a hypochlorite dosing system (bulk chemistry). The addition of a hypochlorite injection system would require a hypochlorite storage facility, computerised injection equipment, dedicated hypochlorite piping and injection nozzles, and a residual chlorine monitor in the discharge water. Various drawbacks of this system can include enhanced corrosion, and potential negative public opinion generated by the use of chemicals.

With more than one modification being applicable to each section of the system, there are multiple solutions and combinations available. Figure 20 illustrates possible combinations of antifouling methods within each section of the system.

'DESIGN IN DISCOMFORT'

Figure 20. Possible Combinations of Antifouling Methods in the System

- The coloured boxes indicate the characteristics that can be changed in each section of the system.
- The coloured boxes are arranged left to right in order of ease of implementation.
- Within the key, the bullet points state the multiple 'antifouling methods' that could be used to change the characteristic, though often only one is suitable at any particular location in the system.
- Antifouling methods are detailed below.



PHYSICAL

Q **Water Flow**
- Ram Pump
- Twin Pipes
- Tippler Tank
- Pipe Diameter
- Screen Mesh Size

V **Water Velocity**
- Ram Pump
- Twin Pipes
- Pipe Diameter

P **Water Pressure**
- Ram Pump
- Twin Pipes
- Pipe Diameter
- Pressure Pulse
- Water Hammer

T **Water Temperature**
- Solar Heat

A **Anoxia**
- Shut In

SURFACE CHEMISTRY

M **Material**
- Copper Nickel
- SPC Coating
- FRC Coating

MECHANICAL

S **Scraping/Abrasive**
- Pigging
- Pressure Washing
- Tippler tank
- Manual Scraping

BULK CHEMISTRY

C **Chemicals**
- Hypochlorite
- Electrochlorination
- Copper-Aluminium Electrolysis
- Copper-Chlorine Electrolysis

7.1 ANTIFOULING METHODS

The following describes some of the antifouling methods that could be used on an open loop seawater PTO system. The addition of the coloured boxes (above) show that one particular method may be able to change just one of the four characteristics of the system e.g. electrochlorination will only change the water chemistry. In comparison, some of the methods can influence two characteristics e.g. using twin pipes would change the physical conditions of the system. If the twin pipes were copper nickel lined, this could change the physical conditions, and surface chemistry of the system.

The philosophy of 'Design in Discomfort' should always be employed. Incorporating more of these methods into a particular design would serve to make colonisation by marine organisms more difficult and therefore create less suitable conditions for biofouling.

7.1.2 Physical Conditions

Twin Pipes (Discharge) V Q P A

Instead of one main large diameter discharge pipe, two smaller diameter pipes could be used to carry water from the discharge tank back to the sea.

Advantages

- In times of low water volume, outflow can be directed through one smaller diameter pipe increasing flow velocity making settlement less likely.
- One pipe could be closed off to 'go anoxic'; thereby killing biofouling organisms whist the other pipe can continue to be used for discharge.
- The pipe not being used could be cleared of biofouling by pressure washing or scraping by pigging.
- Both pipes would be available for use during peak times to carry larger volumes of water.
- Chemical free.

Disadvantages

- High CAPEX – Doubling of pipe in low pressure lines may be expensive, but less so than high pressure line.
- Development of anoxia in the closed pipe could lead to the build-up of hydrogen sulphide.

Open Discharge Channel V Q

Water from the turbine is discharged directly into an open culvert or 'manmade stream' leading back to the sea, removing the need for pipes. With no pipes, biofouling is likely to be less of an issue.

Advantages

- No specialised discharge piping is needed if an open channel is used.
- Chemical free.
- The open channel would allow easy monitoring of discharge water.
- If biofouling occurs, there is easy access for pressure washing or scraping.

- In times of low or no flow, the channel may dry out leading to desiccation of biofouling organisms.
- The open channel could be coupled with the tippler tank below.

Disadvantages

- Regulations currently demand discharge outlet below low water line.
- High CAPEX - The cost of constructing an open culvert may be high relative to installing a pipeline.
- An open channel will still foul.

