Dealing with biofouling

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## Is there an environmentally friendly and economically attractive coating for the shipping industry?

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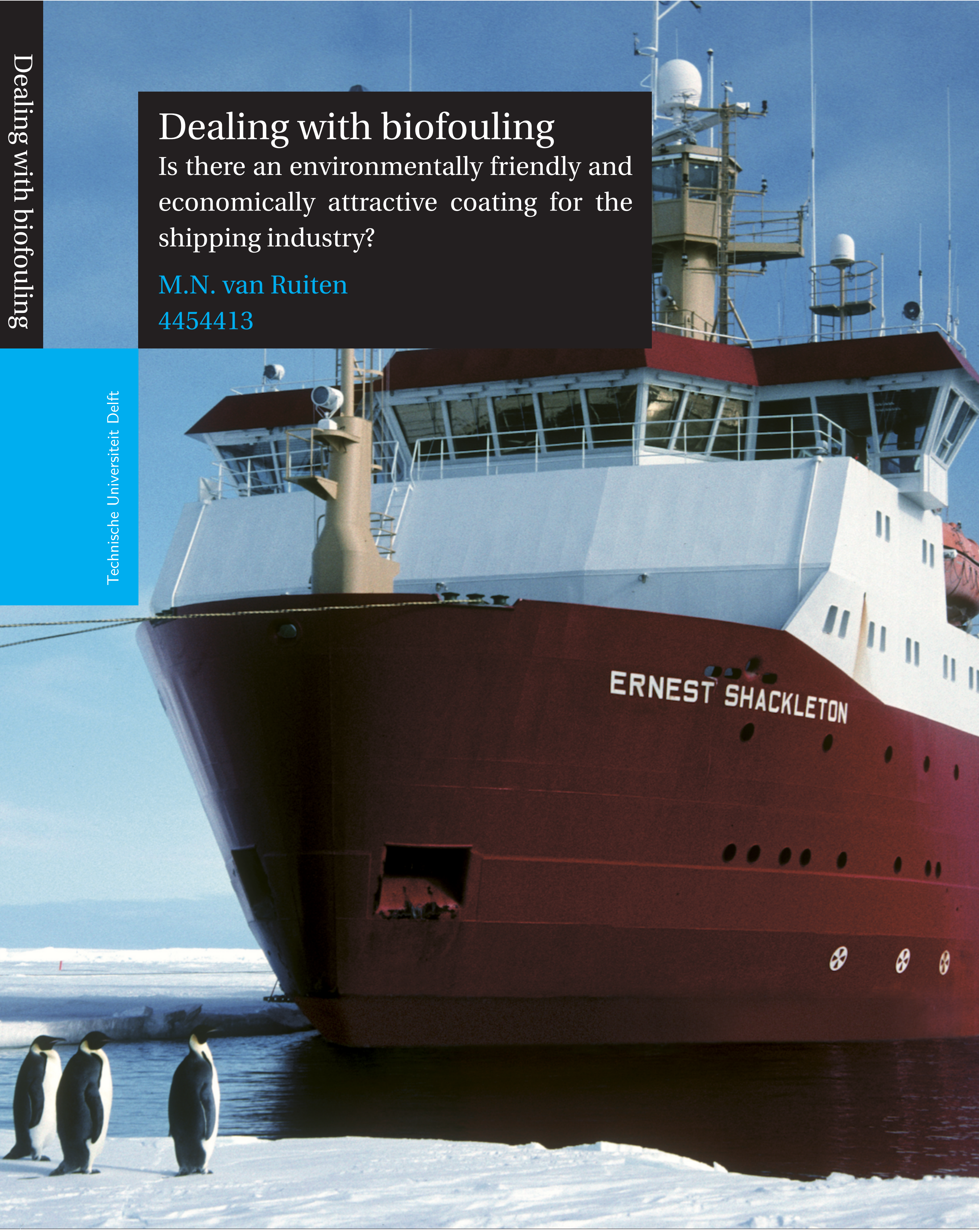


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# Dealing with biofouling

## Is there an environmentally friendly and economically attractive coating for the shipping industry?

by

Martijn van Ruiten

Delft University of Technology

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|---|---|
| Student number: | 4454413 |
| Project duration: | September 3, 2018 – October 24, 2018 |
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TU Delft

# Preface

*M.N van Ruiten*
*Delft, October 2018*

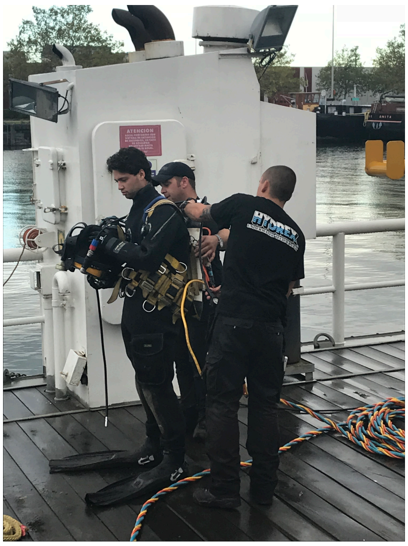
This thesis is the result of researching the main question: 'Is there an environmentally friendly and economically attractive coating for the shipping industry that deals with biofouling?' A survey is done based on a multi-criteria analysis to determine the best coating system for the shipping industry. This thesis contains the results of my Bachelor final project, which is part of the requirements of my bachelor degree in Civil Engineering at the Delft University of Technology. This project was done from the beginning of September to the end of October, 2018.

For two months I have been working on this research and writing the report. I experienced this period as a very instructive period in which I learned many new things about the current approach in the shipping industry but also the problems that come with it. By seeing the coating industry in practice, I saw a lot of points for improvement. Also I learned to find qualitative information by searching for documents and by interviewing companies who are familiar with this subject.

Hereby I want to thank my first supervisor Dr. Ir. Ralph Lindeboom for the good guidance during the research. For questions and professional advice, I could always contact him. In addition, I would like to thank my second supervisor, Prof. Dr. Ir. Luuk Rietveld, for the necessary support for the bachelor thesis. I also want to thank the companies I received information from, without whose cooperation I would not have been able to conduct this analysis. I also benefited from debating issues with my friends and family.

I hope you enjoy your reading.
Martijn van Ruiten

Delft, 2018



# Contents

# 1

# Introduction & Problem Analysis

A hot topic these days is the tremendous amounts of plastic particles in our seas and oceans. Everybody is aware of this big problem. But in this thesis an even bigger problem is described about the continuous pollution of our inland waterways and oceans. This problem is not very noticeable because it takes place under water but it is one of the biggest maritime disasters.

Transport by sea is economically attractive, efficient and very useful. And that has been the case for thousands of years. The sea is a rougher, more aggressive environment for man-made objects than we experience on dry land. Water, mainly salt water, is highly susceptible to cause corrosion. This affects the main material of a vessel, namely steel. Another big problem is cavitation erosion, and there are particles in the water such as ice, sand, gravel and lava that can affect the vessel. Also the growth of biofouling will occur. Aquatic organisms are an undesirable fouling on the hull, rudder and propeller. The growth increases the roughness and drag of the vessel and has major negative effects on the propulsion power which increases the fuel consumption. A vessel needs a coating for the protection and to deal with the negative effects that take place. All these factors are a challenge for the shipping industry.

When a new antifouling coating is applied to an average vessel of between 50 and 100.000 tons, usually every three years, about 15 tons of biocides are sprayed on the hull. (Rompay, 2012) Biocides are highly toxic chemical compounds with a lethal effect on living organisms including humans. Of these 15 tons of biocides, a large part of harmful volatile organic compounds (VOC) enters the air, which is highly undesirable and could harm the environment. During the application of the coating, toxic substances are lost and end up in the water and in the air in the form of waste or over-spray. Due to the self-polishing aspect of these coatings, an immediate, large-scale distribution of biocides are released in the water that pollute the shipyards and the surrounding waters including sediments.

These antifouling coatings, that are used all over the world, have a very undesirable effect due to the release of large amounts of copper oxide and a number of other biocides, such as the extremely toxic herbicides Irgarol 1051 and Diuron, in the oceans, especially around ports, marinas and anchorages. (William H. Simendinger, 2000) Copper, zinc and even tin containing antifouling paint particles are found both along the shore and contaminating the sea bed, where they behave similarly to bottom sediment particles and they are ingested by filter feeders and over time leach toxic heavy metals into the marine environment. (Turner, 2010) Copper has a long history of use and even nowadays copper oxide accounts for the most used biocides in antifouling paints, but it has shown to have serious environmental concerns. (LIFE Fit for REACH)

Eventually the vessel returns to the dry dock so that the depleted coating layer can be renewed. The 15 tons of biocides originally in the coating is spread over the places where the vessel has sailed, has cleaned, or has anchored. (Rompay, 2012) The water is polluted and the sediment at the bottom is contaminated. When this is multiplied by the entire world fleet, we arrive at enormous amounts of highly toxic chemicals that end up in the open waters every year. The highest concentrations of toxic substances can be found in ports and shipyards. The pollution of the sediment in oceans, ports and inland waterways is the major problem caused by this current approach.

