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Marine Renewable Energy Converters and Biofouling: A Review on Impacts and Prevention

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***Abstract*—In recent years, a number of studies have been performed to assess the damages caused by biofouling, which is simply the attachment of organisms to a surface in contact with water for a period of time. This explanation sounds fairly straightforward, but there are several organisms that cause biofouling, many different types of affected surfaces, and therefore many solutions dealing with this problem. Regarding the marine renewable energy emerging and promising area of research, this paper aims to provide a review of the biofouling issue in the context of Marine Renewable Energy Converters (MRECs). The proposed review will specifically highlight biofouling impacts on MRECs and solutions to prevent fouling. In addition, a discussion will highlight challenges that MRECs market needs to undertake to overcome the biofouling problem.**

***Keywords*—Marine renewable energy converters, biofouling, corrosion, microorganisms, marine environment.**

I. INTRODUCTION

Corrosion and biofouling have been impetus for investigating interactions between microorganisms and solid surfaces. This phenomenon is essential in a marine environment, where zooplankton is relatively diverse and abundant, but finds, although in smaller proportions, in freshwater environments. Marine biofouling can affect boat hulls, harbor constructions and piers as well as underwater engineering installations [1]. Fishing and fish farming are also affected, with mesh cages and trawls harboring fouling organisms. In Australia, biofouling accounts for about 80% of the pearling industry's costs [2]. Gold- and silicon-based components of micro-electrochemical drug delivery devices are susceptible to biofouling, as are machines in the papermaking and pulping industries and underwater instrumentation [3]. Minimally adhesive coatings are currently being investigated for use as fouling release coatings on marine equipment. The attachment of organisms to the ship hull can dramatically increase drag and therefore fuel consumption. A mechanically stable, non-toxic coating is desired to prevent the adhesion of foulants [4]. Organism groups that contribute to marine biofouling include seaweeds, bivalves, crustaceans and barnacles. Marine biofouling can be divided into two groups: *1)* Microfouling organisms and *2)* Macrofouling organisms.

A. Microfouling Organisms

Biofouling process is not as simple as it seems because the agencies do not stick on the substrate as a sucker. Indeed, the complex process often begins with the production of a biofilm. It is a film made of bacteria, such as *Thiobacilli* or other microorganisms, which forms on a material when conditions are right [5]. These organisms are primarily bacterial and microbial in nature and quickly colonize any substrate placed in seawater. They form part of a sticky coating commonly referred to as a biofilm. Biofilms are a considerable nuisance, accumulating in thicknesses sufficient to obscure marine surfaces and adding considerably to the difficulties of operating subsea. They also provide both a food source and a convenient interface to which the larger organisms, the macrofoulers, can adhere.

B. Macrofouling Organisms

The growth of a biofilm can progress to a point where it provides a foundation for the growth of seaweed, barnacles and other organisms [6]. Macrofoulers cause additional and even more severe problems for subsea operators. This grouping includes many larger animals and plants that may attach as individuals or in large colonies, such as barnacles, mussels, polychaetes, and various species of bryozoans and hydroids: Fouling and abrasive suspended particles growth [7]. When the biofouling growth is in contact with the marine renewable devices, it will affect wave machines more than submerged tidal systems. However, even at 5 m submerged depths, the tidal systems and in particular the rotor hubs (low-velocity parts) will be covered with fouling [8].

In this particular context, this paper aims to provide a state of the art review that highlight the biofouling phenomena; from its understanding to the prevention solutions with a focus on marine renewable energy converters.

II. BIOFOULING DEVELOPMENT MODES

Attachment and growth of living organisms on man-made immersed surfaces is a complex colonization process. In marine environment, any MREC could be colonized by bodies such as bacteria, diatoms, protozoans, algae and invertebrates [9-10]. Figure 1 summarizes the four sequences of a typical fouling installation process: Biochemical conditioning, bacterial colonization, installation of single-celled species, and installations of multicellular species [11].

