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Table of Contents

Evaluating organotin-free catalysts as EU-REACH compliant solutions for biocidal silicone-based marine coatings

Author/s: Anna Szczotok-Piechaczek, Jotun AS

Abstract: The EU-REACH (European Union's Registration, Evaluation, Authorisation, and Restriction of Chemicals) regulation prohibits the use of organotin compounds in products, including trace amounts such as catalysts, when combined with biocides. This regulatory requirement has created a significant challenge for the marine coatings industry, particularly in the formulation of silicone-based fouling-release coatings containing biocides. Traditionally, organotin catalysts played a crucial role in achieving the necessary balance between curing time and pot life, ensuring efficient application while maintaining coating performance.

This study focuses on solutions that comply with EU-REACH regulations while addressing the critical challenge of curing kinetics. Various alternative catalysts, including metal-based and organic compounds, were evaluated for their impact on curing speed, pot life stability, and overall coating performance. Key performance indicators such as curing time and temperature, pot life, and fouling-release properties were analysed to ensure that regulatory compliance does not compromise functionality.

The results demonstrate that organotin-free catalysts can effectively facilitate curing, maintaining the desired coating performance, and offer a promising path toward developing EU-REACH compliant fouling-release coatings.

Keywords: Organotin-free catalysts, Biocides, Silicone-based coatings, Fouling-release coatings

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Machine learning approaches to assess fouling on field samples

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Abstract: After short term deployment of model coatings or long-term deployment of panels in the field, assessment of fouling levels requires expert knowledge about local fouling communities due to high variances in phenotypical appearance, depends on the individual who is doing the assessment, has single-image sampling inaccuracies for certain species, and lacks spatial information. We established two different approaches for an automated analysis of microscopy or photographs, based either on object recognition [1] or on semantic segmentation [2]. If samples are immersed only for a short time, usually the diversity of attached species is limited, and a dominating species such as diatoms can be identified. Here, a highly efficient object recognition approach has been established that enables the quick and automated analysis of microscopy data. When immersion durations are longer, the diversity increases, and the accuracy of object recognition approaches start to suffer. To analyze panels after field exposure, an approach for automatic image-based macrofouling analysis has been developed based on semantic segmentation. A dataset with dense labels was established for field panel images and a convolutional network (adapted U-Net) for the semantic segmentation of different macrofouling classes was developed. The establishment of macrofouling localization allows for the generation of a successional model which enables the determination of direct surface attachment and in-depth epibiotic studies.

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Keywords: Macrofouling Analysis, Object Recognition, Semantic Segmentation, Successional Models, Epibiotic Studies.

Macro-Fouling on Biocidal and Non-biocidal Antifouling Coatings in the Arabian Gulf and the Sea of Oman

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Abstract: Biofouling is the major problem in all submerged surfaces in non-sterile environments. Although antifouling marine coatings have been used to limit or prevent biofouling, not much is known about their effect on the composition of micro- and macro-organisms in the Arabian Gulf and the Sea of Oman. The current study aims to investigates the effectiveness of different antifouling coatings in preventing biofouling on submerged surfaces in two distinct locations: the Arabian Gulf (Abu Dhabi, UAE) and the Sea of Oman (Muscat, Oman). The antifouling coatings tested included Hempaguard X7 (X7), Hempasil X3+ (X3), Dynamic 9000 (D), and Globic 9500M (G), with clean plastic panels used as controls. Panel photos were made at three intervals over one year: at the beginning (2 months), middle (7 months), and end (12 months) of the study. While all coatings reduced macrofouling, their performance varied.

The X7 coating was the most effective in both locations, with the least macrofouling observed. However, macrofouling growth was more pronounced in Abu Dhabi compared to Muscat. In Abu Dhabi, sedentary polychaetes dominated the biofouling community, while in Muscat, encrusting bryozoans were more common on control panels. Macrofouling began to appear on some of the coatings after 8 months, indicating that the coatings' effectiveness might decrease over time. Clear spatial and temporal changes in biofouling communities were observed at both locations. In Muscat, macrofouling was only recorded on the D and G coatings. These findings suggest that the differential performance of the coatings and variations in biofouling species can be attributed to several factors, including environmental conditions, the presence of different species, and the specific chemical and physical properties of each antifouling coating. This study highlights the complexity of biofouling and suggests that antifouling strategies may need to be tailored to specific marine environments for optimal results.

Keywords: Arabian Gulf, Gulf And Sea Of Oman, Antifouling Coatings, Field Studies, Antifouling Strategies.

Encapsulated biocides for long lasting, low impact anti-fouling coatings to meet coming legal requirements

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Abstract: Maintaining a clean hull is critical for the maritime industry, especially as IMO regulations increasingly demand lower carbon intensity. Meanwhile, rising environmental concerns, stricter coatings authorization, and tight regulations in key Asian markets have intensified the need to minimize biocide usage. The challenge remains: How can effective antifouling performance be achieved without excessive biocide application?

EnCoat ApS is a specialized R&D-based company that has developed patented silica encapsulation technology for improving the utilization of organic biocides while significantly minimizing the use of cuprous oxide in antifouling coatings. This technology is a biocide-specific solution, which uses sol-gel technology to produce a mesoporous silica aerogel shell with the active compound as a core, for controlling the leaching of the biocide from a coating into the marine environment. The most widely used co-biocides, including organometallic and organic compounds, that are approved or under review in the EU, have been encapsulated. The gel additive products have a high loading capacity (typically 75 w/w%). The low amount of inert encapsulation material (silica) used in the coating can minimize the surplus of the cuprous oxide by reducing the necessary amount of biocide with up to 50%. Pilot-scale production confirms that the encapsulated material can be produced at a larger scale without compromising quality.

In copper containing coatings it has been shown that cuprous oxide can be reduced by up to 50 w/w% when implementing encapsulated co-biocide. This technology has demonstrated robust antifouling performance in advanced binder systems — even at low biocide loadings with significant copper reductions. The next challenge is to reduce each co-biocide to a very low level (1 w/w%) and still achieve an acceptable antifouling efficacy. Combining low concentrations of encapsulated biocides may be a major step in meeting the Asian requirements under implementation. To develop functional coatings, it is important to maintain wet coating stability and dry coating film properties, which can be achieved by adapting already existing formulations.

This presentation will share examples of encapsulated material characteristics, new updated results for anti-fouling coatings (especially self-polishing copolymer antifouling systems) containing encapsulated material, including some coating properties, static tests and patch tests, and initial tests of a gel additive in fouling release coatings.

Keywords: Encapsulation, Silca Encapsulation Technology, Sol-Gel Technology, Mesoporous Silica Aerogel Shell.

Documenting and explaining how silica additives can reduce cuprous oxide in antifouling coatings to improve sustainability

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Abstract: Copper continues to serve as a robust deterrent against biofouling, despite being used in coatings at high loadings with less-than-optimal release rates. However, the excessive leaching from these coatings raises significant environmental concerns, as copper infiltrates marine ecosystems and disrupts their delicate balance. Regulatory pressures, the push for greener solutions, and cutting back on costs by minimizing cuprous oxide are driving the exploration of strategies to reduce copper emissions without compromising antifouling performance.

Cuprous oxide function is to protect the coating film against hard fouling through toxicity and polishing. When reducing the amounts of cuprous oxide - the polishing properties of the coating film must be kept intact.

A promising approach to reduce copper content in coatings includes the use of silica additives to optimize copper release and keep polishing rate. Therefore, there is a need for further research to understand these mechanisms and further develop the formulations without compromising the mechanical properties and fouling resistance of the coatings.

This study aims to better understand the impact of silica additives like aerogel-encapsulated co-biocides and fumed silica on the performance of coatings, while also examining the feasibility of reducing cuprous oxide loadings. The key seems to be to understand water absorption and distribution connected to cuprous oxide and silica, which plays a role in the hydrolysis of the binder system.