The current approach that dominates the market for protecting the hull of the vessel and preventing biofouling, consists of a zinc primer and an epoxy anti-corrosion paint consisting of copper oxide and other chemicals in a soluble form. (William H. Simendinger, 2000) The process, to prevent fouling to attach to the hull, is done by leaching of these chemicals. These substances kill a part of the aquatic organisms when they try to attach themselves to the hull of the vessel. These poisoned organisms end up in the sediment at the bottom of the sea and/or port. This will contaminate the sediment even more. About 80% of the vessel owners use paint containing copper and/or zinc as an antifouling coating. (National Institute for Public Health and the Environment, 2018)

The chemicals accumulate in the sediment. Over all these years, the sediment consists of millions of tons of these toxic substances. This happens gradually and continuously instead of suddenly and temporarily. As a result, this situation is not perceived as a disaster, and the use of biocides is not yet prohibited.

Another major problem is the transportation of aquatic organisms from their own ecosystem to another. During the stay of a vessel in a port, the aquatic species attach themselves to the hull. If these organisms survive the transport from the port of origin to the final destination, a couple of options can occur. It can die off because of the change in the environment; it can survive with little environmental impact; or it can harm their new ecosystem. This happens if the organisms become copper tolerant or biocide tolerant and are way stronger than the native species. (National Geographic, 2010) Marine ecosystems are local. If these ecosystems are transported to other places, so when these ecosystems are no longer native, serious environmental problems can arise in these areas. (MEPC, 2011) This can cost the government a large sum of money to clean up the damage and can result in major economic problems. It is much more efficient and cheaper to prevent the transport of these aquatic organisms instead of trying to clean up the damage afterwards.

One infamous example of such an environmental issue is the zebra mussel. Accidentally introduced in the North American Great Lakes from the Black Sea in 1988. A lot of the Great Lakes native mussel population were starved out by the arrival of the tiny mollusk. Also, a lot of human-made structures were affected. Going from the intake pipes of factories to vessel rudders. (National Geographic, 2010) The cost is very high to clean up the damage occurring in pipes and on vessels. The bill goes up to $60 million each year. The polluted waterways cost over $5.000 each hour. The total cost to the United States of the zebra mussel invasion is estimated at $3.1 billion over ten years. (U.S. Department of state, 2001-2009)

This is called the 'Non-Indigenous Species' problem (NIS-problem). This is the most commonly used term in non-scientific circles. The antifouling coatings have to be repaint regularly because the chemicals are released quickly in the water. This method gains huge profits for the current coating business. Especially for the sellers and appliers of these coating systems. This market will grow to U.S.$ 9.22 billion by 2021 (annual growth Rate of 8.6 percent between 2016 and 2021). (www.coatingsworld.com, 2016)

Do the people want their waterways and oceans being polluted with highly toxic compounds? Do the people want the next generations living in a toxic environment? Do the people want toxic compounds still enter their food chain? The sediment is already very poisoned but the faster a proper workable solution is available, the less ecosystems are being damaged. We urgently need an alternative working solution that is acceptable for governments, port authorities, environmental movements and the shipping industry.

# 2
# Questioning

## 2.1. Main-Question

The main-question of the research can be formulated as follows:
Is there an environmentally friendly and economically attractive coating for the shipping industry that deals with biofouling?

## 2.2. Sub-Question

The sub-questions of the research can be formulated as follows:

1. Are there any other alternative coating systems available?
2. Is the coating non-toxic and are there no particles leaching into the water?
3. Are the sediments of rivers and ports better protected from pollution?
4. Does this benefit the sediment and water quality and therefore public health?
5. Is the alternative a better solution for preventing the spread of invasive organisms?
6. Is there an improvement in fuel consumption and a decrease of greenhouse emissions?
7. Are zinc anodes still required or not?
8. Is there a general improvement in the protection of the hull?
9. Does the vessel maintain its speed or even improve it in comparison with the toxic coatings?
10. Does this approach benefit the general economy (income and employment)?
11. Are the cleaning systems for non-toxic coatings convenient enough to be useful?

## 2.3. Research Objective

The aim of this research is to make a statement about the question 'Is there an environmentally friendly and economically attractive coating for the shipping industry that deals with biofouling?'. The solution must be examined so that the total picture is correct. In the search for a new solution for the shipping industry, the system must meet a number of conditions compared to the existing practices:

- Safe for public health
- No damage to the environment
- No excessive fuel consumption
- Cheaper or comparable costs

By answering the various sub-research questions, we can check whether the solution meets the requirements. The other aim of the research is to determine whether the world population still wants toxic substances to enter the water through the general use of the toxic antifouling coatings.

## 2.4. Target Group

First of all this analysis is made for the shipping industry to help them make economically acceptable decisions to prevent the negative and toxic effects of biofouling. Secondly, it offers valuable data to groups that are working to safeguard and improve the environment, especially of our waterways, lakes, seas and oceans. And lastly it allows groups that want to secure and improve the health of people, flora and fauna to understand the highly toxic effects of the currently dominantly used biofouling approaches.

# 3
# Method

## 3.1. Introduction
The method consists of several parts. Firstly, a literature study was done to do more thorough research into the existing approach in the shipping industry. There are two commonly used coating systems that are used today and dominate the market. We will compare a third variant by using a multi-criteria analysis to choose a suitable filter system. Eventually the analysis will show the best coating system based on several criteria.

## 3.2. Literature Study & Data Research
To go deeper into this research it was necessary to apply a literature study. This included looking at the current approach in the shipping industry and the problems that this entails.

In this chapter a comparison is made between the two existing coating systems and a third alternative coating:
• Biocidal Antifouling Coating (Biocidal AF-Coating): Continuous release of toxic chemicals to keep down biofouling.
• Fouling Release coating (FR-Coating): Mechanical method due to the speed of the ship, organisms release faster on non-stick coating and chemical effects of toxic substances.
• Hard, Inert Coating: Very hard coating, no releases of compounds, fouling will occur but must be cleaned off.

From the existing data collected over the years and calculations, we can make this comparison based on a multi-criteria analysis.

## 3.3. Multi Criteria-analysis
To investigate whether the Hard, Inert Coating offers a better solution, we apply a multi-criteria analysis. On the basis of a weighted summation method, a ranking between the three coating systems has been determined. In the case of a weighted summation, the scores of the criteria are multiplied by standard weights after standardization and then added to each variant. The criteria are: protection and longevity, fuel consumption efficiency, environmental concerns, initial cost, lifetime cost, time efficiency and the possibility to clean.

To perform the multi-criteria analysis, a number of steps must be taken. First an effect table was made to determine the scores per criterion. Thereafter, the weight of each criterion was determined by weighing each criterion against each other by involved parties. Subsequently, the criterion scores were multiplied by the weight factor after standardization to determine the ranking. Finally, a conclusion could be drawn. This is further elaborated in chapter 5.

## 3.4. The cleaning aspect
By means of an underwater observation, photographs were made of the underwater cleaning. By comparing the photographs before and after cleaning, it can be checked how efficiently this happens and which tools are used. These tools are explained in chapter 7.

# 4
# Literature study

## 4.1. Protection and Longevity

A life time schedule is made to give a better view on how many times a vessel with different coating systems need to visit a dry dock for painting or for cleaning. The lifetime schedules, shown in figure 4.1/4.2/4.3 is based on a period of 25 years.