Tippler Tank V Q

The turbine discharges onto a pivoting tank. As discharged water fills the tank, the tippler becomes heavier and at a certain point overbalances and empties, releasing a large volume of water to discharge line.

Advantages

- Chemical free.
- This is simple technology with minimal maintenance due to only one moving part.
- The irregular flow pattern and sudden rush of water along the discharge line may prevent biofouling or detach organisms in the early stages of settlement.
- The tippler tank system could be coupled with the open discharge channel above.

Disadvantages

- The tippler tank technology is untested in this application and intermittent flow may replicate seashore wave conditions, inadvertently encouraging growth.
- The water velocity may not be sufficient to deter settlement of biofouling organisms.

Ram Pump V Q P

Water collected in the discharge tank flows, in part, to the discharge line via a ram pump. This sends a high-pressure pulse of water along the discharge line to disturb settling.

Advantages

- Chemical free.
- Simple low maintenance pump technology.
- The intermittent pressure pulse down discharge line may discourage settlement of or detach existing biofouling organisms.
- The irregular flow pattern and sudden rush of water along the discharge line may prevent settlement of or detach existing biofouling organisms.
- This could be coupled with the open discharge channel above.

Disadvantages

- Ram pump technology is untested in this application and the pressure pulse created may not be sufficient to deter settlement of biofouling organisms.

Twin Pipes (High Pressure) V Q P A

A single larger diameter high pressure pipe leading from the ram/pump to the turbine would be replaced by two smaller diameter pipes.

Advantages

- Two narrower diameter pipes would carry water at higher velocity than a single larger diameter pipe, making settlement of fouling organisms less likely.
- In times of less wave action and thereby less water being pumped, one pipe could be used, whilst the other is closed off, maintaining high velocity in the active pipe.
- The closed pipe would be allowed to go anoxic to kill organisms or be cleared of biofouling by pressure washing or scraping.
- Chemical free.

Disadvantages

- High CAPEX – Increased cost of doubling pipe system and incorporating additional valves to allow switching of pipes underwater.

Water Hammer P

The rapid closure of valves in the system when there is a high rate of water flow would result in ‘water hammer’. Water hammer occurs when the flow of water changes abruptly and pressure increases suddenly. This could be done in any pipeline on the system that is fitted with valves and a ram-pump. The actual pressure pulse generated will depend on the water velocity, length of pipe and valve closure time. It is unknown whether the pressure pulse generated by a water hammer in the system would be sufficient to have an impact on biofouling organisms.

Advantages

- Chemical Free.
- Uses existing valves and pipework in the system, meaning no modification needed.
- Water hammer technology has shown promising results keeping fouling out of in experimental ultrafiltration systems (Broens 2012).

Disadvantages

- This technology is not tested in large commercial applications and the pressures generated are highly specific to the individual application and operating conditions.
- The application of a water hammer for antifouling requires further investigation and testing before being commercially applied.
- If the forces generated by the occurrence of water hammer are too great, damage may be caused to the pipes and valves in the system.

Pressure Pulse P

It is unknown whether the seawater pumping ram within the system will provide the same sort of ‘pressure pulse’ to water being forced into the high pressure line. It is also unknown whether a dedicated ram pump would provide a sufficiently large pressure pulse to have an impact on biofouling organisms at the discharge line. However, a piezo-electrical device has been developed which sends a pulsed pressure wave through the water to both deter settlement and kill attached biofouling organisms (Schaefer *et al*. 2010). A similar device could be incorporated into the system near the inlet screen and in the discharge tank.

Advantages

- Chemical Free.
- Electrical pressure pulse shows very promising efficacy against freshwater zebra mussel biofouling in trials.
- Reported to have lower CAPEX and OPEX (operating expenditure) than hypochlorite dosing.

Disadvantages

- The electrical pressure pulse system would require an electricity supply inside the pipework system increasing CAPEX and OPEX.
- Due to the size of electrodes needed, the electrical pressure pulse system is most likely to be unsuitable in narrower diameter pipes.