We use laboratory experiments, field testing, and material characterization on systematic series of coatings to unravel the influence of silica additives on polishing rates, cuprous oxide leaching rates, and overall antifouling efficacy. Hereby we show test examples of copper measurements, leached-layer formation, and static exposures of experimental coatings prepared with fumed silica or/and copper pyrithione-embedded aerogels.

Keywords: Copper, Cuprous Oxide, Silica Additives, Fumed Silica, Copper Oxide Leaching, Copper Pyrithione-Embedded Aerogels.

Biofouling in-water assessment with ROV and deep-learning based image recognition software

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Abstract: Biofouling growth on ship hulls significantly increases hydrodynamic resistance, leading to higher fuel consumption to maintain cruising speed. This, in turn, raises operational costs and contributes to increased greenhouse gas emissions. Additionally, biofouling in the shipping industry is a major vector for the spread of Invasive Alien Species (IAS), posing a serious threat to marine biodiversity.

To address these concerns, the International Maritime Organization (IMO) introduced a resolution in July 2023 regulating biofouling management on ships. A key requirement of this resolution is the periodic inspection of hulls to assess biofouling levels, to perform the cleaning process with the right timing. Currently, such inspections are primarily conducted by professional scuba divers, exposing them to potential risks. However, these inspections could be efficiently performed using robotic systems enhanced with artificial intelligence (AI) technologies.

Following a comprehensive literature review on in-water biofouling assessment, we evaluated sensing methods, movement control systems, and analysis software types. Our approach is based on a professional Remotely Operated Vehicle (ROV) equipped with a high-definition camera for piloting and as a sensing method, videos and images are then elaborated with image recognition software based on deep-learning.

To develop and train the deep-learning software for the image recognition software a database has been created containing archived images of samples from raft tests available at the CNR-IAS and images and video collected by the ROV data during missions conducted according to a standardized protocol.

The collected images were processed with an image editing software to generate segmentation masks, which were used to train neural networks to perform segmentation. The software runs on a server and is accessible via a web-based Graphic User Interface (GUI).

The software is based on a deep learning model that allows it to identify key areas for analysis and segment these areas into three categories: clear surface, soft fouling, and hard fouling.

After segmentation and classification, the percentage of each category is then reported to align hull inspection results with the IMO resolution ratings. Additionally, the software features a stitching function to create a comprehensive visual representation of the inspected vessel's hull.

Keywords: AI, Robotic Inspections, Remotely Operated Vehicle (ROV), Image Recognition Software-Based, Deep Sensing.

Efficient underwater removal of ship hull fouling using blue diode laser technology and an automated handling system (FoulLas²)

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Abstract: Biofouling on commercial shipping vessels remains a critical challenge, adversely affecting fuel efficiency, operational costs, and contributing to the spread of invasive species. Our research introduces a robotic cleaning system that integrates a blue laser diode as a direct emitter into a magnetic crawler platform. This system employs advanced process control strategies to enable precise, non-contact cleaning of hull coatings, thereby addressing the demands of the commercial shipping industry.

The blue laser module is engineered for direct emission, facilitating targeted irradiation that efficiently removes biofouling while preserving the integrity of protective coatings. The magnetic crawler ensures reliable adhesion and maneuverability over the geometries typical of ship hulls. Critical process parameters are meticulously optimized to accommodate a range of commercial coating systems and varying biofouling intensities.

Experimental validation is conducted on a simulation test rig comprising a floating raft equipped with modular test plates. These plates, each measuring 1 m x 1.20 m, are mounted on both sides of the raft and arranged to form a continuous test surface exceeding 6 meters in length. The system design allows for geometric modifications of the test bodies, providing a versatile platform for evaluating cleaning performance under realistic conditions. Experiments systematically assess the impact of varying biofouling stages, different coating systems (both commercial and experimental), and diverse process parameters.

Preliminary results indicate that the blue laser-based approach significantly enhances cleaning efficiency and mitigates the spread of invasive species. The process is non-abrasive, unlike many other cleaning techniques, and ensures that neither coating material nor residues from polymer-based brushes enter the ecosystem. Moreover, no additional water treatment is necessary, as the laser irradiation induces a time-delayed necrosis of the biofouling tissue, thereby enhancing biosecurity

Keywords: Robotic Cleaning System, Non-Contact Cleaning Of Hull Coatings, Cleaning Efficiency, Non-Abrasive, Laser Irradiation.

Regulating Hull Cleaning: A Commercial Perspective

Author/s: Karl Lander, Environmental Services Director Subsea Global Solutions

Abstract: As the value of clean hulls becomes more apparent to both vessel performance and management of invasive species, so too has the criticality of effective regulation at both the local and global levels. This presentation will highlight how the commercial hull cleaning industry is participating in, and reacting to, these regulatory advancements. Ongoing regulations, standards and best practices development at the IMO, ISO and AMPP will be discussed with a focus on how technology can both play a role within, and be hindered by, these standards.

A brief overview of emerging technologies will be shared as a background to the complexities involved in establishing regulations on topics such as hull grooming, capture, treatment, and autonomous operations. A case study on achieving compliance with New Zealand's mandated biofouling inspection program for short and long stay vessels will conclude the presentation.

Keywords: Hull Cleaning, IMO, Hull Grooming, Biofouling Capture, New Zealand.

Exploring Swelling Behaviour and Antifouling Properties of Highly Crosslinked Zwitterionic Polymers

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Abstract: Zwitterionic polymers have gained significant attention for antifouling applications due to their exceptional hydration and tunability of properties.[1] However, their inherent softness in the swollen state can lead to mechanical instability, limiting long-term durability in harsh marine and biomedical environments. Increasing crosslinking density while preserving high hydrophilicity offers a strategy to enhance mechanical robustness without compromising antifouling efficiency.[2]

In this study, zwitterionic poly([N-2-(methacryloyloxy)ethyl-N,N-dimethyl]ammoniopropane-1-sulfonate) (SPE) hydrogels were copolymerised with varying amounts (1 - 50 %) of the crosslinker 2-(4-benzoylphenoxy)ethyl methacrylate (BPEMA) to investigate their swelling behaviour and antifouling performance in different electrolyte conditions. The swelling response was primarily governed by the antipolyelectrolyte effect, where increasing salinity modulates electrostatic interactions within the polymer network. Even at crosslinker concentrations as high as 50%, which significantly restricted swelling, the hydrogels maintained excellent antifouling properties, effectively preventing marine organism adhesion. These findings highlight the potential of highly crosslinked zwitterionic hydrogels as durable, fouling-resistant materials suitable for applications in challenging environments.

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Keywords: Zwitterionic Polymers, Mechanical Instability Solution, Enhance Mechanical Robustness, Zwitterionic Hydrogels.

Paint leach rate screening method to shorten product development process

Author/s: Heleen Keustermans, Janssen PMP.

Abstract: ECONEA® (tralopyril) is a metal-free antifouling agent for use in marine antifouling coatings to prevent the growth of a wide range of hard fouling organisms on ship hulls, aquaculture nets, or other marine structures. As ECONEA® gains more and more market share, the number of product development projects from paint manufacturers is also increasing. A time-limiting factor for the development of new antifouling coatings is static and dynamic field testing to demonstrate sustained antifouling protection for extended periods of time. To pre-select the most promising candidate coating formulations eligible for time-consuming field testing, a comparative biocide leach rate test can be used at an early stage of development.

Existing ISO and ASTM methods describe a methodology for the determination of biocide leach rates from antifouling coatings. However, this method is cumbersome and time consuming and therefore limits the testing capacity. In addition, it is not easy to apply a test coating with a consistent film thickness to a cylinder. And finally, as ECONEA® rapidly degrades in seawater, quantitative analysis of leaching water for ECONEA® and its degradation products, is a complex matter. To overcome all these disadvantages, Janssen PMP has developed a modified, simplified method for leach rate measurements, allowing a large number of experimental coatings to be tested for leach rate in parallel with reference coatings with a known antifouling performance. Specific methods have been developed for both ship hull paints and aquaculture net coatings. An additional advantage is that, given the substantial increase in test capacity, test objects can remain exposed for multiple months, even years to investigate and compare the leach rate behavior over a long period. The ability to screen multiple test paints for their leach rates at an early stage in the research process has the potential to significantly shorten the overall product development timeline.