**Biocidal AF-coating:**

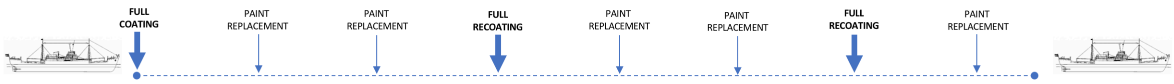



Figure 4.1: Lifetime schedule over 25 years

**FR-coating:**

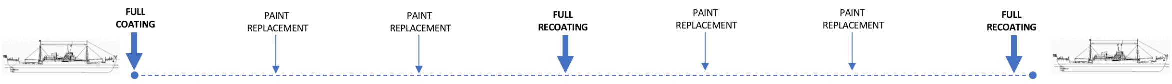



Figure 4.2: Lifetime schedule over 25 years

**Hard, Inert Coating:**

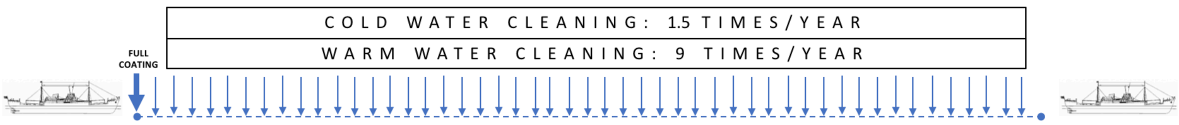



Figure 4.3: Lifetime schedule over 25 years

**Conclusion:**
From the above life time schedules, the vessels with an Biocidal AF-Coating should visit the dry dock the most for repainting and full recoating (±8 times in 25 years). The life time schedule of the FR-Coating is more or less the same (±7 times in 25 years). The Hard, Inert Coating lasts the whole life time of the vessel and no repaint is required except for some touch-ups. On the other hand this coating needs to be cleaned regularly. For vessels in warm waters the frequency is once every six weeks or two months in order to keep the fouling never more than light slime. In cold water with a constantly moving vessel the cleaning may be as infrequent as over once or twice a year. All these values are averages, these can change due to a number of factors such as the sailing time, sailing speed, if a ship had lain idle for some time, water temperature, etc. Because the Hard, Inert Coating lasts for over 25 years, much less paint is used and much less associated waste is created. It can be estimated that if 80% of the world fleet would switch from Biocidal AF-Coatings to Hard, Inert Coatings,

12 million liters of paint don't have to be applied every year, which saves significantly on material resources and associated transport costs. An overview is shown in table 4.1.

| Biocidal AF-Coating | FR-Coating | Hard, Inert Coating |
|---|---|---|
| The Biocidal AF-Coating is a soft coating and is fairly easily damaged. Needs to visit a dry dock on average 8 times in 25 years | The FR-coating is a soft coating and is easily damaged. Needs to visit a dry dock on average 7 times in 25 years. | Tough, flexible. Very corrosion resistant. Lasts lifetime of vessel with only minor touch-ups. No repaint required. |

Table 4.1: Overview Protection and Longevity

## 4.2. Fuel Consumption Efficiency

A fouled hull requires as much as 40% more power to drive it through the water. One U.S. Navy study even put the figure as high as 86% when a badly fouled vessel is cruising at speed. (MAREX , 2013)

A major difficulty in assessing hull efficiency is the sheer number of factors affecting fuel consumption: ship design, engine efficiency, fuel quality, speed of sailing, draft, trim and list, propeller design and condition, as well as ambient factors such as wind, waves, swell, currents, water depth, water temperature and salinity.

Frictional resistance of the hull against the water has to be isolated from this mass of data before accurate measurement and comparison of coating efficiency can even be attempted. Differentiating hull performance from propeller efficiency is particularly difficult. But the job is actually even more complex: Measurements taken during steering, acceleration and deceleration are inherently unreliable.

And most importantly, what about long-term efficiency? Biocidal AF-Coatings gradually lose potency during use and even the most effective of them accumulate some degree of fouling. Mechanical damage from chains or debris creates roughness, particularly on the FR-Coatings. Repair of coatings – touching them up in dry dock – results in surface roughness. For examples of degraded hull coatings, see appendix A. Only the Hard, Inert coating is immune from general degradation. (MAREX , 2013)

Besides these factors, a calculation is made about the fuel consumption of the three different variants from existing data from laboratory experiments to real life tests. The existing data used for the fuel consumption were:

- The start resistance against the water of the three different coating systems of a freshly applied hull. This is achieved from the frictional resistance of the tested coatings versus towing speed.
- The time when the different stages of fouling occurs over months and years.
- The additional shaft power of the different stages of fouling.
- Visit for repainting during the lifetime of a vessel (over 25 years) and the number of times a vessel gets cleaning each year. (section 4.1)

The values of the start resistance of the coating system against water and the stages of fouling of a ship over 25 years, are calculated (appendix B) and the results of the additional shaft power (%) are plotted in Figure 4.4. The impact of degradation of a vessel over 25 years, if it is badly maintained, are added to the calculations and plotted in the graph B.10 in appendix B.

**Conclusion:**
As a result, the following graph is achieved:

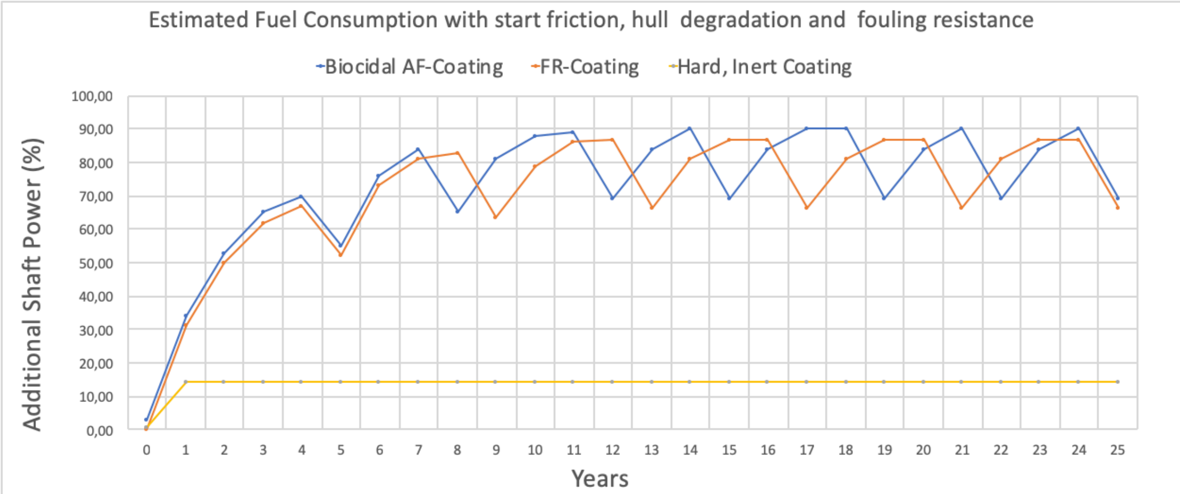



Figure 4.4: Fuel Consumption Efficiency based on start resistance and fouling resistance of the hull

An overview is shown in table 4.2.

| Biocidal AF-Coating | FR-coating | Hard, Inert Coating |
|---|---|---|
| Unfouled hull gives 2 - 4% inefficient fuel consumption. (Schultz, 2007) Usually sails with slime, this results in ±45% inefficient fuel consumption. | Unfouled hull gives the smoothest surface. Usually sails with slime, this results in ±45% inefficient fuel consumption. Can foul badly if ship has long lay-ups in ports or anchorages. | Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save ±30% or more on fuel compared to a Biocidal AF-Coating or a FR coating. |

Table 4.2: Overview Fuel Consumption

## 4.3. Environmental Concerns & Public Health

The compounds are shown in table 4.3/4.4/4.5 from a paint product from each of the three variants. The compounds are from the MSDS (material safety data sheet) of the different paint products in Appendix C.

**Biocidal AF-Coating:**

| **Compound** | **Safety Risk** |
|---|---|
| Di-Copper Oxide | - Very toxic to aquatic life (with long lasting effects)<br>- Harmful if swallowed<br>- Causes serious eye damage<br>- Harmful if inhaled |
| Zinc Oxide | - Very toxic to aquatic life (with long lasting effects)<br>- Harmful if inhalation<br>- Target Organs: respiratory system |
| ROSIN | - May cause an allergic skin reaction |
| Xylene | - Explosive; mass explosion hazard<br>- Suspected of causing cancer<br>- Very toxic to aquatic life (with long lasting effects) |
| Solvent Naphtha | - Flammable liquid and vapor<br>- May be fatal if swallowed and enters airways<br>- Causes skin irritation<br>- Toxic to aquatic life with long lasting effects |

| | |
|---|---|
| Bis(1-hydroxy-1H-pyridine-2-thionatoO,S) copper | - Harmful if swallowed<br>- Causes skin irritation<br>- Causes serious eye damage<br>- Fatal if inhaled<br>- Very toxic to aquatic life |
| Ethylbenzene | - Highly Flammable liquid and vapor<br>- May be fatal if swallowed and enters airways<br>- Causes eye irritation<br>- Harmful if inhaled<br>- May cause respiratory irritation<br>- May cause drowsiness or dizziness<br>- Suspected of causing cancer<br>- May damage fertility or the unborn child<br>- Causes damage to organs through prolonged/repeated exposure<br>- Very toxic to aquatic life (with long lasting effects) |

Table 4.3: Safety risks of the compounds (Pubchem)

**FR-Coating:**

| **Compound** | **Safety Risk** |
|---|---|
| Penthane-2,4-dione | - Flammable liquid and vapor<br>- Harmful if swallowed<br>- Toxic in contact with skin<br>- Causes eye irritation<br>- Toxic if inhaled<br>- May cause respiratory irritation<br>- Suspected of causing genetic defects<br>- Causes damage to organs<br>- Harmful to aquatic life with long lasting effects |
| Dioctyltin Dilaurate | - Causes severe skin burns and eye damage<br>- Causes serious eye damage<br>- Suspected of damaging fertility or the unborn child<br>- May cause damage to organs<br>- Causes damage to organs through prolonged<br>or repeated exposure<br>- Harmful to aquatic life with long lasting effects |

Table 4.4: Safety risks of the compounds (Pubchem)

**Hard, Inert Coating:**

| **Compound** | **Safety Risk** |
|---|---|
| 100% Copper-Free | 100% Non-Toxic |
| 100% Tin-Free | 100% Non-Toxic |
| 100% Zinc-Free | 100% Non-Toxic |
| 100% Biocide-Free | 100% Non-Toxic |

Table 4.5: Safety risks of the compounds

**Conclusion:**
Based on the analysis of the MSDS (Appendix C) of the three different coating systems, the safety risks are shown. The Biocidal AF-Coating and the FR-Coating pose a threat to marine ecosystems by causing genetic damage and even killing these organisms. As soon as these substances enter the food chain, they can endanger the health of all living people. The Hard, Inert Coating has no tin, copper, zinc and biocides. And is proven to be 100% non-toxic. (A.