Anoxia A

Valves would be used to periodically close off pipe sections so that biofouling organisms present consume available oxygen and die through lack of oxygen. These could then be removed by scraping, pressure washing or by the water flow through the system when in normal use. This method could be used where twin pipe systems are installed or in low wave conditions when the system is idle.

Advantages

- Chemical Free
- Anoxia will kill all aerobic macrofouling and microfouling organisms.

Disadvantages

- Sulphate-reducing bacteria will thrive in the anaerobic conditions producing hydrogen sulphide. Pipes would have to be thoroughly vented to disperse the hydrogen sulphide safely before normal operation resumes.
- Closure time required to turn anoxic would depend on temperature, the volume of water in the system, and number and species of biofouling organisms in the system.
- The required closure time could range from hours to several days.
- Dead macrofouling organisms may detach from the pipeline causing blockages in valves or turbine nozzles.

Solar Heat T

Solar panels based on shore (perhaps at the turbine house) could be used to heat water from the discharge tank, which is released into the discharge line to kill organisms.

Advantages

- Chemical free.
- The heat shock is used to kill or retard growth in biofouling organisms.

Disadvantages

- It is unknown whether the volume of water would be too large for the required temperature to be achieved. (Suggested Treatment 40°C for 1hr to kill zebra mussels).
- High CAPEX – Installation of solar panels, pumping system and additional valves required to deliver hot water to the system.

7.1.3 Surface Chemistry

Fouling Release Coating (FRC) M

Commercially available FRCs commonly used to coat the hulls of ships could be used to coat the inside of both high and low pressure pipelines, the inlet screen, the discharge tank and discharge line.

Advantages

- The coatings are biocide free, reducing toxic residues in the water
- The coatings are reported to last up to 10 years on the hulls of ships.
- The FRCs have the lowest CAPEX of antifouling paints.

Disadvantages

- It may be impractical to recoat the inside of pipes once they are installed.
- The FRCs are ineffective in areas of low water velocity i.e. they may be unsuitable for discharge line.

90-10 Copper Nickel Alloy M C

Copper nickel alloy could be used to line the inside of the discharge tank or pipes in the system; this could be all the pipes in the system, or either the high pressure line(s) alone, or the low pressure line(s). The inlet screen could also me made from copper nickel instead of e.g. stainless steel (a common screen material).

Advantages

- Copper nickel has been shown to be highly successful at reducing the attachment of biofouling organisms.
- Copper nickel lined steel pipes are commercially available.
- Low maintenance therefore low OPEX.

Disadvantages

- Higher CAPEX than steel pipes.
- High CAPEX – It may be impractical to construct entire pipework system from copper nickel lined pipe due to high cost.

Self Polishing Copolymer (SPC) M C

Commercially available SPCs are commonly used to coat the hulls of ships. They could be used to coat the inside of both high and low pressure pipelines, the inlet screen, the discharge tank and discharge line.

Advantages

- Proven to be successful antifoulants on ship hulls.
- They last up to 5 years on ship hulls.
- The dual action biocide and low surface energy of the SPC prevents attachment in fast and slow flowing water.

Disadvantages

- Antifouling chemicals are released to the water.
- It may be impractical to recoat inside of pipes once installed.

7.1.4 Bulk Chemistry

Freshwater C

Rainwater or freshwater from a stream or other source could be collected on shore and then used to 'flush' the system periodically. The rapid change in salinity will kill many biofouling organisms.

Advantages

- Chemical Free
- The collection of rainwater would be possible where there is no access to mains water.

Disadvantages

- It is not known how long the freshwater would have to persist in the system for organisms to be killed (short exposure, e.g. rainwater into rock pools, has no detrimental effect on fouling organisms there).
- Collection and storage of freshwater could be difficult, depending on the volume of the system to be flushed.
- Permission would need to be sought to discharge fresh water into the sea

Electrochlorination C

An electrochlorination system could be used to generate chlorine on site to be piped along and injected into the system at the inlet screen, various points along the high pressure line, the discharge tank, and various points along the discharge line. Depending on the chlorine concentration, this will either deter settlement of, or kill biofouling organisms.