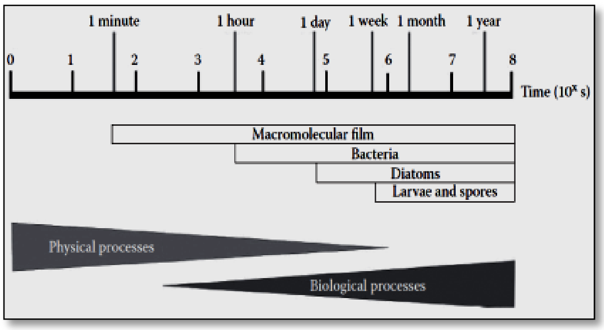
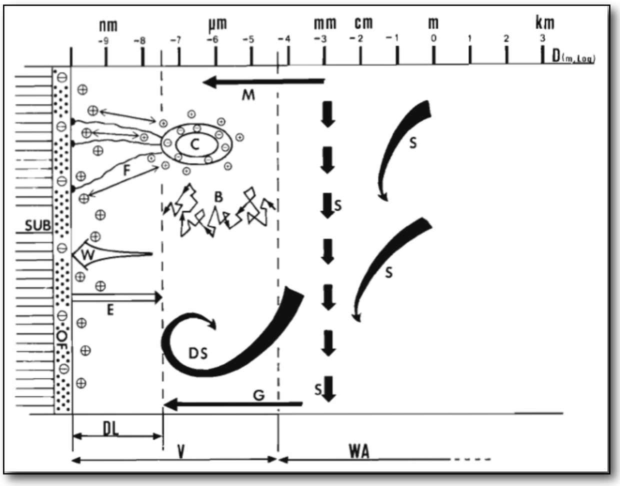


Fig. 1. Highly schematized colonizing sequence
leading to the establishment of a fouling community [9].

Biochemical conditioning describes the adsorption of dissolved chemical compounds (mostly macromolecules) to any surface in the first moments after contact with natural seawater. This instant (hereafter simply called “immersion”) may be the extrusion of a growing sea grass blade from its sheath, the appearance of a new crustacean carapace after moulting, the emergence of a fresh rock surface after breakage or the experimental immersion of a glass slide, etc. The concentration process of organic molecules at interfaces (solid/liquid, liquid/gas) is purely physical and “spontaneous” [12]. Bacterial colonization of the area consists of one reversible approach phase (adsorption) and an irreversible fixing phase (adhesion). At the first step in the sequence of colonization (biochemical conditioning) bacterial adsorption is mainly governed by physical forces: Brownian motion, electrostatic interaction, gravity, Vander-Waal forces [13-16]. When the two bacteria cells from surface, which constitute the adsorbed macromolecular film, are mainly negatively charged [17-19], the opposing repulsion and attraction electric forces tend to immobilize the cell at a distance of 15 to 20nm [20]. This electrostatic barrier may be filled by the production of polysaccharide fibrils (mainly of glucose and fructose). The establishment of covalent bonds between the bacterial glycocalix and macromolecular film pushes the adsorption phase to blend in an adhesion phase. Similar mechanisms have been described for yeasts [21], unicellular algae [22], spore [20], and polychaetes larvae (Fig. 2) [23]. The colonization by unicellular eukaryonts step includes the arrival of yeasts, protozoa and diatoms, with a clear quantitative dominance of the last one [24-26]. Benthic diatoms attach by the secretion of mucus [27-28] and densely cover the areas of broad substrate and contribute significantly to the chemical/biological evolution of the substrate. Subsequently, the colonizers protozoa feed of microorganisms (bacteria, yeasts, diatoms and other protozoa) [29].



B: Brownian motion; C: bacterial cell; DL: electrostatic double layer; DS: downsweep (microturbulence); E: electrostatic repulsion; F: bacterial fibrils anchored to adsorbed macromolecules; G: gravity (for a horizontal surface); M: bacterial motility; OF: organic film of adsorbed macromolecules; S: currents and macroturbulence; SUB: substratum; V: viscous boundary layer; W: Van-der-Waal's forces; WA: water body.

Fig. 2. Bacterial adsorption: dominating forces as a function of distance from the previously adsorbed macromolecular layer [11].

One to several weeks after immersion the substratum bears a highly differentiated and 3D structured microbiotic community. Several days to weeks after biochemical conditioning the last and longest phase of colonization, which is, colonization by multicellular eukaryonts, begins with the settlement of meroplanktonic larvae and algal spores. This overlaps with the continued recruitment and evolution of the microepibiotic community [11]. After these 4 successive stages, the community soiling evolves continuously by mechanisms such as disturbance, facilitation, inhibition, tolerance, etc. [30-31].