Wijga, 2008) This will benefit the public health. An overview is shown in table 4.6.

| Biocidal AF-Coating | FR-Coating | Hard, Inert Coating |
|---|---|---|
| Contaminates the marine environment/life and sediments with toxic biocides, the food chain and humans. (J. Gonzalez, 2008) High VOC when applied. Prevents some NIS but furthers others. | Leaches harmful oils, alters enzymes in barnacle glue; some silicones catalysed by highly toxic dibutyltin laurate. Medium VOC. Some reduction in fuel consumption/GHG. Can help limited spread of NIS but alters it. | Non-toxic in use, conditioning and cleaning. Low VOC. Combined with cleaning gives lowest fuel consumption / GHG emission. Cleaned before vessels sail prevents spread of NIS. |

Table 4.6: Overview Environmental Concerns

## 4.4. Initial Costs and Overall Costs

In figures 4.5 and 4.6 the initial costs and overall costs are shown.
**Conclusion:**

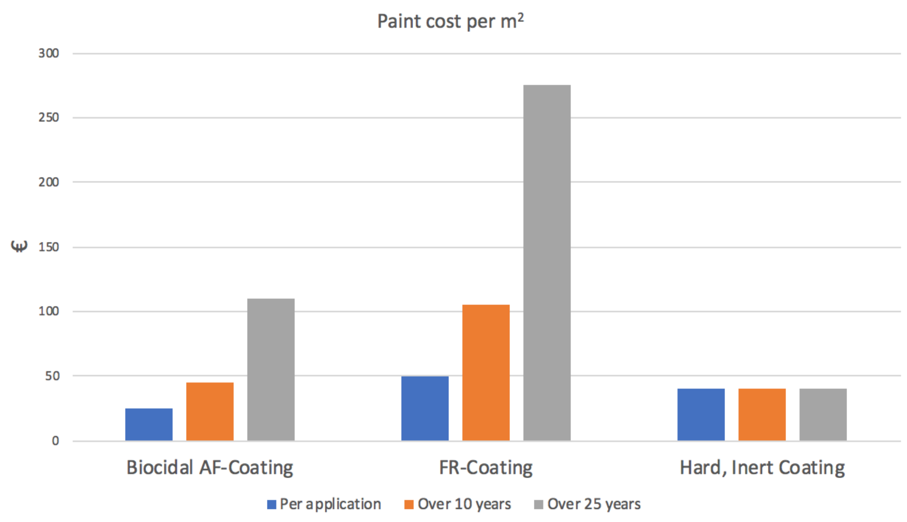



Figure 4.5: Estimated paint costs over three periods of time (in €/m²) (ECOTEC-STC)

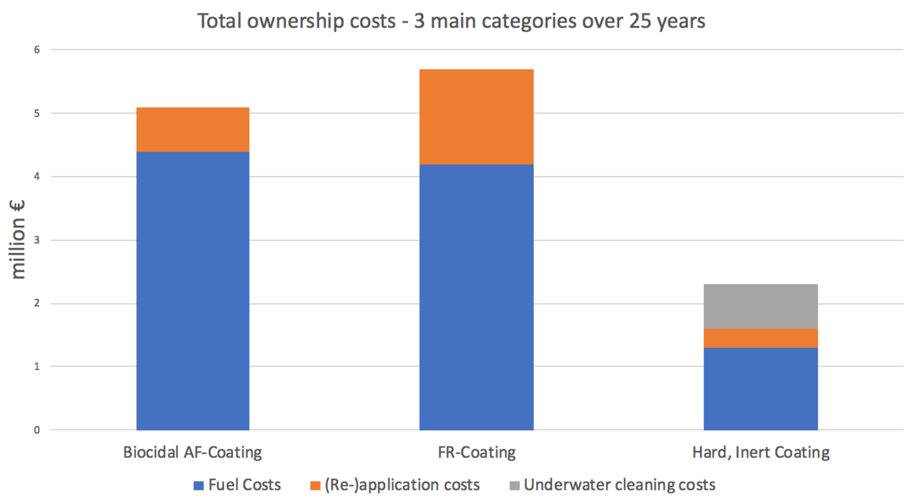



Figure 4.6: Estimated total ownership costs over 25 years 1000-TEU container, data used from (ECOTEC-STC)

An overview is shown in table 4.7.

| Biocidal AF-Coating | FR-Coating | Hard, Inert Coating |
|---|---|---|
| Overall cost including (re-) application, maintenance and additional fuel consumption is twice that of the hard, inert coating. Initial application is the cheapest: ±25 euro/m2. | Overall cost including (re-) application, maintenance and improved fuel consumption is more than two times that of the hard, inert coating . Initial application is the highest of all three: ±50 euro/m2. | Overall cost is half that of a Biocidal AF-coating and more than a half of a FR-coating. Initial application is more than a Biocidal AF-Coating ±45 euro/m2 Cleaning costs are included. |

Table 4.7: Overview Initial and Lifetime Costs

## 4.5. Time Efficiency

The time efficiency is calculated on the basis of the time a vessel spends in a dry dock and/or the time a vessel spends during cleaning. The data is gained from the life time schedule shown in section 4.1. In appendix D the calculations can be seen for Cargo Ship with a hull surface of 9000m². Knowing that a visit at a dry dock takes on average 2,5 weeks and the time to clean a ship takes on average 6 hours, the expectations on time efficiency could be made. The vessels with the Biocidal AF-Coating and the FR-Coating must not be cleaned. They spend time to visit the dry dock for repainting and for an inspection of the vessel. The control must be done once every 5 years. (U.S. Coast Guard Research and Development Center, 2006) They can combine the inspection with the repainting. The vessel with a Hard, Inert Coating must not go to the dry dock for repainting, only for the inspection of the vessel once every 5 years. This dry dock time is less long because no repainting is needed, the inspection takes on average 4 days. Cleaning should be done 1,5 times in 25 years in cold water and 9 times in 25 years in warm water. Cleaning could be done when the ship is busy with other operational works and in this case could not be seen as extra time lost. In figure 4.7, the time efficiency of the different coating systems can be seen.

**Conclusion:**

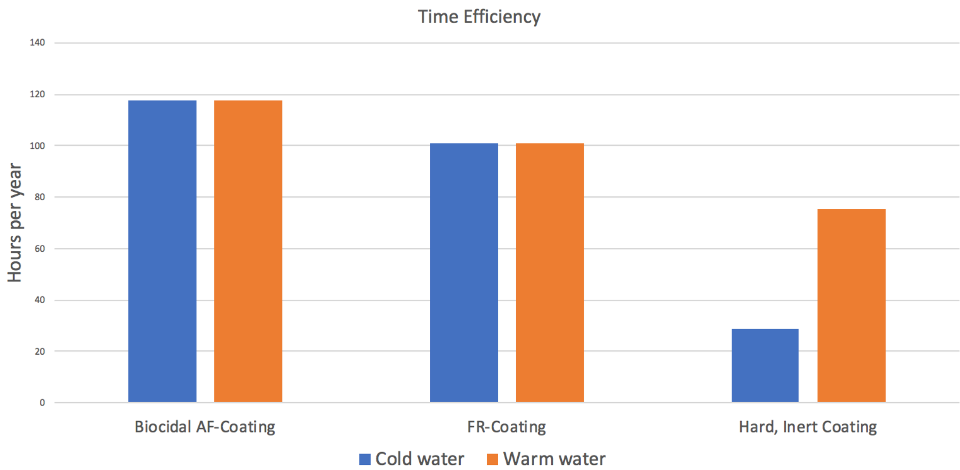



Figure 4.7: Time Efficiency in hours spend on dry docking and/or cleaning

The above results in figure 4.7 are based on average values. The results aren't fixed ones and depend on different factors. We can see that the Hard, Inert Coating has the best time efficiency for vessels in cold and warm water. Another remark is that the cleaning must be done more repeatably and the time a vessel has to go to the dry dock is in the same period of time which can be seen as a disadvantage for the shipowners to do more repeatably cleaning work. An overview is shown in table 4.8.

| Biocidal AF-coating | FR-coating | Hard, Inert coating |
|---|---|---|
| Visit to dry dock on average 8 times each 25 years. Multiple coats and lengthy curing times can mean 2 - 3 weeks in dry dock for a full repaint. | Visit to dry dock on average 7 times each 25 years. 2-3 weeks in dry dock for a full repaint. Multiple layers needed lengthy curing times | Applied once to a hull. No need to repaint beyond minor touch-ups during routine dry docking. Must be cleaned regularly |

Table 4.8: Overview Time Efficiency

## 4.6. Possibility to in-water cleaning

**Biocidal AF-Coating:**
Cannot be cleaned underwater without the hazard to the environment. It is also invariably destructive to the coating which becomes depleted more rapidly. One US Navy source estimated that a single cleaning could remove 30% - 51% of the remaining antifouling coating. (Ingle, 2007) This is hazardous to the environment and expensive to the shipowner/operator. See in Appendix E Figure E.1. the footage of in-water cleaning of a Biocidal AF-Coating.