Advantages

- Commercially available electrochlorination systems are widely used.
- Hypochlorite can be fed constantly or pulsed into the system to provide continuous protection.
- Electrochlorination systems can be automated, requiring less human intervention.
- The OPEX is generally lower than liquid hypochlorite dosing as transport and storage of hypochlorite are not required.

Disadvantages

- Chemicals in use
- There would be a requirement for monitoring of excess chlorine in the discharge water, and permission would need to be sought to discharge into the sea
- Approximately 0.5mgl^{-1} of free chlorine is corrosive to steel and other construction materials, hence there may be corrosion problems.
- High CAPEX – The initial purchase of specialist generating and injection equipment could be high.
- OPEX – Electricity consumption can be high depending on water volume being treated.
- Studies show electrochlorination is not as affective as copper chlorine electrolysis.
- The use of toxic chemical dosing may attract negative public opinion and permission would need to be sought to discharge into the sea.

Copper-Aluminium Electrolysis C

An electrolysis system using copper and aluminium anodes could be used to generate cupric ions and aluminium hydroxide in seawater using a separate unit on site. This ion 'dosed' seawater could be piped along and injected into the system immediately inside the inlet screen, various points along the high pressure line, discharge tank and various points along the discharge line. Anodes could also be placed directly into the system to generate ions *in situ*.

Advantages

- There are commercially available copper-aluminium systems which are widely used.
- The electrolysis system can be automated, requiring minimal human intervention.
- If large anodes were used, they would take longer to erode, requiring less routine maintenance (lower OPEX).

Disadvantages

- Chemicals in use

- High CAPEX – The initial purchase of specialist generating and injection equipment could be high.
- OPEX – The electricity consumption of an electrolysis system might be high depending on water volume to be treated.
- Studies show copper-aluminium is less effective than copper-chlorine electrolysis.
- Permission would be needed to discharge the effluent into the sea

Copper-Chlorine Electrolysis C

An electrolysis system using copper and mixed metal oxide anodes to generate cupric ions and chlorine in seawater using a separate unit on site could be used. The ion 'dosed' seawater could be piped along and injected into the system immediately inside the inlet screen, various points along the high pressure line, discharge tank and various points along the discharge line.

Advantages

- Copper chlorine electrolysis uses 5-10 times less chlorine than conventional hypochlorite systems.
- Copper chlorine electrolysis is proven to be successful and is commercially available.

Disadvantages

- Chemicals in use
- High CAPEX – The initial purchase of specialist generating and injection equipment could be high.
- High OPEX – The electricity consumption of an electrolysis system can be high depending on water volume to be treated.
- Permission would be needed to discharge the effluent into the sea

Ozone C

An electrical system could be used to generate ozone on site which could be injected into the system immediately inside the inlet screen, various points along the high pressure line, the discharge tank and various points along the discharge line.

Advantages

- Constant feed and timed dosing of ozone can both be used.
- Ozone dosing is used in a variety of industries; most notable for microfouling control.
- Ozone dosing systems are commercially available.
- Ozone neutralises sulphide reducing the risk of toxic hydrogen sulphide production.

Disadvantages

- High CAPEX – Expensive initial purchase of specialist equipment.
- High OPEX – The electricity consumption of an ozone generator can be high depending on water volume to be treated.
- Excess ozone must be removed from outlet water as it is toxic.
- Ozone is corrosive and may cause damage to the system.
- Permission would be needed to discharge the effluent into the sea

Hypochlorite Dosing C

In this setup, an electrical system is used to dilute and administer bought-in hypochlorite to the system. Aqueous hypochlorite can injected into the system immediately inside the inlet screen, various points along the high pressure line, discharge tank and various points along the discharge line.

Advantages

- Hypochlorite is cheap.
- Hypochlorite can be constantly fed or pulsed into system to provide constant protection.
- Commercially available hypochlorite injection systems are widely used.
- Injection systems can be mostly automated, requiring minimal maintenance.
- Hypochlorite neutralises sulphide thereby reducing the risk from toxic hydrogen sulphide

Disadvantages

- Chemicals in use.
- High CAPEX – The initial purchase costs of specialist injection equipment and construction of a hypochlorite storage facility are likely to be high.
- High OPEX – The electricity consumption of an injection system can be high depending on water volume to be treated.
- Approximately 0.5mgl^{-1} of free chlorine from the hypochlorite would be corrosive to steel and other structural materials.
- Excess chlorine and chlorine by-products in the discharge water must be monitored.
- Permission would be needed to discharge the effluent into the sea.