Keywords: Aquaculture, Antifouling coatingS, Biocide, ECONEA, Tralopyril, Hard fouling, Dynamic Field Testing, Leach Rate Measurement, Leach Rate Behaviour.

Advancing Marine Coating Formulations with Selektope®: Insights from Silyl Acrylate Systems

Author/s: Ida Friberg – (I-Tech AB)

Abstract: This presentation explores the integration of Selektope® (medetomidine) into silyl acrylate-based marine coatings to enhance antifouling performance. Selektope® is highly effective against barnacle fouling at very low concentrations (0.1% by weight), with a non-lethal, temporary, and reversible effect on barnacle larvae. Its unique mode of action involves stimulating the octopamine receptor in barnacle larvae, causing them to swim away and preventing settlement, with no risk of resistance development. The molecule is biodegradable and has been tested and approved in over 3,000 vessels and more than 30 commercial paints by leading paint manufacturers.

Silyl acrylate co-polymer (SAP)-based coatings are widely used as self-polishing coatings (SPCs) in marine antifouling applications. These systems rely on controlled hydrolysis in seawater to maintain a thin leach layer and consistent biocide release. However, the inclusion of Selektope® introduces challenges related to in-can stability, particularly gelation caused by the simultaneous presence of water, Selektope®, and metal ions (Zn^{2+}, Cu^{2+}). The root cause analysis reveals that hydrolyzed silyl acrylate polymers can crosslink in the presence of these ions, leading to gelation.

To address this, the presentation details formulation strategies to prevent gelation and ensure high in-can stability. Key approaches include minimizing water content in the wet paint, using water scavengers such as tetraethyl orthosilicate (TEOS) and para-toluenesulfonyl isocyanate (pTSI), and optimizing the order of ingredient addition. Adsorbing Selektope® onto carrier particles (e.g., ZnO, SiO_2) and maintaining low levels of polar and protic solvents further enhance stability. The adsorption and desorption behavior of Selektope® on inorganic pigments is influenced by the solvent, with non-polar, aprotic solvents favoring adsorption.

Experimental results from in-can stability testing demonstrate that the combined use of TEOS, pTSI, and hydrophilic silica significantly slows gelation. Field tests conducted on the Swedish West Coast confirm that coatings formulated with Selektope® and pTSI exhibit significantly reduced barnacle fouling compared to the control (containing no Selektope), with the biocide effectively released from the coating matrix.

The presentation concludes that stable, high-performance silyl acrylate-based antifouling paints can be achieved by minimizing water and free Selektope® content, employing appropriate scavengers and carrier materials, and optimizing formulation procedures. The successful commercialization of Selektope® in multiple SPCs, including silyl acrylate-based paints, underscores its value as a proven, efficient, and sustainable solution for marine biofouling control.

Keywords: Selektope, Medetomidine, Silyl Acrylate, Silyl Acrylate Co-Polymer, Barnacle Fouling.

Monitoring of antifouling copper in target marinas

Author/s: Kevin Long, Regulatory Compliance Limited

Abstract: In 2016, Member States developed a novel approach to assessing the environmental risk of biocidal antifouling yacht coatings, moving away from the generic MAMPEC OECD-EU marina scenario and adopting a probabilistic approach based upon multiple marina assessment per ecoregion (Baltic, Baltic Transition, Atlantic, Mediterranean). MAMPEC requires some 30 variables to define a marina, and it is generally understood that to obtain useful predicted results from MAMPEC many of those variables need to be correct.

Incorrect parameterisation of an individual marina may lead to misleading results that over- or under-estimate risk, which would jeopardise the principles of product safety assessment and the subsequent regulatory decision-making process. The Antifouling market is considered to be a mature market, such that the models should, to a large extent, reflect the current environmental pressures. In order to test this, site monitoring of copper levels has been undertaken in several of the marinas included in the new approach, the results of which are presented alongside predicted copper levels to provide an overview of the predictive capability of the multiple marina assessment approach.

Keywords: MAMPEC, Copper, Marina Assessment, Regulatory, Models, Copper Levels.

Microalgae as a Nutrient Source for *Amathia verticillata* Growth in Seawater: A Pilot Scale Study

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Abstract: Marine ecosystems are complex environments where various organisms interact to maintain ecological balance. Among these organisms, bryozoans, such as Amathia verticillata (BAV), play a crucial role in biofouling formation. The availability of suitable nutrient sources is a key factor influencing the proliferation of BAV, particularly in raw seawater. The primary growth factor for BAV is the availability of microalgae, which serve as a critical nutrient source. Microalgae provide essential organic compounds, such as carbohydrates, lipids, and proteins, which support the metabolic requirements of BAV. This study aims to evaluate the effectiveness of different microalgal species in promoting the growth of BAV in seawater by conducting batch-scale and pilot-scale experiments.

A series of batch-scale experiments was conducted using microalgal species Picochlorum, Phormidium, a combination of both (Picochlorum and Phormidium), and a mixed culture containing Chlamydomonas reinhardtii, Picochlorum, Phormidium, and sludge. Each of these microalgae was individually cultivated with BAV for a period of 16 days to evaluate growth performance and nutrient uptake efficiency. To facilitate BAV attachment, carbon steel coupons were introduced, and a concentrated microalgae biomass (50 mL) was supplied as a nutrient source daily to maintain a concentration of 0.5 g/L. Among studied microalgal species, Picochlorum demonstrated higher growth and adaptability under high salinity conditions. In addition, the results indicate that Picochlorum effectively utilized nutrients from seawater. The removal efficiencies of total organic carbon (TOC), total nitrogen (TN), sulfates (SO_4^{2-}) and chlorides (Cl-) were 77%, 67%, 32% and 55%, respectively. In contrast, C. reinhardtii, Phormidium, and the mixed culture exhibited limited growth under the same high-salinity conditions, indicating lower effectiveness as a nutrient source for BAV.

Following the results from batch experiments, a pilot-scale investigation was conducted in a 55L open tank system over a period of 30 days using Picochlorum to support BAV growth. Carbon steel coupons were introduced for BAV attachment, and 1.4L of well-grown Picochlorum culture was daily supplied as a nutrient. The removal efficiencies of TOC, TN, chloride and sulfates in seawater was 66%, 63%, 28%, and 42%, respectively. Furthermore, the BAV and algae cell quantification were measured using a Flow Cytometry (FCM) providing further evidence of BAV proliferation when supplemented with Picochlorum as a nutrient source. The study identifies Picochlorum as a nutrient source for BAV in raw seawater at a pilot scale.

Keywords: Bryozoan Amathia Verticillata (BAV), Microalgae, Picochlorum, Phormidium, Chlamydomonas Reinhardtii, Flow Cytometry, Seawater, Nutrient Removal.

Sustainable Hull Maintenance Strategies and decision support tool HullMASTER (Hull MAintenance STrategies for Emission Reduction) - Case Studies of RoPax Vessel routes in Baltic Sea Region

Author/s: Lena Granhag (1), Youngrong Kim (1), Maria Lagerström (1), Erik Ytreberg (1)

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Abstract: The decision support tool HullMASTER (Hull MAintenance STrategies for Emission Reduction) assess the life cycle costs of different hull maintenance strategies for different vessels and trades. The HullMASTER tool include ship characteristics as well as environmental conditions. The Baltic Sea is an unique maritime environment with a large salainty gradient, where is can be challenging to determine optimal maintenance strategies. To illustrate the use and outcome of HullMASTER we in this study examplify by RoPax routes in different regions/ with different salinity, within the Baltic Sea Area.