In summary, most of the mechanisms may be - and frequently are - combined to form a multifactorial antifouling adaptation, which effectively covers the range of potential colonists (Fig. 1).

III. Marine Renewable Energy Converters Performance Alteration

Biofouling proliferation concerns most artificial constructions in marine environment consisting in non-natural materials, such as treated wood, metal, glass, rubber, rigid plastic, concrete, or fiberglass. It is defined as unwanted growth on materials; in contrast, development and succession of befouling in some artificial reefs is wanted for marine fauna and flora.

In our context, it has been shown an increase in species abundance with increasing structural volume and complexity of artificial reefs [32-33]. For example, fouling on artificial structures can cause large economic costs by impairing equipment performance or life span [34].

Biofouling can easily cause obstructions in MRECs and/or increase the weight and drag, thus significantly affecting the device performance (Fig. 3) [35].

Wave power buoys floating on the surface may be heavily overgrown by epibiotic assemblages and this may, literally, become a technical burden. The dynamics and thus the buoys ability to extract energy from an ocean wave is determined by the size and shape of the buoy, the mass of the moving parts, together with the power take-off system [36]. Biofouling will change the mass of the buoy and the flow of water around the buoy.

Fig. 3. Colonization by mussels on protective structures of the Horn Rev offshore wind farm in Denmark.

It is therefore important to investigate how it will affect the energy absorption of a wave energy converter, and ideally, wave power buoys should be formed in a way that fouling has a negligible impact on performance [34]. Fouling may negatively affect buoy buoyancy and dynamics but also include the upper parts of the rope. The extra weight in temperate waters, mainly caused by mussels, e.g. Blue mussels (Bivalvia) and barnacles (Cirripedia) may be more than 10 kg/m^2 thus adding extra weight (Fig. 4), whereas algae more likely only will affect buoy dynamics and not its weight [37-39].

Two potential performance issues for marine current turbines are the roughening of the turbine blades due to impact, cavitation or scour due to particulates, and the fouling of the turbine blades by marine growth [40-41]. In this context, there is a clear need for high reliability given the difficult maintenance access issues in the underwater environment.

There have been few studies to investigate roughness effects or fouling on marine current turbines. In [42], potential effects of barnacles have been investigated. The lift and drag coefficients for an aerofoil covered with idealized barnacles of different sizes and distribution densities were determined using a wind tunnel. The lift to drag ratio decreased with both increasing barnacle size and distribution density. It was concluded that the presence of barnacles would have a detrimental effect on turbine efficiency. In [43], the potential effects of an increase in blade roughness or blade fouling using a numerical model have been investigated. It has been assumed that the presence of roughness or fouling would increase the drag coefficient by up to 50% [44]. Biofouling has been shown to reduce turbine blades efficiency and therefore decreasing the overall power generation [42]. Similarly, biofouling may decrease the power conversion rate for wave energy converters through added inertia [36]. Furthermore, biofouling may damage protective coating and interfere with sensitive areas necessary for monitoring and maintenance [45].

Fig. 4. Heavily fouled directional waverider buoy [38].

IV. BIOFOULING PREVENTION

In the case of marine renewable energy equipment, the adverse effects caused by the biological settlement (biofouling) are well known: High frictional resistance, due to generated roughness, which leads to an increase of weight and subsequent potential speed reduction and loss of maneuverability. To compensate for this, higher consumption is needed, an increase of the frequency of dry-docking operations, i.e. time is lost and resources are wasted when remedial measures are applied. A large amount of toxic wastes is also generated during this process [46-47], deterioration of the coating so that corrosion, discoloration, and alteration of the electrical conductivity of the material are favored [48], introduction of species into environments where they were not naturally present (invasive or non-native species) [49-50].

Since antiquity and until the beginning of the era of the great marine sail, large ships were severely disabled by Lepadomorpha and other marine organisms. To combat them, Phoenicians, Egyptians and Romans used several techniques: dubbing of the hull by a second shell in wood, copper or lead [51]. In addition to tars, first known recipes paintings protective and biocides were invented by the shipyards of a former navy sailing: Lime-based paints have initially been utilized [52]. At Christophe Colomb time, waxy coatings were used (mixture of pitch, tallow or other grease with the beeswax) [52].