7.1.5 MECHANICAL

Pressure Washing S

High pressure water could be used to remove biofouling organisms from the system. This would only be applicable where access is possible, such as at the discharge tank or perhaps the inlet screen (necessitating divers). If an open discharge channel were to be used, it could also be cleaned by pressure washing.

Advantages

- Chemical free.
- Pressure washing is simple to undertake (although it is more complex underwater).
- Washing can be carried out as and when needed.

Disadvantages

- Not all areas of the system are accessible to pressure washing.
- Washing could become expensive if dive teams are required to access submerged parts of the system.

Pigging S

Specialised ‘pigs’ equipped with brushes could be inserted into pipework to scrape the interior surface clean. These can only be used in pipes and are unsuitable for use at the inlet screen or discharge tank.

Advantages

- Pigging often employs simple technology which will remove biofouling effectively.
- Pigging is often a quick process, meaning minimal system downtime.

Disadvantages

- Specialised, expensive pig launch and trap sections are often required.
- The scraping action of the pig could damage a metal pipe liner or antifouling paint coating.

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APPENDIX 1 – Biofouling Organisms

Bivalve Shellfish

Blue Mussel (*Mytilus edulis*)

Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Hard Biofouling	Adults 5-10cm. Settling Juveniles 1-2mm	5-10m	5 - 20°C	Coastlines of North Atlantic Ocean from Russian White Sea to southern France.

Lifecycle

- Blue mussels have a partial spawning in Spring followed by another in late Summer
- Adults release 5 – 8 million eggs to the water column. Eggs are 60-90µm diameter.
- The eggs hatch to a ciliated trochophore larva.
- The trochophore larva becomes a veliger, persisting 4-6 weeks filter feeding in the plankton when it develops into the pediveliger settling stage.
- When approximately 260µm long, the pediveliger undergoes primary settlement at a location away from mature mussels.
- After several weeks the 1-2mm juvenile detaches to drift again in the water column to find a permanent substrate to which to attach.
- The young adult attaches to a substrate or other mussels using a strong byssus thread.

Biofouling Traits

- Blue mussels are commonly found on water inlet screens, harbour walls, piling, aquaculture cages, offshore wind turbine bases and existing wave power devices.
- Mussels attaching to other mussels, forming a mussel bed can lead to formation of growth more than 50cm deep.
- When mussels die the shells may detach and drift in strong currents, causing blockage of screens and tubes in hydraulic systems.

Barnacles

Acorn Barnacle (*Semibalanus balanoides*)

Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Hard Biofouling	Adults up to 15mm in diameter	Generally less than 100m. Common in the intertidal zone	Gonad maturation inhibited above 15°C. Mean monthly temperature must be below 7.2°C for successful reproduction.	Coastlines from Spitsbergen in the Greenland Sea to Northwest Spain.

Lifecycle

- Copulation takes place in the UK from November to early December.
- Fertilised embryos are held in egg sacs and incubated in the mantle cavity over winter by the adults.
- Nauplii larvae are released from the adult between February and April in synchronisation with the spring algal bloom. Hatching takes place later in the north and east of UK.
- Nauplii larvae develop in the surface waters for about two months. They pass through six nauplii stages before eventually developing into a cyprid larva.
- Cyprid larvae are specialised for settlement. Peak settlement occurs May to June in the east and north of UK.
- Barnacles cement themselves to substrate using a very strong glycoproteinous glue.

Biofouling Traits

- Barnacles are commonly found on water inlet screens, buoys, hulls of ships, piers and harbour walls.
- Adults grow densely packed on the substrate.
- Unlike mussels, barnacles not form thick communities. Growth rarely exceeds 30mm thick.
- They are extremely difficult to detach from a substrate once cemented in place.