Findings indicate that optimal hull management can save operators up to €9.3 million and reduce socio-environmental damage costs by €7.9 million over ten years compared to a less proactive baseline. Notably, biofouling pressure decreases from the high-salinity Skagerrak and Kattegat to the low-salinity Baltic Proper, emphasizing the need for tailored maintenance strategies. Among the coatings analyzed, non-biocide foul-release coatings are the most sustainable choice, reducing emissions to the ocean and the atmosphere. These findings will provide practical guidelines for sustainable hull management strategies, contributing to enhanced operational efficiency and marine environmental protection.

Keywords: HullMASTER, Life Cycle Costs, Baltic Sea, Coatings Analysis, Practical Guidelines, Hull Management

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Relevance of the hydrolysis state of silyl(meth)acrylate-based coatings on their antifouling performance

Author/s: Louisa Vogler (M.Sc.) and Axel Rosenhahn, Ruhr University Bochum, Germany

Abstract: Self-polishing copolymers (SPCs) have been widely used to overcome the detrimental ecological and environmental effects caused by marine biofouling on man-made surfaces.[1] Among the different polymers used in SPCs, trialkylsilyl (meth)acrylates are one of the most prominent hydrolyzable compounds in binders.[2] As shown previously for hydrolyzable copolymers containing methyl methacrylate (MMA) and triisopropylsilyl acrylate (TiPSA), the attachment of the marine diatom Navicula incerta was reduced after being pre-leached for 3 days, while nearly no reduction was observed for the bacterium Pseudomonas sp.[3] As these results suggest that the hydrolysis state of the TiPSA may be linked to the reduction of microorganism attachment, we performed a systematic study of a TiPSA-based homopolymer coating and thoroughly characterized the hydrolysis state at the water-polymer interface. Therefore, we used various surface analytical techniques including infrared spectroscopy as well as sessile droplet and captive bubble water contact angle goniometry. In addition, dynamic attachment assays with the marine diatom Amphora sp. and the marine bacterium Cobetia marina were carried out. We found that the hydrolysis state and the associated change in wettability due to surface hydrolysis have a decisive influence on the water absorption capability of the coatings and revealed that the hydrolysis state severely impacts the antifouling performance of the binder against both organisms.

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Keywords: Trialkylsilyl (Meth)Acrylates, Binders, Hydrolyzable Copolymers, Tipsa-Based Homopolymer, Antifouling Performance.

Study of the marine antibiofouling impact of TiO2 and Ti-Cu-O films deposited by aerosol assisted chemical vapor deposition

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Abstract: Current antifouling measures are mainly based on the more or less controlled release of biocides. They have major drawbacks. The most worrying of these is their ecotoxicity [1]. They are harmful to non-target organisms [2]. The development of light-induced catalytic coatings is a promising alternative. It is more environmentally friendly. TiO2 and Ti-Cu-O films with a Cu content of 16% M Cu/(Cu+Ti) are deposited by aerosol-assisted metal organic chemical vapor deposition (AAMOCVD). The surface topography of TiO2 films is characterized by the formation of microflower-like structures with nanometric petals that induce a high specific surface area. These surface characteristics are not present in Ti-Cu-O films.

Nevertheless, the latter exhibited strong photocatalytic activity in the degradation of Rhodamine B. A leaching test in seawater over 36 days showed a release of copper (Cu) of 0.14 µg cm-2 day-1 an amount considered to be low and in line with standards. The study focused on the effect of these films on the adhesion and maturation of a biofilm of a biological model representing the adhesion of marine bacteria, Vibrio harveyi (DSM19623). The results show a photobiocidal effect of TiO2 films illuminated with visible light on 69% to 82% (for structured TiO2 films) of the adhered bacteria. These TiO2 films also inhibited biofilm formation by 85%. Ti-Cu-O films showed a 64% inhibition of bacterial adhesion compared with TiO2 films with or without the microstructures, in addition to their photo-biocidal effect when illuminated with visible light on 69% of adhered bacteria. In the absence of visible light, a biocidal effect of the Ti-Cu-O films was obtained on 20% of the adhered bacteria. This result is related to the release of copper during the adhesion process. This provides a continuous biocidal effect, even in the absence of light.

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Keywords: Antifouling, TiO2 films, Ti-Cu-O, Photocatalytic Activity, Photo-Biocide.

Investigation of critical copper release rates in European coastal waters

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Abstract: A given antifouling biocide will only be effective against its target(s) so long as its release rate does not fall below the minimum required to prevent their settlement, also known as the critical release rate [1]. Cuprous (I) oxide is the most frequently employed biocide in antifouling coatings today and acts to inhibit fouling through the release of copper ions [2]. A critical release rate for copper of 10 μg cm-2 day-1 is often referenced in the literature but originates from a study in Atlantic waters carried out 75 years ago [3]. More recent studies indicate however that the critical release rate may vary between different coastal waters and be well below 10 in some areas, such as the Baltic Sea [4].

In this study, the critical release rates of copper from antifouling coatings to inhibit macrofouling was investigated in European coastal waters, with study sites in Atlantic (Arcachon, France), Kattegat (Hundested, Denmark) and Skagerrak (Tjärnö, Sweden) waters. The efficacy of various antifouling coatings with differing copper contents (from 6 to 32 wt%) and their release rates were evaluated during a six-month field study, employing a combination of visual inspection and X-ray Fluorescence (XRF) analysis. The aim of the study was to determine the critical release rate of copper to deter macrofouling organisms at each site and to investigate whether it differs depending on the composition of the local fouling community.

The findings of this study indicate that a release rate of 7 μg cm-2 d-1 was sufficient to inhibit macrofoulers at all three sites during static conditions. Results also indicate that the critical release rate is a parameter that coating manufacturers can optimize, as the performance of the coatings was not solely dependent on the copper release rate. A release rate of 7 μg cm-2 d-1 could serve as a benchmark for dose optimization of coatings for both the yacht and ship sectors to reduce their environmental impact.

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Keywords: Copper, Cuprous Oxide, Critical Release Rates, Macrofouling, Field Study

Project 0: comparing the impact of fouling on 6 different fouling control systems

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Abstract: In this work we evaluated the impact of hull fouling on sailing performance, conducted for Foundation 0 as part of the design process for SY Zero—a 70-meter fossil fuel-free sailing yacht. Given that this vessel primarily relies on wind propulsion, minimizing resistance is crucial. To assess the effects of hull fouling and explore potential mitigation strategies, we conducted a study that focused on testing the antifouling effectiveness, surface characterization, and friction resistance of six different fouling control systems. Drag measurements of different coating systems showed variations of approximately 100% at the model scale. When scaled up using the Granville method, the increase in drag was even more pronounced. Two type of coatings demonstrated superior performance in this investigation excelling in both efficacy and drag performance.

Keywords: Hull Fouling, Sailing Yacht, Antifouling Coatings, Granville Method, Drag Measurement.

Applying Multi-Criteria Decision Analysis (MCDA) to Evaluate Sustainable Biofouling Alternatives in Norwegian Sea-Based Aquaculture

Author/s: Marina Hauser (Miljøstiftelsen Bellona), Rakib Ahmed (Sintef Manufacturing), and Paritosh Deshpande (NTNU).

Abstract: Biofouling presents a significant challenge in marine aquaculture, reducing water flow, lowering oxygen levels, impairing feed intake, and facilitating pathogen spread. To mitigate biofouling, various antifouling strategies are employed, with copper-based biocidal coatings on nylon nets being the most common. Since 2017, the organic biocide tralopyril has also been used in Norwegian aquaculture. Additionally, biocide-free alternatives exist, including silica-based hydrophobic coatings and uncoated high-density polyethylene (HDPE) nets. However, while biocide-based coatings raise toxicity concerns, biocide-free options require more frequent cleaning, leading to higher operational costs and environmental risks due to microplastic release from pressure washing. Consequently, the sustainability implications of antifouling strategies remain unclear.