**FR-Coating:**
FR-Coatings are easily damaged and must be cleaned extremely gently which is only useful if the fouling is no more than a biofilm. Great care must be taken to make sure that only the mildest of tools are used and the integrity of the coating is not compromised through careless or aggressive cleaning. (Rompay, 2012)

**Hard, Inert Coating:**
An experiment was set up to determine the amount of substances released during cleaning. These tests were carried out in tanks with a restricted amount of water to avoid dilution effects. The toxicity tests performed on the water samples before and after the treatments, gave no evidence of toxic effects from the released substances. It was therefore concluded to be unlikely that the release of substances during cleaning will have a harmful effect on surface water quality. (ECOTEC-STC) See in Appendix E Figure E.2. the footage of in-water cleaning of a Hard, Inert Coating.

**Conclusion:**
An overview is shown in table 4.9.

| Biocidal AF-Coating | FR-coating | Hard, Inert Coating |
|---|---|---|
| Could not be cleaned. It has been developed to prevent fouling by the release of chemicals. If you clean this coating, you accelerate this release process and you will eventually damage the coating and toxic biocides will be released into the water. If this coating is cleaned in a dry dock, released chemicals find its way back to the port/sea. | A FR-coating system can be cleaned, but this must be done in a cautious manner. These coatings are very fragile and can be damaged quickly. Some of these coatings are toxic, causing a physical change in the organisms. These organisms can also suffocate through the use of silicones. | Fouling can accumulate with these coatings on the hull. But they can be cleaned in or out of the water without the release of toxic substances that can damage the environment. In addition, cleaning the hull will reduce fuel costs because the vessel has less resistance. |

Table 4.9: Overview possibility to in-water cleaning (The Hydrex Group, 2011)

# 5
# Consideration of alternatives

## 5.1. Multi Criteria-Analysis

### 5.1.1. Effect Table

The scores per criterion for the various coating systems are placed in the effect table 5.1. The criteria are explained in appendix F. In appendix G the standardization effect table is shown including the weight tables. We opted for a linear scale, since this option is the most representative for this multi-criteria analysis.

| | Biocidal AF-Coating | FR-Coating | Hard, Inert Coating |
|---|---|---|---|
| Public health | - - | - | + + |
| Longevity | 3,125 years | 3,57 years | +25 years |
| Protection | - | - - | + + |
| Time Efficiency | 117,6 hours | 100,8 hours | 52 hours |
| Initial costs | 25 € / m2 | 50 € / m2 | 45 € / m2 |
| Lifetime Cost | 5,1 million € | 5,4 million € | 2,3 million € |
| Environmental problems | - - | - | + + |
| Fuel efficiency | 45% inefficient | 45% inefficient | 15% inefficient |

Table 5.1: Effect Table

### 5.1.2. Weight Factors

To calculate the weight of the criteria, each criterion has been weighed against each other. The maximum number to be given is a ten, and the lowest possible number must be zero. To arrive at a weight, the scores are added per criterion. These total scores per criterion represent the weights of the criteria. The maximum score for a criterion is 60 points. These weights are determined by four different involved parties. Namely from the standpoint of a shipyard, shipping company and a coating company. The weight tables are shown in Appendix G.

### 5.1.3. Determination of Ranking

To determine the ranking of the three variants, the standardized criterion scores have been multiplied by the specific weight per criterion. The criterion scores have been standardized by giving the results of the effects table a score from 0 to 1, as can be seen in Appendix G.

| | Biocidal AF-Coating | FR-Coating | Hard, Inert Coating |
|---|---|---|---|
| Total score per variant | 0,3 | 0,2 | 0,8 |
| Ranking | 2 | 3 | 1 |

Table 5.2: Ranking of the Alternative Coating Systems

After multiplying the criteria with the weights, a total score per variant could be found. The ranking and total score per variant are shown in table 5.2. The Hard, Inert Coating has the best score based on the several criteria and is ranked first. This coating system is found to be a better system in comparison to the coating systems that are used today in the shipping industry.

# 6
# The Best Solution

## 6.1. Introduction

From the multi-criteria analysis, the conclusion can be made that the third coating system (Hard, Inert Coating) gives the best results. The next logical step is to explain the technology and practices and how it can solve the current problems in the shipping industry, going from ocean pollution to the protection of the mankind.

## 6.2. What Is The Best Practice

The hull is thoroughly prepared so that the coating adheres perfectly. This will guarantee its lasting the lifetime of the vessel.

If a vessel currently has a Biocidal AF-Coating or a FR-Coating, this should be replaced as soon as possible with a Hard, Inert Coating which can be cleaned repeatedly in the water without suffering any damage and, in fact, with improvement after each cleaning. The Hard, Inert coating is applicable on every type of vessel. Going from large cargo ships, to pleasure boats.

If a vessel had lain idle for some time at a port so that the hull has become fouled to any degree, the hull should be cleaned in-water before the vessel sails. Afterwards, the ship would be inspected by a classification society and receive a clean bill of health.

The vessel thus sails at an optimum performance, resulting in minimal fuel consumption and therefore minimal GHG emissions. Arriving at a foreign port, the vessel presents a certificate form a classification society or some other qualified body showing that:

- The hull coating is non-toxic and non-polluting.
- The hull was 100% clean on sailing and therefore on arrival. (vessel generally does not pick up fouling when sailing)

The port of arrival rewards such a vessel with reduced port fees. The opposite also applies. If a vessel arrives with a toxic system and in a fouled state, the port authority imposes a penalty and requires that it should be cleaned immediately, with precautions taken to reduce pollution and prevent the spread of NIS.

If the vessel remains any significant length of time in the port of arrival so that fouling builds up, it is again cleaned in the water in port and a certificate is again issued before she sails off. If applied consistently by all ports, this approach will eventually bring about a very desirable result: the ports will remain clean, vessels will sail with unfouled hulls, fuel consumption will drop, GHG will be reduced, NIS will not be spread. And it will benefit the public health. (The Hydrex Group, 2011) This approach is shown in figure 6.1.

## 6.3. Answers To The Problems

### 6.3.1. Answer To Woldwide Pollution

The way to avoid pollution of toxic chemicals released directly from a vessel's hull into the oceans, ports and inland waterways, will only permit coatings which are non-polluting, not leaching, not harmful, and non-toxic in any way to the marine environment.

The hard coating does not leach any destructive chemicals like herbicides, pesticides, heavy metals or harmful oils into the water. It is inert and does not produce any chemical reaction when immersed in sea water or fresh water. (A. Wijga, 2008) The sediments of ports, rivers and oceans are better protected from pollution. Besides that, the water quality will benefit and therefore public health. (The Hydrex Group, 2011)

### 6.3.2. Answer To Fuel Penalty And Greenhouse Gases (GHG)

The way to keep the fuel consumption as low as possible from the point of view of the hull is:

- Hydro-dynamically efficient hull
- Hull which is smooth and remains smooth over time and does not add resistance
- Keep the hull fouling free. In-water cleaning on the right type of coating
- Inspect the vessel before sailing and, if the hull is fouled, clean it before leaving the port

The hard, inert coating is made to clean in-water whereby no toxic chemicals are leached into the water. By cleaning and keeping the hull smooth, the lowest resistance will be reached and a higher speed will be achieved. The vessel can save 30% or more on fuel compared to the Biocidal AF-Coating or FR-coating. (The Hydrex Group, 2011)

### 6.3.3. Answer To The NIS-problem

Vessels should be inspected before they sail and cleaned if the hull is fouled. This serves a dual purpose of preventing the spread of NIS and reducing fuel consumption. The marine organisms will stay at their own ecosystem and won't invade other ones somewhere over the world. This will save a lot of money for the governments. The spread may cause a major economic problem in some countries. The Hard, Inert Coating is made to be cleaned in-water, so the aquatic organisms stay at their own environment and won't harm others.