Tube-building Organisms

Tube-building Amphipod (*Jassa falcata*)

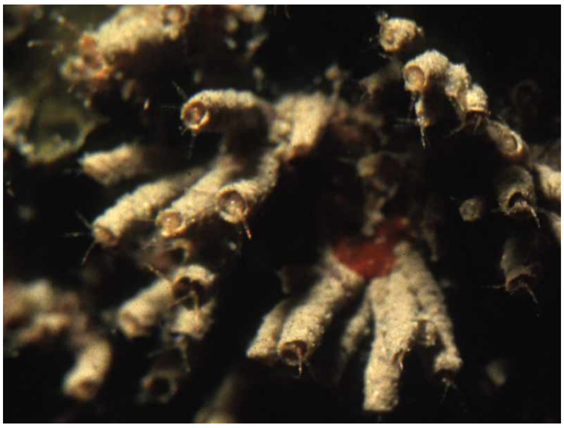
Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Hard Biofouling	Adults up to 13mm Long. Construct tubes 15-20mm long	Found to 490m	1.5°C - 24°C. Experiments show greatest numbers of offspring produced at 10°C.	Common around entire coastline of the UK

Lifecycle

- Mating occurs after the female amphipod molts.
- Embryos are brooded in a maternal pouch and the offspring hatch and crawl away to build a tube not far from their parents.
- Females spend their time within their tubes feeding, mating, and tending their young.

Biofouling Traits

- *Jassa spp*. are commonly found on hard structures such as rocky shores, piers and pilings. They are also found on buoys and the hulls of ships.
- They prefer areas of stronger current and good water flow which supplies oxygen and nutrition.
- Their tube dwellings are constructed from organic material collected from the surrounding habitat.
- Many tubes form large mats or nests, which contribute to biofouling. It is the presence of tubes rather than the organism that cause fouling issues.



Tube-building Organisms

Polychaete Tubeworm/Keel Worm (*Pomatoceros triqueter*)

Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Hard Biofouling	Adults 3.5mm wide and up to 25mm long	Found to 70m	Unable to build tubes below 7°C.	Common around coastlines from Northwest Europe to the Mediterranean

Lifecycle

- The males release primary spermatocytes and females release primary oocytes into the water column for external fertilization to occur.
- Once developed, larvae live a pelagic life for approximately 2-3 weeks in the summer. However, in the winter this time increases to approximately 2 months.
- Maximum settlement is observed in April, June, August and Sept-Oct.
- Once settled onto the substrate the worm forms a temporary delicate semi-transparent tube, which dissolves over time when calcareous material is added.
- The permanent tube is formed by a secretion of calcium carbonate (obtained from sea water).
- Growth is rapid and sexual maturity is reached in approximately 4 months.
- The adults never leave their tubes. They feed by using cilia to induce a small water current which transports food particles towards the mouth.

Biofouling Traits

- Keel worms colonise new or artificial substrates very quickly.
- They are commonly found on hard structures such as rocky shores, piers and pilings.
- They have little preference for fast or slow flowing water and survive well in both.
- In Bantry Bay, southwest Ireland, fouling by these tubeworms caused a 65% mortality of scallops and prevented scallops from recolonising the area after collection by fishermen (Burnell *et al.*, 1991).
- It is the presence of tubes rather than the organism that cause biofouling issues.

Bryozoans
Moss Animals

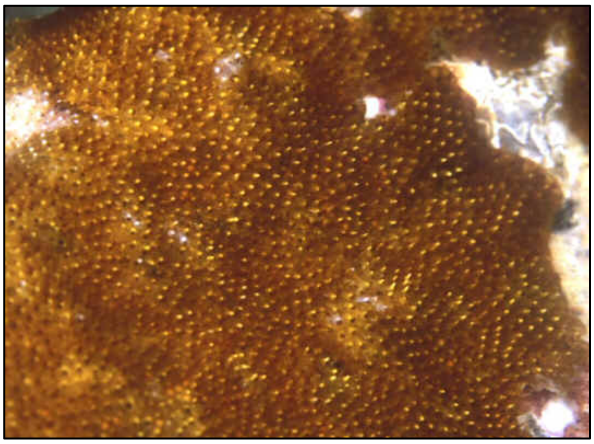
Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Hard Biofouling	Individual zooids approximately 1mm long. Encrusting colonies a few millimeters thick and approximately 10cm diameter Erect colonies may be up to 6cm high	Found to 100m	1.5°C - 24°C. Experiments show greatest numbers of offspring produced at 10°C.	Common around entire coastline of the UK