The study aims to address this decision dilemma by conducting a comprehensive sustainability assessment of available antifouling coatings, supporting Norwegian aquaculture stakeholders in selecting sustainable alternatives. The study was conducted as part of the project "Circular and Environmental Effects for Aquaculture Nets," funded by the Norwegian Retailers Fund.

A Multi-Attribute Value Theory (MAVT) approach was applied due to its capacity to integrate stakeholder values and incorporate both qualitative and quantitative data. The MAVT framework is a method within the spectrum of Multi-Criteria Decision Analysis (MCDA) and included six structured steps: (1) defining antifouling alternatives, (2) identifying evaluation criteria, (3) weighting criteria through stakeholder input, (4) assessing alternative performance, (5) ranking alternatives, and (6) conducting a sensitivity analysis.

Expert stakeholders from the aquaculture industry, equipment manufacturers, net repair and recycling facilities, and academic researchers participated in defining alternatives and selecting the assessment criteria. Four antifouling strategies were compared: (i) inorganic biocide-based coating (copper-based), (ii) organic biocide-based coating (tralopyril-based), (iii) biocide-free coating (silica-based), and (iv) no coating (pure HDPE nets). These alternatives were evaluated against environmental, social, economic, and technical criteria. Weighting was determined via stakeholder surveys and interviews, where technical performance (32%) was ranked highest, followed by environmental (30%) and economic (29%) sustainability. Social sustainability was considered less critical (9%) by the expert stakeholders. Impact assessment of the four alternatives across selected assessment criteria was done through field visits and literature data and finally the scores were analyzed using DECERNS software to determine the final ranking.

The results indicated that inorganic biocide-based coating (copper-based) ranked highest, emerging as the preferred alternative. Biocide-free coating (silica-based) followed in second place, while uncoated HDPE nets ranked third. Organic biocide-based coating (tralopyril-based) received the lowest score, making it the least preferred alternative. However, the differences between alternatives were modest, and minor adjustments in weighting or the inclusion of additional criteria could alter the ranking. Sensitivity analysis revealed that increasing the weighting of environmental sustainability above 60% would shift organic biocide-based coating (tralopyril-based) to the top rank while lowering inorganic biocide-based coating (copper-based) to the bottom.

A key limitation of this study was the availability of data, which restricted the inclusion of certain sub-criteria and underscored the need for further research to enhance the accuracy for evidence-based decision-making. Despite this limitation, the study provides valuable insights to assist stakeholders in selecting sustainable antifouling strategies and advancing circular economy practices. By integrating environmental sustainability, economic feasibility, and technical performance, these findings support more informed decision-making in aquaculture. This research represents one of the first systematic comparisons of net coating sustainability, establishing a foundation for future studies and practical decision support in the industry.

Keywords: Aquaculture, Tralopyril, Copper, DECERNS Software, Fish Nets, Antifouling

Microplastics released from antifouling coatings: comparison of coatings and evaluation of release mechanisms

Author/s: Matthias Bork, Soren Kiil, Kim Dam-Johansen - CoaST, Department of Chemical and Biochemical Engineering, DTU

Abstract: Recent microplastic surveys suggest that antifouling coatings are likely a significant source of microplastics. Among the various antifouling microplastic release pathways, release during sailing has been highlighted as a largely unknown pathway. To evaluate this pathway, an experimental methodology was developed where antifouling coatings were exposed to relevant environmental conditions and the microplastic release was monitored. This study builds on a methodology presented by researchers at RISE, with a few critical modifications such as increased sailing speeds up to 3.2 knots and reduced particle counts in control measurements. The released particles were analyzed for concentration, size and composition using an improved automated SEM/EDX methodology.

Using the measured particle size and concentration data, the proportion of the polishing rate attributed to particle loss was estimated. Different coatings were compared based on this contribution to the polishing rate.

It was found that self-polishing and controlled depletion polymer coatings both released significant amounts of particles. In contrast, particle counts from fouling release coatings was comparable to the control measurements.

Further investigation into this is planned for this year. Particles were generally described as fragments of 1-20 µm circle equivalent diameter. The median particle size increased with the exposure time of the coating, indicating that larger particles are released as the leached layer develops and/or smaller particles agglomerate over time. However, the particle size and shape observed under SEM/EDX do not necessarily reflect the size and shape the particle had in suspension, or how it was released from the coating. For example, a 20 µm particle likely does not leave the coating as a spherical particle, leaving a 20 µm gap behind. It is more likely that it peels off in thin fragments from the uppermost soluble pigment-leached layer of the coating. This is supported by the observation that the microstructure of the majority of particles was similar to that of the leached layer, when observed through cross-sectional evaluation. Furthermore, the thickness of the particles was observed to be around 1-2 µm for the majority of particles with a 1-20 µm circle equivalent diameter, further supporting this microplastic release hypothesis.

Keywords: Microplastics, Polishing rate, Leaching, Coatings

Evaluating Ultrasonic Antifouling Technology: Effectiveness Against Biofouling and Potential Impact on Marine Mammals

Author/s: Micaela Machado Querido, Pernille Bohn, Torben Madsen,, Rémi Maguet (DHI, Hørsholm, Denmark)

Abstract: Biofouling on ships may lead to major economic costs, due to increased fuel consumption, decreased speed or damages to parts of the vessel relying on free flow of water. Furthermore, the transfer of non-indigenous species can lead to biodiversity loss and disruption of ecosystems.

Antifouling coating is the most widespread method to prevent biofouling. Ultrasonic antifouling systems present a non-chemical solution which can be used as an alternative to antifouling coating or a complementary technology. An ultrasonic antifouling system consists of ultrasonic transducers that can be installed on the hull and in niche areas like propellers, sea chest, and sea water cooling systems.

Ultrasonic transducers are designed to prevent of biofouling by emitting high-frequency sound waves that disrupt the organisms´ attachment process. The technology holds potential to protect some of the areas on vessels which might be difficult to protect with antifouling coatings, while reducing the chemical pressure on the environment. Variables amongst the offered ultrasonic technologies include the applied frequency or range of frequencies as well as the power used to induce vibrations.

The objective of the study was to test the efficacy of an ultrasonic transducers and their potential impact on marine cetaceans (e.g., whales, dolphins and porpoises).

Transducers were installed in an oil tanker (on the propeller, cooling system and part of the hull) and in a diving vessel (on the hull) to monitor the biofouling on the surfaces and create different scenarios for measurement of environmental levels of ultrasonic sound waves around the vessels.

Underwater sound measurements were conducted to model the propagation of the ultrasonic waves from each vessel into the surrounding marine environment.

The potential impact on marine cetaceans was assessed by comparing the frequency spectrum of the ultrasonic waves with the hearing capacity of these mammals groups and literature data for adverse effects.

The question is whether marine growth prevention by use of ultrasound shifts the environmental impact from release of toxic chemicals to emission of underwater radiated noise at ultrasonic sound frequencies outside the normal sound spectrum of a vessel? The study was supported by a grant from the Danish Maritime Fund.

Keywords: Antifouling, Ultrasonic TECHNOLOGY, Vessels, Impact, Marine MAMMALS

Investigating the Impact of In-Water Cleaning on Coating Performance and Cleaning Efficiency Using a Lab-Scale System

Author/s: Pascal Alexander Guth, Huichao Bi, Kim Dam-Johansen - (CoaST, Department of Chemical and Biochemical Engineering, Technical University of Denmark (DTU))

Abstract: Marine biofouling, characterized by the settlement of microorganisms, algae and marine organisms on submerged structures, presents large challenges to the maritime industry and oceanic environments [1]. Increased hydrodynamic resistance on vessels arising from biofouling leads to greater fuel usage, increased greenhouse gas emissions, and diminished functional effectiveness [2]. Biofouling, furthermore, possesses a large role in the distribution of non-indigenous species, which disrupts native aquatic ecosystems and also biological diversity [3]. Maintaining a ship's hull free from biofouling is important for alleviating such detriments, and underwater cleaning is emerging as a key approach for limiting the accumulation without the necessity of routine dry-docking [4], [5]. By means of buildup elimination as a vessel proceeds in service, in-water cleaning improves ship efficacy, lengthens the serviceable duration of fouling control coatings and reduces ecological repercussions. Nevertheless, the correlation between diverse cleaning processes and coating types affects both the degree of fouling removal and the durability of protective layer.