### 6.3.4. Answer For The Mankind

Who benefits from this approach? Just about everyone who is involved. Shipowners and operators save huge amounts of money by reducing fuel consumption. Port authorities and governments benefit by eliminating the pollution of the ports and stop the spread of NIS to avoid the harming of the marine ecosystems. Also reducing greenhouse gases and the pollution caused by biocides. Because this approach is non-toxic it will benefit the public health and our next generations.

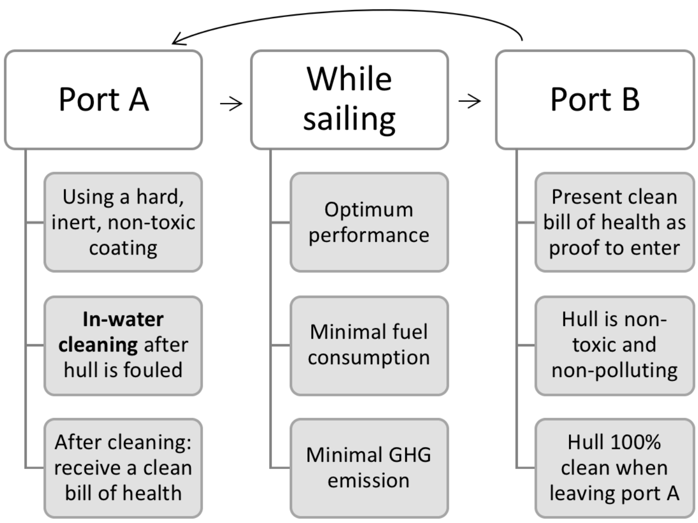



Figure 6.1: The Best Approach, a Hard, Inert Coating System

# 7

# Cleaning Aspect

## 7.1. Introduction

The Hard, Inert Coating gives the best results. But the system differs from the other two coating systems. The cleaning part must not be forgotten, otherwise the workability of the Hard, Inert Coating is less efficient. This process of in-water cleaning will be explained in this chapter.

## 7.2. Why Cleaning?

Any level of fouling, including biofilm or slime, results in inefficient fuel consumption. The increase in fuel consumption due to increased resistance in comparison with a clean hull may be as much as 50% (IMO, 2002). A vessel with a clean hull moves faster through the water and uses less energy. There is currently no hull coating available which will not foul. Some coatings are more resistant to heavy fouling than others; some coatings make it harder to heavy fouling to adhere; some are easier to lose fouling while traveling, particularly at speed. But all coatings will foul, even if the fouling is limited to slime and weed. This fouling results in negative consequences shown in table 7.1.

| | Additional Shaft Power (%) | Additional Fuel in 2020 (millions tonnes) | CO2 Emissions (million tonnes) | Additional Fuel Cost (billion) |
|---|---|---|---|---|
| Freshly applied Coating | 0 | 0 | 0 | 0 |
| Deteriorated coating or thin slime | 9 | 44 | 134 | 22 |
| Heavy slime | 19 | 92 | 279 | 46 |
| Small calcareous fouling or macroalgae | 33 | 160 | 486 | 80 |
| Medium calcareous fouling | 52 | 253 | 768 | 127 |
| Heavy calcareous fouling | 84 | 408 | 1238 | 204 |

Table 7.1: Estimated effect of effective fouling control on annual fuel consumption and CO2 emissions [for all shipping]. All figures are projected to 2020 and are compared to a fouling free hull (the increased shaft power as a function of the fouling degree is obtained from Schultz (Schultz, 2007) and is based on his calculations for an Oliver Hazard Perry class frigate sailing at 15 knots) (IPPIC, 2009)

The only way to remove this, is by cleaning it off. This can be done in dry dock using pressure washing with widely varying results depending on the type of coating and the degree of fouling. Or it can be done underwater with a variety of methods. Vessel hull cleaning is an essential part of operating a vessel efficiently and economically. Having decided hull cleaning is essential, it is worth looking at how to get it done in a cost-effective and environmentally safe manner.

## 7.3. How To Clean

There are two main choices: clean in dry dock or clean underwater. Cleaning in dry dock using pressure washing is applicable on all coatings unless the fouling has become too heavy to wash off. In theory, even Biocidal AF-coatings can be cleaned in dry dock. But the waste water and biocides should be handled with care. FR-coatings, providing the fouling is limited to slime, can also be cleaned in dry dock by low pressure water jet because these hulls are very smooth. The major problem with cleaning in a dry dock is that it is too expensive to dry dock a vessel with the frequency to keep the hull free of fouling (once every 6 weeks). Besides that, the vessel's operating schedule will be interrupted too much. But there are several useful techniques and methods of underwater cleaning under research and development. The best practice at this moment of underwater cleaning (Rompay, 2012) consists of the following elements:

1. Divers specially trained and experienced in underwater vessel hull cleaning
2. Self-propelled mechanical underwater cleaning machines with rotating tools (or scrapers in the case of heavy fouling) which are kept in contact with the hull by suction and steered by a diver (these are used to clean the fouling off the larger areas of the hull such as the vertical sides or the flat bottom)
3. Smaller mechanical tools to clean areas where the larger machines cannot reach or clean
4. Hand scrapers and tools to clean niche areas
5. The above are best accomplished with the vessel at anchor rather than quayside, allowing easy access to all parts of the hull including the flat bottom. When the vessel is against the quay, diving to clean the vertical side next to the quay will be difficult by fenders, and the flat bottom is often too close to the harbour bottom to allow the diver easy access and freedom of movement. An alternative, if the vessel has to be cleaned while moored rather than at anchor, is just to clean the outer side of the hull. When the vessel reaches its destination, it can be moored facing the opposite direction and the side of the hull which was not cleaned before, can now be accessed easily for cleaning. It is not ideal since the vessel sails with half the hull fouled to some degree at least. It is preferable to clean a vessel at anchor and this can be done while bunkering or other normal operations are in progress so as not to disrupt operations.
6. Cleaning is best done by well trained and equipped divers operating from dedicated work boats set up for rapid and efficient dive support, using fast, powerful hydraulic rotating tool cleaning machines (explained in subsection 7.4.2). Done this way, using two or more work boats with several diver teams on each, the largest VLCCs (Very Large Crude Carrier) can be cleaned 100% in 6 - 12 hours. The cost of effective, rapid cleaning is dwarfed by the savings that will be gained as an immediate result. Usually the payback will be achieved before the next crossing is complete.
7. Independent verification of the cleaning where there is any doubt about the performance of the company employed.

## 7.4. Efficient cleaning: Underwater Observation

### 7.4.1. Footage underwater

See Appendix H for the footage of underwater cleaning.
Just as the Hard, Inert coating is applicable to every type of vessel, so are the cleaning tools. Going from a cargo ship to pleasure boats. This is explained in the section 7.4.2.

### 7.4.2. Used Tools

A range of systems is available for various applications on all types of vessels; from propellers on small pleasure boats up to the hulls of 400 meter container ships. All kinds of fouling can be removed very effectively; light slime as well as thick layers of heavy marine growth. The units can be used with different brushes for different conditions of fouling. The range of tools needed for cleaning in-water are shown beneath. All kind of brushes can be attached to the cleaning units. Some brushes are very soft for light fouling. Some are very rough, made of iron wire to clean heavily fouled hulls. Some of the brushes are shown below figure 7.1.

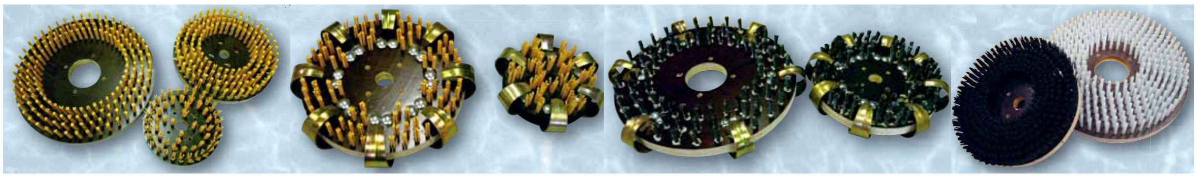


Figure 7.1: Rilsan Brush (grass, slime, small barnacles), Rilsan Scraper (Barnacles), Steel Scraper (very dense fouling), Polyprop (grass slime, very fragile surfaces) (Subsea Industries, 2018)

### The Hand Unit

The hand unit is the smallest model specially designed for cleaning and polishing vessel hulls, propellers and thrusters (see figure 7.2). It is very handy and can be easily taken into difficult corners and niches while still obtaining the desired results. (Sub. Ind., 2018) In figure 7.3, the specifications are shown.