Arsenic was then widely used in inorganic form [54]. Mercury and organomercury (long known as agricultural pesticides) have also been used by sailing ships [54].

From the beginning of the 18th century, it has been started using copper sheets nailed on the submerged parts of the shell of certain ships, which had the same effect more sustainably but more expensive. Cinnabar red and white lead (very toxic) could be added between the copper and wood, to effectively combat shipworms [52]. Tributyltin has been very used between 1960 and 1990 (almost all boats wore it during 1970 years [55]). Too toxic, it leaves place to copper salts (primarily Cu20). However the Cu20 is easily bioaccumulated [56]. Since 1990, diuron and irgarol are among the first alternatives to organotin compounds, but other alternatives were tested, including for example peroxides, which reacts with seawater to create hydrogen peroxide and very soluble metal ions in the water. Peroxides of strontium, of calcium, of magnesium, of zinc were therefore tested but they were found much less ecologically toxic, but often less effective, more expensive or less durable [56-57]. At this time, studies conducted in the USA on different types of vessels show that there are alternatives economically and environmentally acceptable, including for submarines or very large ships such as aircraft carriers, for example with the organometallic copolymers [58].

Among all the different solutions proposed throughout navigation history, tributyltin self-polishing copolymer paints (TBT-SPC paints) have been the most successful in combating biofouling on ships. The widespread use of these paints, estimated to cover 70% of the present world fleet in [59-60], has led to important economic benefits [46], [61].

Unfortunately, TBT-SPC paints affect the environment. In this context, numerous anti-biofouling measures such as mechanical, chemical, and biological methods are in practice but their effects on the biofouling are not remarkable. In addition, the commercially available antifouling paints such as tributyltin (TBT) and copper sulphate are highly toxic to the non-target aquatic organisms [62]. The TBT contributes to the development of antimicrobial tolerance and impose pseudo hermaphroditism in marine invertebrates [63].

In 1990, the International Maritime Organization (IMO) adopted a resolution recommending governments to adopt measures to eliminate anti-fouling paints containing TBT. In October 2001, IMO adopted a new international convention on the control of harmful anti-fouling systems on ships, which will prohibit the use of harmful organotins in anti-fouling paints used on ships and will establish a mechanism to prevent the potential future use of other harmful substances in anti-fouling systems [64]. After that, it was established that a good biocide for use in an anti-fouling system has the following characteristics: Broad spectrum activity, low mammalian toxicity, low water solubility, no bioaccumulation in the food chain, not persistent in the environment, compatible with paint raw materials, favorable price/performance [65].

Recently used anti-fouling techniques include methods based on the combined activity of copper ions and a booster biocide (e.g. diuron). However, these technologies have an effectiveness duration estimated between 2.5 and 5 years, which require shroud and cover at regular intervals [64]. In this context, electrochemical foul prevention was undertaken. Indeed, it is perceived to have lower environmental impacts when compared to biocide release coatings and have a much-increased operational life spans resulting from no consumption of coating based chemicals. Experimental validation of such a biofouling prevention approach has been undertaken at the Hatfield Marine Science Center and demonstrated minimal electrochemical parameter degradation. In addition, no algae growth was observed over the course of the testing time. This performance was identical to that of fresh, un-aged biocidal coatings (Fig. 5) [35].

All the above-cited anti-fouling new technologies are however still in test and there is not yet enough feedback to ascertain their environmental impact.

The main anti-fouling approaches are summarized in Table I.

V. CASE STUDY FROM OREGON STATE UNIVERSITY

In the context of MRECs, a critical issue is to evaluate biofouling impact on their different components/materials. Indeed, marine renewable energy devices are composed of several materials and each of them will have a different impact (Fig. 4).

For that purpose, the Northwest National Marine Renewable Energy Center of the Oregon State University has conducted a study from April 2009 to February 2010. In this context, several materials of a typical tidal energy installation have been immersed. In fact, material coupons, which might be used in the rotor, drive train, or foundation were deployed in the seabed.