Lifecycle

- Following fertilization, larvae are produced and released to the water column.
- The planktonic larvae settle quickly, attaching to the substrate with adhesive sacs.
- Settled larvae then undergo metamorphosis to an adult individual or 'zooid'.
- Asexual budding of one zooid gives multiple clones forming a sessile colony of genetically identical individuals.
- The hard portion of the colony is made from chitin, polysaccharide or calcium carbonate which the organism lays down.

Biofouling Traits

- Bryozoans are commonly found on hard structures such as rocky shores, piers and pilings. Encrusting colonies are also extremely common on ship hulls.
- Bryozoans contribute to overall 'roughness' of a hull, having a profound effect on drag.



Hydroids

Common Flower-head (*Ectopleura larynx*)

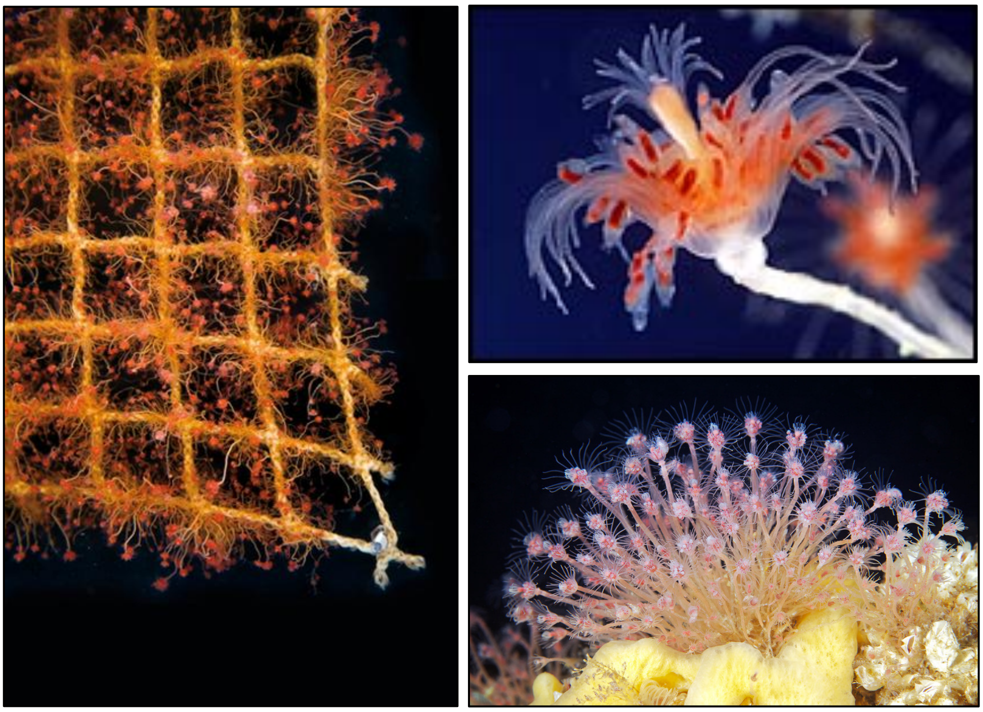
Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Soft Biofouling	Adults 40-60mm long	Found to 100m. Common in shallow waters.	1.6°C - 12°C.	Common around entire coastline of the UK

Lifecycle

- The adult ‘ringed tubularia’ consist of a bushy stem ending with a polyp with tentacles.
- Many ringed tubularia form a colony on a substrate.
- The ringed tubularia reproduce in two ways:
  - Small jellyfish-like organisms reproduce sexually while attached to the ends of the stems. New polyps hatch immediately out of the eggs produced.
  - The second manner is asexual: loose pieces of the colony are carried currents and can attach at a new location.