Figure 7.2: The hand device without brushes attached (Sub. Ind., 2018)

Specifications:

- Dimensions:
  - Length: 300 mm
  - Width: 180 mm
  - Height: 60 mm
- Weight: 5 kg
- Hydraulic requirement: 20ltr/min @ 140 bar

Figure 7.3: Specifications of the hand unit (Sub. Ind., 2018)

### The Pod Unit

The pod unit is a single tool unit designed for cleaning all types of marine fouling from yachts and smaller vessels to offshore oil & gas platforms (see figure 7.4). The brush rotation speed is adjustable by the diver to achieve an optimum hourly cleaning rate. The pod unit is ideal to clean smaller areas such as bilge keels, propellers and the rudder. Niche areas that are hard to reach also pose no problem for this flexible one brush unit. (Sub. Ind., 2018) In figure 7.5, the specifications are shown.

Figure 7.4: The pod unit (Sub. Ind., 2018)

Specifications:

- Dimension:
  - Machine diameter: 235 mm
  - Brush diameter: 300 mm
- Weight in air: 9 kg
- Weight in seawater: 1 kg
- Cleaning rate: 300 m2/hour
- Depth rating: 70 m
- Hydraulic requirement: 20ltr/min @ 140 bar

Figure 7.5: Specifications of the pod unit (Sub. Ind., 2018)

### The Twin Brush Unit

The twin brush unit consists of two halves connected by a hinge joint and is designed for cleaning light and heavy marine fouling from offshore oil & gas platforms, jetties, piles, windmills and other round structures as well as middle sized vessels (see figure 7.6). The equipment has a self-balancing feature, which allows the operator to use the tool safely and effortlessly for extended periods. The removal of very thick layers of marine fouling proved to be no problem at all for this cleaning unit. Besides being ideal to clean rounded surfaces, the twin brush unit is also a very good choice when cleaning middle sized vessels fast and efficiently. (Sub. Ind., 2018) In figure 7.7, the specifications are shown.

Figure 7.6: The twin brush unit (Sub. Ind., 2018)

Specifications:

- Dimensions:
  - Length: 450 mm
  - Width: 800 mm
  - Height: 250 mm
- Weight in air: 23kg
- Weight in seawater: 1 kg buoyant
- Cleaning rate: 450 m2/hour
- Depth rating: 70 m
- Hydraulic requirement:40ltr/min @ 140 bar

Figure 7.7: Specifications of the twin brush unit (Sub. Ind., 2018)

### The Four-Wheel Drive Unit

The design of the underwater hull cleaning unit will stand up to the most difficult underwater cleaning conditions encountered on various types of vessels (see figure 7.8). The downward pressure of the brushes can be adjusted throughout the operation and follow the contours of the hull. Cleaning speeds of up to 1500 m² per hour can be established with a powerful four-wheel drive system. Both light and very heavy fouling can be treated with the appropriate pressure and tools so damage is prevented to the underlying paint layers. It is designed for larger vessel hulls or other large, reasonably flat surfaces. The four-wheel drive unit is regularly used to clean large cruise ships. This operation takes full advantage of the versatility of the unit. The specific shape of the vessel makes the four-wheel drive system the best choice for the job. The fact that the machine can be put into reverse and has heads that self-adjust to the contours of the hull makes these complex areas so much easier to clean. (Sub. Ind., 2018) In figure 7.9, the specifications are shown.

Figure 7.8: The four-wheel drive unit (Sub. Ind., 2018)

Specifications:

- Dimensions:
  - Length: 1240 mm
  - Width: 1040 mm
  - Height: 45 mm
- Weight in air: 133kg
- Weight in seawater: 10 kg buoyant
- Cleaning rate: 1500 m2/hour
- Depth rating: 70 m
- Hydraulic requirement:80ltr/min @ 140 bar

Figure 7.9: Specifications of the drive unit (Sub. Ind., 2018)

The Hydraulic Power Unit

The PP018 hydraulic power unit (See figure 7.10) is proficient for running one and two brush units. It is an efficient and reliable power unit that is easy to handle and transport.
The PP100 hydraulic power unit (See figure 7.11) is proficient for running all the cleaning units. In appendix I, the specifications of the hydraulic power units are shown.

Figure 7.10: The PP018 Hydraulic Power Unit (Sub. Ind., 2018)

Figure 7.11: The PP100 Hydraulic Power Unit (Sub. Ind., 2018)

The Cleaning Energy Consumption

The cleaning energy consumption is calculated in appendix I. The calculations were based on a ship with a 9000 square meter hull. In results are shown in table 7.2 below.

| | **Time [Hours]** | **Work [kWh]** | **Energy Costs (€)** |
|---|---|---|---|
| **The Pod Unit** | 30 | 402 | 320,4 |
| **The Twin Brush Unit** | 20 | 268 | 213,6 |
| **The Four-Wheel Drive Unit** | 6 | 468 | 151,31 |

Table 7.2: Cleaning energy consumption of a 9000m2 hull with the different cleaning units

## 7.5. Is The Infrastructure Ready To Adapt?

While industrial quality underwater cleaning is available now, the infrastructure is far from mature. As the industry changes to this non-toxic economically efficient system, this infrastructure will have to build up so that hull monitoring and high quality underwater cleaning become more and more available around the world. When the gasoline engine automobile was first invented there was no network of gasoline stations around the world. But it did not take long for such a network to be established. Nowadays one has to work fairly hard to run out of gasoline and not have a station nearby. As the need to clean these automobiles became apparent, the car wash was invented and has now become a regular feature in gasoline pumps and service stations. As mobile phones become a part of life, so do charging stations at airports, in airplanes, trains and cars. As the Internet becomes another utility, so WIFI becomes available on airplanes, cruise ships, at airports, restaurants and coffee shops, let alone in every house and office building. One can logically expect the same phenomena to apply to underwater vessel hull cleaning as more and more shipowners realize that the solution to fuel saving and environmental protection is a Hard, Inert, Non-Toxic Coating coupled with routine underwater cleaning. It is worth mentioning here that the idea of a "car wash" for vessels has been considered but no workable version has been devised because of the insurmountable obstacle presented by the extreme variety of hull shapes and sizes and by the differences between conditions and physical laws which apply under the water and those which apply on land. However, lately more research is done to find an applicable and a faster solution for cleaning. The idea is feasible, but the details are not released so far because the patents are not finished yet. This is an industrial cleaning method and could clean 100.000 square meters in an hour. The future of fast in-water cleaning is going to the right direction.

# 8 Conclusion

The best approach examined by multiple criteria, is the use of a Hard, Inert Coating. Toxic compounds, like zinc anodes and copper, won't be released into our waterways anymore. Therefore, the sediments of rivers and ports are better protected from pollution. Which benefits the water quality and the public health.

The Hard, Inert Coating is the solution to prevent the NIS (non-indigenous species) problem. Because the vessel will be cleaned before leaving the port, no more marine organisms will be transported from their own ecosystem to another. Governments and port authorities will save a lot of money by preventing this problem.

Clean hulls will give less resistance and will save a lot of fuel consumption and improve its speed. The ship operators/owners will save a lot of money each year. The Hard, Inert Coating loses ±15% of the shaft power and the Biocidal AF-Coating and FR-Coating ±45%. With the degradation factor of the Biocidal AF-Coating and FR-Coating systems added, the fuel consumption inefficiency is ±75% and for the Hard Inert coating ±15% because no degradation will occur in the case of the hard coating. Worldwide, the Hard, Inert Coating system could save $70.000.000.000 worldwide in one year. (Rompay, 2012) The sixteen largest ships in this world provide just as much pollution as 800 million cars. If you save 30 percent on fuel, it's like you're taking 240 million cars off the road.

The cleaning part must not be forgotten, otherwise the workability is less efficient. From underwater observation, the existing cleaning systems for non-toxic coatings are convenient enough to be useful. But the better systems are invented, the easier the cleaning aspect will become. And the faster the shipping industry is able to adapt to this system.

As Hard, Inert Coatings are clean and do not emit harmful substances, more jobs in North-West Europe will be created. Currently, most ships go for repairs to dry docks in southern Europe and the Persian Gulf. Ruling on the use of toxic compounds are less observed here. By introducing a Hard, Inert Coating repainting is no longer required and ships can be dry docked without any negative effects on the environment. In other words they can dry dock "clean". This will substantially increase the amount of work for ship repair yards in North-West Europe as owners do prefer these yards for technical and availability of service reasons.

The paint of the Hard, Inert Coating lasts its whole lifetime, except for some touch-ups. The other two coating systems must visit the dry dock about every 3-4 years. It can be estimated that if 80% of the world fleet would switch from Biocidal AF-Coatings to Hard, Inert Coatings, 12 million liters of paint don't have to be applied every year, which saves significantly on material resources and associated transport costs.

The use of a 100% non-toxic coating to tackle the age-old problem of biofouling, will benefit the ecosystems all over the world. Different from the current situation, no more marine organisms will be polluted and killed. No more toxic chemicals will be released into the sediments of our ports, rivers and oceans. No more toxic substances will be absorbed by organisms and end up in our food chain. Our public health is continuously in danger by the fact that the toxic chemicals are released continuously day in day out.