The effectiveness of underwater brush cleaning was evaluated using a laboratory-scale cleaning system [6]. Laboratory testing provides a controlled environment for the systematic evaluation of underwater cleaning and its effect on coatings. This artificial setup allows for an accurate and comprehensive evaluation of both cleaning efficiency and coating durability. To replicate realistic fouling conditions, samples were exposed to the natural sea environment on an exposure platform in the Baltic Sea. In addition to the cleaning device, different brush types with different geometries and bristle stiffness were designed and tested to investigate their effects on different fouling control coatings. This study allowed for a systematic analysis of how brush geometry and cleaning parameters - such as force applied - affect the efficiency of biofouling removal from different surfaces. In addition to cleaning efficiency, the effect of brush cleaning on coating integrity was also investigated. The results were correlated with the mechanical properties of the coatings. This comprehensive approach provides valuable insights for optimizing underwater cleaning strategies to improve biofouling management while ensuring coating longevity.

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Keywords: In-Water Cleaning, Marine Coatings, Optimisation, Cleaning Efficiency

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Field study of copper release rates and the risk assessment of antifouling paints for pleasure crafts

Author/s: Petter Andreassen, Tonje Nordby – (Jotun A/S)

Abstract: When conducting risk assessment of antifouling paints it is necessary to determine the release of the biocides and substances of concern, like copper and zinc from Cu_2O, CuSCN and ZnO. Under the EU-BPR, it is of particular importance to measure the release rate from pleasure crafts when moored inside closed marinas.

The US Navy Dome method1 is the only available recognized method for direct in situ measurement of copper release from the hulls of moored vessels. The method is expensive, impractical for routine use and difficult to standardize.

There are ASTM and ISO standards available based on laboratory experiments. However, after two round-robin tests, it was found that the inter-lab and intra-lab variations were high and concluded that the results of these standards were not suitable for direct use in risk assessments.

The ISO 10890 Mass balance calculation method was developed as a response to this, to give conservative estimates for the total release over the lifetime of the product. The underlying principle is that a paint cannot release more biocide than was present in the paint when applied. However, when a boat is moored, the ISO 10890 method will strongly overestimate the release rate, typically by approximately 3x versus the US Navy Dome2. Finnie (2006) developed correction factors to improve the estimates of environmental copper release under mooring conditions.

These correction factors have been challenged by Lagerstöm and Ytreberg3. They have developed a method with direct measurement of the metal content on tiny plastic panels, before and after seawater immersion, using a portable XRF instrument. The testing has been limited to short term exposure of thin films in Swedish waters and not always inside sheltered marinas.

A new field test method is presented, which is more robust and less resource demanding. A large painted panel, that better simulates the hull of a boat, was immersed at mooring sites all over Europe, representing both Baltic, Baltic transition, Atlantic and Mediterranean waters with salinity levels ranging from 3 to 38 ‰. The leaching rate was determined with optical microscopy and verified with SEM-EDX and chemical analysis. The results were in line with the Dome method and indicated that the XRF study strongly overestimated the release rate for boats lying idle inside sheltered marinas.

The data suggests that the environmental risk assessment should be refined with site and product-specific copper release rate measurements (Tier 2).

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Keywords: Copper, Antifouling, Coatings, Field test, Release rate, Marinas

Biodegradable Components and Formulations for biocide- and microplastic-free self-polishing coatings (BioSHIP)

Author/s: Philip Kensbock (1), Nina Winkler (1), Tim Heusinger von Waldegge (2), Dorothea Stübing (2), Bernd Daehne (3), Soyla Kraus (3), Elena Perabo (4), Stefan Gartiser (4).

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(4) Hydrotox GmbH Laboratory for Ecotoxicology and Water protection a Dr Brill Institutes Company

Abstract: Traditional antifouling coatings rely on biocide technologies that exert toxic effects on fouling organisms. Currently, heavy metal biocidal agents, such as copper or zinc, are widely used in commercial shipping. These agents accumulate in sediments and continuously expose marine organisms in the benthic zone to their toxic properties. Consequently, numerous approaches have been explored in recent years to mitigate this environmental impact. As further detailed, the release of polymer components from the coating surface is also critical concerning microplastic pollution. A new technically promising approach within the "BioSHIP" project aims to transform established self-polishing coatings to maintain their antifouling efficacy while eliminating heavy metal salts as biocidal agents and preventing microplastic release. This is achieved through a hydrolysis-driven mechanism that enables surface regeneration and fouling removal.

The primary focus of Momentive lies in the development of novel raw materials and, in collaboration with Fraunhofer IFAM, the formulation of coating solutions that prevent fouling adhesion while ensuring that any released components are biodegradable. The polymer fragments and other constituents released into the water via hydrolysis are designed to undergo biodegradation by marine microorganisms under ambient conditions, ultimately breaking down into demonstrably non-toxic degradation products such as carbon dioxide, water, biomass, and minerals.

This innovation not only meets market demands but also offers significantly improved environmental compatibility, helping to reduce the ecological footprint of the shipping industry and minimize microplastic emissions.

The project follows a structured development pathway, encompassing raw material synthesis, coating formulation, biodegradability and ecotoxicity assessments, followed by field trials and demonstration tests. This comprehensive approach ensures the thoughtful advancement of coating technologies while providing realistic insights into antifouling performance, long-term stability, and cleaning efficiency.

Keywords: BioSHIP Project, Biodegradable, Non-Toxic, Coating, Technology

The Green Nature of Silicone and Its Weight of Evidence

Author/s: Tomoya Kakudo - (Shin-Etsu Chemical Co., Ltd.)

Abstract: Silicone plays an important role in the antifouling and fouling-release chemistry because of its versatile features, such as a low surface tension and the active substitution of alkoxy groups in the triisopropylsilyl methacrylate (TIPSMA) polymers[1]. Like other chemicals, a careful attention has been paid to show the green nature of silicone. Herein, the author highlights a recent progress of the social responsibility and scientific findings in connection with silicone.

It is noteworthy to remind that the European comission has just recently decided to close the proposal to nominate octamethylcyclotetrasilixane (D4), decamethylcyclopentasiloxane (D5), and dodecamethylcyclohexasiloxane (D6) as POPs.[2] This means silicone of today can be utilized with less environmental concerns. On top of this fact, a method manufacturing silicone with less CO2 emission has been devoted by author's group. These facts associated with their weight of evidence as well as the prospect of new silicone structures will be delivered in the poster presentation.

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Keywords: Silicone, Green, Carbon Footprint, New Chemical Structure.

Systematic variation of lubricant viscosity of slippery liquid-infused porous polydimethylsiloxanes and impact on colonization by physiologically distinct bacterial strains

Author/s: Sabrina Böer, Regina Kopecz, Axel Rosenhahn – (Analytical Chemistry – Biointerfaces, Ruhr University Bochum)

Abstract: The colonization of natural and artificial surfaces presents a significant challenge across various industries, including marine environments, drinking water supply, wastewater treatment, and biomedicine. Succession of surface colonization can strongly vary between bacterial species and depends on various factors such as the expression of bacterial surfactants, Zeta potentials or cell motility [1-3]. Slippery liquid-infused porous surfaces (SLIPS) have emerged as a promising candidate to prevent biofouling by immobilizing a lubricant within a micro-/nanoporous substrate, creating an inert, repellent interface. The present work investigated biocompatible SLIPS based on macroporous polydimethylsiloxane (PDMS) substrates. A sugar-templating method was used for matrix fabrication and by using sugars of distinct grain sizes, three different substrate types with a different porosities and surface topologies were obtained. For infusion of the macroporous scaffolds, a liquid paraffin oil series with varying viscosities (68 cSt, 46 cSt, 32 cSt, 22 cSt, 15 cSt) was chosen.