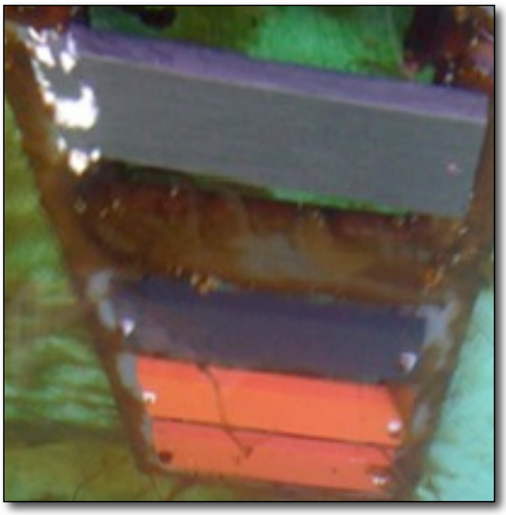


Fig. 5. From top to bottom: Aged electrochemical coating with applied power; Electrochemical coating with no power applied; Three fresh; Un-aged conventional biocidal coatings [35].

The test matrices consist of uncoated and coated coupons, nominally 6.35cm wide, 5.72 long, and 0.32cm thick. For expediency, coupons are attached to a fiberglass plate using a marine grade adhesive. Each plate is secured to the leg of an instrumentation tripod, as shown in Figure 6. The primary purpose of this tripod is to characterize the physical and biological environments at tidal energy sites [10].

A. Composite

1) Glass fiber composite. This composite material could be used for a MREC rotor, hub, or duct/shroud. In general, glass fiber composite performed well, with limited surface fouling after 10 months of deployment.

Fig. 6. Material samples attached to instrumentation tripod [10].

TABLE I. COMPARISON OF KEY ANTI-FOULING SYSTEMS [66].

Antifouling System	**Leaching Rate**	**Life Time**	**Erosion Rate**	**Cost (US $\$/\text{m}^2$) [67]**	**Problems**
(TBT) self-polishing copolymer paints	Chemical reaction through hydrolysis. Reaction zone of ablation 5μm deep	4 to 5 years [54]	< 3μm/month [68].	$680,884	Banned 2008 [69]
(Tin-free) self-polishing copolymers	Chemical reaction through hydrolysis of copper, zinc, and silyl acrylate	5 years	N/A	$1,382,670	Lifetime shorter then TBT-based paint systems; therefore increasing the ship maintenance overall cost
(Tin-free) conventional paint	10 $\mu\text{g/cm}^2$ d [70]	12 to 18 months	N/A	N/A	Hard non-polishing performance leads to coating build-up. Performance only suitable for low fouling environments [67].
Control depletion polymers: copper paint	Physical dissolution, soluble matrix.	3 years	Matrix erodes due to dissolution of coating binder.	$1,357,786	Biocide release not constant, poor self-smoothing, little activity during idle times, higher costs due to necessity of sealer coat on recoats [71]. Slow drying time [67].
Foul release	Low energy surface, leached silicone oils possible use [72]	2 to 5 years	N/A	N/A	In-water cleaning difficult as brushes may damage silicone, foul release coatings are prone to abrasion damage [73]

A barnacle adhered to the edge of one material coupon after 5 months (Fig. 7). In this case, it has been shown a general trend that biological fouling is more common on edges and in crevices than on smooth surfaces.

2) Carbon fiber composite. This composite material could also be used for a MREC rotor, hub, or duct/shroud. As with glass fiber composite, the carbon fiber composite developed minimal surface fouling after up to 10 months of deployment.

B. Aluminum

This material could be used for a MREC rotor. In this case, more than 90% of the exposed surfaces on all aluminum coupons were oxidized during each 3-4 month deployment, as shown in Fig. 8.

After 10 months deployment in marine environment, the surface is almost entirely oxidized and embrittled to the point that one corner of the coupon broke away during routine handling.

C. Stainless Steel

This material could be used for a MREC hub or shroud. In this case, the tested sample developed superficial corrosion along the contact surface between the stainless steel and the fiberglass panel, and a barnacle attached to one edge (Fig. 9). Other stainless steel hardware used to secure instrumentation to the measurement tripod developed more severe corrosion during some deployments. After three months of immersion, the bracket has been oxidized to a failure point (Fig. 10).