Biofouling Traits

- Hydroids are extremely common and problematic on aquaculture cages in Norwegian waters.
- They are also commonly found attached to mussel shells.
- Hydroids are rarely found alone. They are almost always found amongst other soft biofouling organisms in a complex community.



Sea Squirts

Light Bulb Sea Squirt (*Clavelina lepadiformis*)

Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Soft Biofouling	Individuals approximately 40mm long. Colonies 20-50cm diameter.	Found to 50m	1.6°C - 12°C.	Common around entire coastline of the UK

Lifecycle

- The adults release eggs and sperm into the water column for external fertilization.
- Approximately three days after fertilisation, eggs develop into free-swimming tadpole-like larvae.
- The larvae eventually settle and attach to a hard surface using an adhesive on the head.
- In 3-4 days, the tail, nerve cord and notochord from the larval stage are absorbed, leaving only a small mass of nerve tissue. The body and siphons develop quickly from this mass.

Biofouling Traits

- Sea squirts are commonly found in the subtidal zone on hard structures such as submerged rocks and pilings.
- They contribute to the overall ‘roughness’ of the hull of a ship, profoundly increasing drag.
- Spawning occurs in Summer, with growth dying back in Winter leaving a small bud that regrows the following year.

Sponges

Sponge (*Dysidea fragilis*)

Biofouling Type	Size Range	Depth range	Temperature Range	Distribution
Soft Biofouling	Encrusting forms 50cm diameter and 7.5mm thick Massive forms 30cm diameter and 50mm thick	Common in shallow waters.	1.6°C - 12°C.	Common around entire coastline of the UK

Life Cycle

- Sperm released by one sponge is caught by nearby sponges and fertilization of eggs takes place internally.
- Sponge larvae are released to the water column before settling on a substrate where they develop to adults.

Biofouling Traits

- The bodies of sponges clog filters and inlet screens easily.
- They are relatively easy to remove.

APPENDIX 2 - Glossary

Benthic	Organisms living on the bottom of the sea
Biocide	A chemical that destroys life by poisoning
Community	An assemblage of populations of two or more different species occupying the same geographical area.
Cyprid	Larval stage in the lifecycle of a barnacle
Diatom	Photosynthesising algae with a siliceous skeleton.
Eukaryote	An organism with a complex cell or cells, in which the genetic material is organized into a membrane-bound nucleus or nuclei
Gamete	A sex cell containing only one set of dissimilar chromosomes, or half of the genetic material necessary to form a complete organism. Male gametes generally called sperm. Female gametes generally called eggs.
Invertebrate	Animal species that do not possess or develop a vertebral column, derived from the notochord.
Life History	The sequence of events related to survival and reproduction that occur from birth through to death.
Meroplankton	Organisms that are planktonic for only a part of their lifecycle, usually the larval stage.
Pelagic	An organism living in open water, neither close to the sea floor or the shore.
Photosynthesis	The physico-chemical process by which plants, algae and photosynthetic bacteria convert light energy into chemical energy, which is stored as sugars.
Phototrophs	Organisms that carry out photon capture to acquire energy. Negatively phototrophic organisms avoid sunlight.
Phytoplankton	Microscopic plants which use chlorophyll to capture energy from sunlight for photosynthesis.
Plankton	The aggregation of passively floating, drifting, or somewhat motile microscopic organisms occurring in a body of water.

Protozoa	Single-celled eukaryotes that commonly show characteristics usually associated with animals, most notably mobility and heterotrophy.
Rosin	A solid form of resin obtained from pines and some other plants, mostly conifers.
Sessile	An organism that is fixed in one place; immobile.
Spore	A unit of asexual reproduction that may be adapted for dispersal and for survival, often for extended periods of time, in unfavorable conditions.
Surface Energy	The disruption of intermolecular bonds that occurs when a surface is created
Taxon	A taxonomic category or group, such as a phylum, order, family, genus, or species.
Yeast	Single-celled fungi of the phylum Ascomycota that reproduce by fission or budding