Commonly used SLIPS lubricants such as perfluorodecalin or Krytox oils [4] hold the risk of negative ecological effects and bioaccumulation of perfluoroalkyl compounds. As this pitfall has increasingly gained attention in the field of antifouling (AF) material design, we chose paraffin oil for construction of our system due to their classification as harmless for humans and the environment. All systems were evaluated with respect to the impact of lubricant viscosity on fouling resistance and differences in surface colonization based on physiological and biochemical differences between the Escherichia coli, Bacillus subtilis, and Pseudomonas fluorescens. The objective was to identify an optimized substrate-lubricant combination with respect colonization capacities of distinct bacteria. Dynamic attachment assays were carried out and the properties of each system were analysed, including the surface wettability, system stability, surface- and cross-sectional morphology and surface tension of oils. Observed trends were discussed based on the physiological and biochemical differences between the bacterial strains. While the results for B. subtilis and P. fluorescens revealed significant attachment reduction for lower-viscosity lubricants, E. coli exhibited minimal sensitivity towards viscosity changes, which highlighted the impact of cell physiology and motility on surface adhesion. Additionally, fine porous systems incorporating lower-viscosity lubricants showed enhanced stability, being a crucial factor for long-term antifouling performance.

Keywords: Slippery Liquid-Infused Porous Surfaces (SLIPS), Antifouling, Coatings.

Alternative Approaches to Fouling Prevention on Leisure Boat Hulls: Biocide-Free Paint Innovations

Author/s: Santiago Arias, Hempel

Abstract: Controlling fouling on yachts without biocidal antifouling coatings is now a viable option, with biocide-free products becoming widely available over the past decade. The market solution has demonstrated good performance in a growing number of successful applications, proving to be as effective as traditional biocidal coatings.

Despite this progress, traditional antifouling paints containing biocides, such as copper oxide, remain predominant and continue to raise environmental concerns. These chemicals may negatively impact biodiversity and ecosystem health in the waters where leisure boats operate. The release of hazardous substances into marine environments also conflicts with environmental strategies in the EU and certain U.S. states.

This paper will explore the latest experiences with biocide-free antifouling solutions for yachts in both Europe and North America, emphasizing their sustainability benefits. A key focus will be the introduction of an innovative, water-based biocide-free performance recharger that extends the life of existing silicone coatings, allowing for an additional season without repainting. This new technology is transforming the yacht paint industry by delivering consistent high performance while reducing maintenance time, labor, and costs for boat owners and applicators—all with significant sustainability advantages.

Finally, this paper will present industry experiences and future recommendations, highlighting the readiness of the sector to offer environmentally responsible paint solutions. These innovations contribute to biodiversity preservation while enhancing boaters' enjoyment of the water with greater peace of mind.

Keywords: Biocide-Free, Coatings, Antifouling, Yachts, Environmentally Responsible

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Heterodyning and Guided Wave Ultrasonic Technology: A Complementary Solution for Ship Hull Fouling Protection

Author/s: Sasha Heriot, Chris Bell, Garry Churm, Chris Hewitt – (Cathelco)

Abstract: This paper explores the effectiveness of a novel ultrasonic antifouling approach that utilizes heterodyning and guided wave principles as a complementary solution to existing antifouling technologies for reducing biofouling on ship hulls. While traditional ultrasonic antifouling methods have shown limitations in terms of installation complexity and maintenance, this new system offers improved ease of deployment and operation.

Heterodyning and Guided Wave ultrasonic techniques contribute to fuel efficiency by effectively preventing biofouling. Biofouling, the accumulation of marine organisms like algae and barnacles on the hull, increases drag and forces ships to consume more fuel to maintain speed. By preventing biofouling, these ultrasonic methods help keep the hull smooth, thereby reducing drag and lowering fuel consumption. Guided Wave technology channels ultrasonic energy along the hull's surface, providing broader coverage with fewer transducers, ensuring consistent protection across the vessel. Meanwhile, heterodyning technology generates multiple frequencies to target a wider range of fouling organisms, offering a comprehensive antifouling approach that maintains hydrodynamic efficiency.

In addition to presenting two case studies of vessels operating in diverse marine environments, this study also reviews other antifouling technologies to provide a broader industry perspective. Results indicate that heterodyning and guided wave technology can effectively reduce hull fouling, leading to lower maintenance costs and improved fuel efficiency. These findings suggest that this approach can serve as a valuable addition to existing antifouling strategies, enhancing overall vessel performance and sustainability.

Keywords: Ultrasonic Antifouling, Biofouling Prevention, Guided Wave And Heterodyning.

Climate Change and Antifouling Coatings: Impacts on Performance and Biofouling Communities

Author/s: Sergey Dobretsov, UNESCO Chair in Marine Biotechnology, Sultan Qaboos University

Abstract: Climate change is driven by anthropogenic activities that increase greenhouse gas emissions, leading to rising air and water temperatures, ocean acidification, sea level rise, and changes in ocean gyres and rainfall patterns. These environmental shifts are altering marine communities, affecting species distribution and composition. In this presentation, I will provide examples of how rising temperatures and acidification impact biofouling species and communities. Existing studies suggest that climate change will influence the production of bioactive compounds, as well as the growth and composition of biofouling communities. Our research, conducted in tropical and temperate waters, indicates that elevated temperatures increase the mean coverage of macrofouling communities, enhance the settlement of fouling species, and increase diatom densities. Furthermore, climate change will affect the leaching rates and dissolution of biocides, as well as the hydrolysis of copolymers in antifouling coatings. Undoubtedly, as climate change progresses, managing biofouling will become an even greater challenge.

Keywords: Antifouling Coatings, Climate Change, Bioactive Compounds, Macrofouling

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Quantitative Characterization of Hydrogel Layers on Antifouling Coatings

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Abstract: Hydrogel-based antifouling coatings offer a promising approach to reducing biocides in antifouling coatings due to their low fouling properties and synergy with biocides. Recent work reported that when Xanthan gum particles are used as a filler in an antifouling formulation, they form a macroscopic, approximately 150 µm thin, hydrogel layer on top of the coating when in contact with seawater. The self-gelling property of Xanthan gum allows the particles to swell and form an in-situ hydrogel layer capable of retaining copper, thereby improving the efficacy of the coating system, which ultimately resulted in a 50 wt% reduction in $Cu2O$ without compromising antifouling performance for 4 months in the Baltic Sea (Hundested Harbor).

However, the precise characterization and visualization of these thin hydrogel layers remains a challenge, particularly in terms of thickness, homogeneity, and uniformity. In addition, the surface properties of the coating remain unclear after gel formation. In the present study, we describe a systematic approach to measure hydrogel layers on antifouling coatings using advanced imaging and analytical techniques. Optical coherence tomography (OCT) was employed to simultaneously assess the hydrogel layer thickness, surface roughness, and coverage, as well as the underlying coating surface roughness, in a single imaging process while immersed in water. OCT provides non-invasive, high-resolution cross-sectional imaging that allows real-time assessment of the hydrogel swelling dynamics. Using an 880 nm laser OCT, underwater measurements were possible due to the high penetration depth and low absorption of water in this wavelength range.

The results show that the hydrogel structure and the coating surface are highly dependent on the paint formulation aspects. Furthermore, environmental exposure conditions such as salinity play a crucial role in the gel formation process. This is especially relevant for the Baltic Sea region, where a salinity gradient is strongly pronounced. OCT proved to be a reliable tool for in-situ monitoring, revealing significant swelling variations that could affect antifouling efficacy.