D. Steel

1) Common steel. This material is commonly used for a MREC support structure. In addition to bare steel, protection by a zinc anode screwed into the center of the coupon is tested. The surfaces of both coupons were almost entirely oxidized upon retrieval. Anodic protection reduced but did not eliminate oxidation (Fig. 11).

2) Structural steel. As with common steel, in addition to a bare surface, protection by a zinc anode screwed into the center of the coupon was also tested. The protection significantly reduced but did not entirely eliminate oxidation (Fig. 12).

Fig. 7. Barnacle attached to edge of glass fiber composite sample [10].

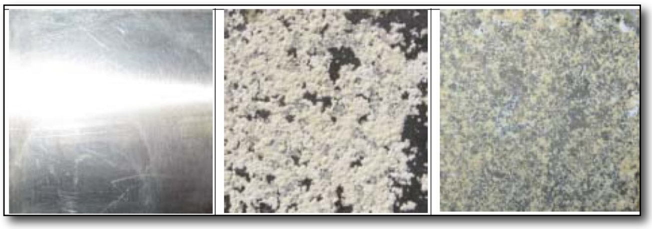


Fig. 8. Aluminum coupon corrosion [10].

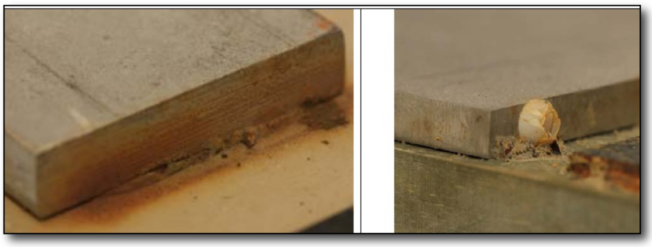


Fig. 9. Stainless steel edge corrosion and biofouling [10].

Fig. 10. Stainless steel bracket corrosion [10].

Fig. 11. Common steel coupon corrosion [10].

Fig. 12. Structural steel coupon corrosion [10].

E. Bearing Materials

Three types of potential bearing materials were tested in terms of operational biological fouling. High-density polyethylene experienced minimal surface and edge fouling. No fouling was visible on either fiber reinforced phenolic resin or low friction liner on stainless backing [10].

VI. CONCLUSION AND PERSPECTIVES

This paper has proposed a state of the art review that highlight the biofouling phenomena; from its understanding to the prevention solutions. A focus on marine renewable energy converters has been attempted even if the marine renewable energy conversion market is a slow-developing one with no effective tidal or wave installed farms [74-75]. In this context, it has been shown that there are several techniques for biofouling prevention/control that are well accepted as they are most least environmentally.

Research and promising assessments are still ongoing. In particular, tests are still ongoing to determine an effective and durable antifouling respecting the environment. Nevertheless, they remain significant aspects that should be taken into account in these tests. In particular, the numerous interactions that happen during the antifouling use. The environment, the engineered coating, and the substrate mainly cause these. Figure 13 summarizes the different interactions that must be taken into account.

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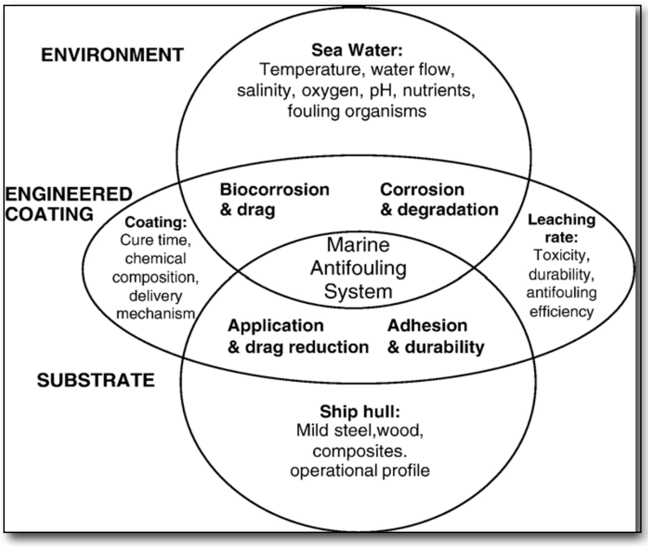

Fig. 13. Key interactive parameters affecting an antifouling coating system [76].

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