This study provides a comprehensive methodology for evaluating hydrogel layers on antifouling coatings. Our on-going OCT study further aims towards interpreting in-situ swelling kinetics, time-resolved dynamics, layer delamination, interfacial integrity, and water diffusion behavior, contributing to the development of more effective, durable, and sustainable antifouling strategies by reducing copper in biocidal antifouling coatings.

Keywords: Hydrogel Coatings, Antifouling, Optical Coherence Tomography, Swelling Behavior, Thickness Measurement, Roughness Measurement, Marine Biofouling.

Field testing and ecotoxicological screening on biocide- and microplastic-free self-polishing coatings (BioSHIP)

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Abstract: The BioSHIP project focuses on the development of a self-polishing marine coating (SPC) and a cleanable hard coating minimizing the release of biocides and microplastics. This will provide a more sustainable and environmentally friendly alternative to keep ships free of fouling and fully operational. With changing laws and increasing restrictions on the use of biocides in marine coatings, and limited options for cleaning ships with biofouling, a solution is needed that reduces the impact on both climate and the environment.

The project partner, Dr. Brill + Partner GmbH in Norderney, Germany, is concentrating on performance testing of the coatings developed by Momentive Performance Materials GmbH and Fraunhofer IFAM. Field tests will take place in the North Sea, the Mediterranean, the Red Sea, the Tasmanian Sea and in freshwater in Germany during the summer seasons 2025-2027 in both hemispheres. The high number of test sites will provide more insight into differences in coating effectiveness and durability under various conditions. In the North Sea, additional cleaning tests will be carried out. Alongside these static immersion tests, dynamic field tests using Dr Brill's test bench RotoMarin® will be conducted to determine the effectiveness of the different coatings by simulating the driving profile of a coastal operating vessel.

Additionally, new test methods are being developed in collaboration with Hydrotox GmbH to assess the biodegradability and ecotoxicology of the developed SPCs.

The company Hydrotox conducts practical tests on the biodegradability of SPCs in accordance with the test strategy for synthetic polymer microparticles described in Regulation (EU) 2023/2055 (Microplastics Regulation). Additionally, defined eluates of the coatings undergo an ecotoxicological assessment using a biotest battery, based on the awarding criteria of the Blue Angel DE-UZ 221 for underwater coatings. The practical laboratory tests are supplemented by database and literature research on the co-polymers, additives, and auxiliary additives used to achieve a comprehensive evaluation of the environmental behavior of the selected coating systems. For biodegradation analysis, the test focuses on homogeneous polymers, as the endpoint CO_2 production describes the mineralization without differentiating between components. Consequently, persistent substances in formulations cannot be reliably ruled out by direct testing of formulated coatings.

For ecotoxicity evaluation, SPC coatings will be eluted using the dynamic surface leaching test (DIN EN 16637-2), and eluates will be tested according to DIN CEN/TR 17105. The first two eluates (after 6 and 18 hours) and the eluate after 64 days (fraction 8 from day 36–64) will be analyzed using luminescent bacteria, algae, daphnia, fish embryo, and umu tests according to ISO standards. Based on the Blue Angel DE-UZ 221 criteria, products must show no significant effects at the following dilution levels to be considered ecologically safe: Algae GA ≤ 4, Daphnia GD ≤ 4, Fish Embryo GEi ≤ 4, Luminescent Bacteria GL ≤ 8, and umuC-Test GEU ≤ 1.5.

Keywords:

Novel Quantification Technique For Marine Biofouling In Cooling Water System

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Abstract: Many industries that employ seawater for a variety of applications are confronted with the critical issue of biofouling. Microfouling, which is the accumulation of objectionable depositions of bacteria, microalgae, diatoms, protozoa, and other organisms, can occur when the structures of an industrial cooling water system are constantly exposed to untreated seawater. This can be followed by macrofouling, which is the accumulation of tiny marine animals, such as mussels, jellyfish, bryozoans, etc. The primary challenge encountered in marine biofouling investigations is the development of effective quantification techniques for micro and macrofouling. Qualitative analysis of biofouling is granted greater attention by researchers than quantification techniques. The primary methods employed by researchers for the qualitative analysis of biofouling include optical microscopy, DNA, molecular sequencing, chemical analysis techniques, in vitro and in vivo fouling organisms screens, field trials, and emerging artificial intelligence technologies. The completion of these methods is a lengthy process, and they are qualitative in nature rather than quantitative. Therefore, the development of a quantitative method for the quantification of biofouling is necessary.

Flow cytometry is typically employed to determine the number of cells in organisms. Flow cytometry is a relatively rapid and precise method for the analysis of marine biofouling. Additionally, flow cytometry, a rapid quantification technique, can establish suitable protocols for the quantification of marine fouling. This information can be used to identify the most appropriate macrofouling remediation technologies for the marine environment. The primary objective of the study is to establish a novel method for the quantification of biofouling, including micro and macrofouling, in cooling water systems. The preliminary study conducted a correlation study between the number of larvae of marine organisms named Bryozoan Amathia verticillate (BAV) and cell counts. The results showed a linear correlation between the number of larvae and cell count with a high R2 value (0.9808). Furthermore, this innovative quantification method can be implemented in numerous industries to detect the initiation of microfouling.

Keywords: Biofouling, Microfouling, Macrofouling, Flow Cytometer

Copper Antifouling Coatings Regulatory Status

Author/s: Tom Bischoff – (American Chemet Corporation)

Abstract: Safe and effective anti-fouling coatings constitute an important part of the drive for sustainable shipping and prevention of invasive species transport. Copper based anti-fouling coatings are some of the most widely used coatings in aquaculture, commercial, and recreational industries. These coatings must be approved for their use by regulatory bodies by demonstrating efficacy and passing an environmental and health risk assessment. This presentation is to provide an update on the regulatory status of copper based anti-fouling coatings in key regions across the globe. It will address recent global regulatory activities and their impact on industry.

Keywords: Copper, Antifouling, Regulatory

Microencapsulation Technology: Advancing Compliance And Safety Of Biofouling Management

Author/s: Volodymyr Pashovych, Carsten H. Baehr – (Arxada AG)

Abstract: Antifouling coatings play a vital role in maritime operations by preventing biofouling on ships and marine structures. Effective biofouling management reduces drag, enhances fuel efficiency, lowers greenhouse gas emissions, and mitigates the spread of invasive species. However, evolving global regulations, such as the Korean K-REACH restrictions on toxic substances, are imposing stricter limits on the use of biocidal active ingredients in antifouling formulations. These regulatory changes present significant challenges for maintaining the performance of traditional coatings while ensuring compliance with new safety and environmental standards.

To address these challenges, microencapsulation technology offers an innovative approach that enhances the safety of antifouling paint without compromising its efficacy. By encapsulating biocidal active substances such as Cuprous Oxide (Cu_2O) and Copper Pyrithione (CuPT), this technology significantly reduces direct exposure during the manufacturing and application processes and also minimizes environmental release. The encapsulated formulations contain less than 1% free active ingredients, effectively minimizing occupational exposure risks for workers at shipyards and potential environmental impact in the vicinity while still delivering the necessary biofouling protection. The safety data sheets of encapsulated Copper Pyrithione and Cuprous Oxide were approved by K-OSHA and as free non-encapsulated content of corresponding active ingredients is less than 1%, deemed non-toxic substances.

This presentation will explore the development and performance of microencapsulated antifouling coatings, demonstrating their ability to meet regulatory requirements while maintaining industry standards for effectiveness. Ongoing static panel testing confirms that encapsulated biocides perform comparably to traditional formulations, ensuring reliable protection against marine fouling. By aligning with evolving health and safety regulations, microencapsulation technology represents a crucial step forward in balancing regulatory compliance, worker safety, and environmental impact towards more sustainable biofouling management in the maritime industry.

Keywords: Biofouling Management, Global Regulations, Biocidal Antifouling Products, Sustainable Innovation, Micro Encapsulation Technology.