# A

# Footage Degradation

In figure A.1 the degradation of vessels with Biocidal AF-Coatings and FR-Coatings can be seen. A vessel's hull experiences an increase in frictional resistance throughout its service life. One significant source of this increased resistance is the increased hull roughness caused by the deterioration of the underwater coating system through damage or corrosion.

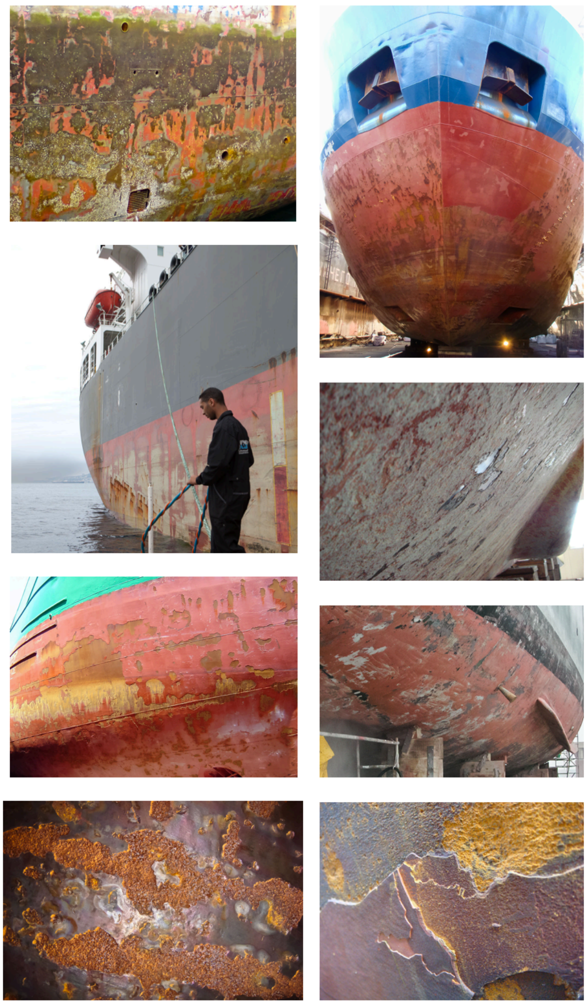


Figure A.1: Degradation of a Biocidal AF-Coating

# B
# Fuel Consumption Calculation

First the start resistance is calculated between the three different coating systems. This was found in an experiment to study the drag characteristics of different variants of coating systems in well-controlled laboratory conditions. Shown in table B.1.(ECOTEC-STC)

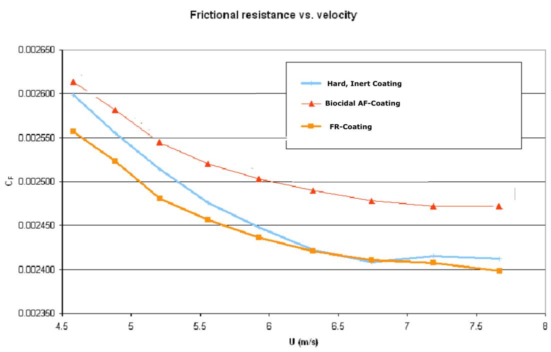



Figure B.1: Frictional resistance of the tested coatings versus towing speed (ECOTEC-STC)

Knowing that an unfouled hull of a Biocidal AF-Coating has 2-4% insufficient fuel consumption (Schultz, 2007) and the FR-Coating is the smoothest and can be set at 0, the ratio can be calculated between the three variants (Figure B.2 and B.3):

| Start Resistance | Difference from graph | Start resistance (%) |
|---|---|---|
| Biocidal AF-Coating | 75 | 3 |
| FR-Coating | 0 | 0 |
| Hard, Inert Coating | 13,3 | 0,532 |

Figure B.2: Ratio between the different coating variants at a speed of 8 m/s

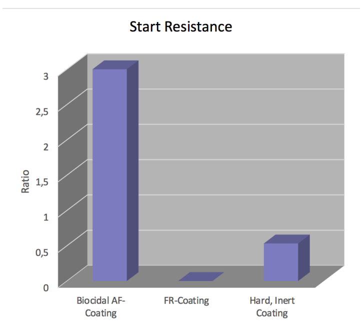



Figure B.3: Ratio between the different coating variants at a speed of 15 knots

These are the values for the start resistance of the different coating systems. Now the resistance of the fouling is calculated. From the table B.1 of Schultz (Schultz, 2007) the increased shaft power as a function of the fouling degree is shown.

| | Additional Shaft Power (%) | Additional Fuel in 2020 (millions tonnes) | CO2 Emissions (million tonnes) | Additional Fuel Cost (billion) |
|---|---|---|---|---|
| Freshly applied Coating | 0 | 0 | 0 | 0 |
| Deteriorated coating or thin slime | 9 | 44 | 134 | 22 |
| Heavy slime | 19 | 92 | 279 | 46 |
| Small calcareous fouling or macroalgae | 33 | 160 | 486 | 80 |
| Medium calcareous fouling | 52 | 253 | 768 | 127 |
| Heavy calcareous fouling | 84 | 408 | 1238 | 204 |

Table B.1: Estimated effect of effective fouling control on annual fuel consumption and CO2 emissions [for all shipping]. All figures are projected to 2020 and are compared to a fouling free hull (the increased shaft power as a function of the fouling degree is obtained from Schultz (Schultz, 2007) and is based on his calculations for an Oliver Hazard Perry class frigate sailing at 15 knots) (IPPIC, 2009)

Now the time of fouling has to be known to calculate the increased shaft power. Visscher has made an analysis of the relation of the duty of ships to fouling, based on the study of 217 vessels. The relation of the degree of fouling to the period spent in port is shown in figure B.4. (Visscher, 1927)

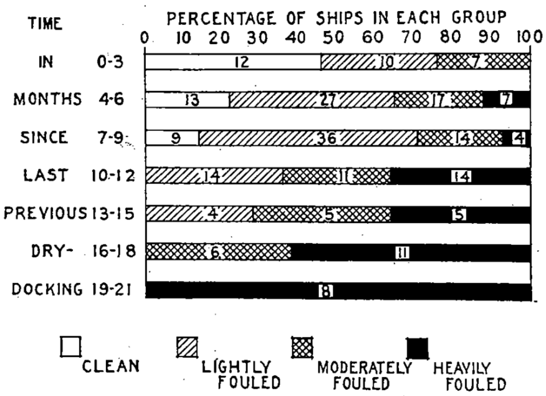



Figure B.4: Relation between amount of fouling and amount of time between dry dockings (Visscher, 1927)

The additional shaft power over a time period of 3 months can be calculated with the percentage of ships in each group (figure B.5 and B.6).

| Fouling over months | |
|---|---|
| 0 months | 0 |
| 0-3 months | 13,95 |
| 4-6 months | 22 |
| 7-9 months | 23,2 |
| 10-12 month | 34,75 |
| 13-15 month | 35,45 |
| 16-18 month | 44,4 |
| 19-21 month | 52 |
| 22-24 month | 52 |
| 3 years | 52 |
| 4 years | 52 |

Figure B.5: The additional shaft power over a time period of 3 months can be calculated

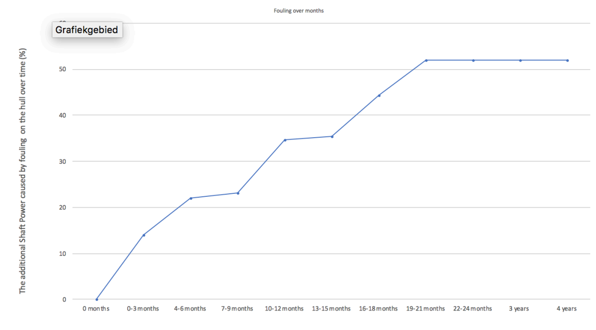



Figure B.6: The additional shaft power over a time period of 3 months can be calculated

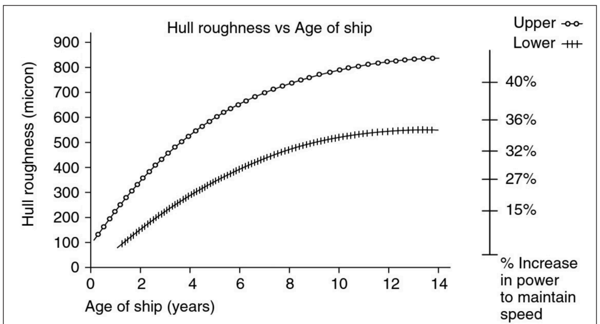
In excel the calculations for the total additional shaft power is made (figure B.7):

| Years | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biocidal AF-Coating | | | | | | | | | | | | | |
| **Basis resistance** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Degradation** | 0,00 | 0,00 | 4,00 | 10,00 | 15,00 | 21,00 | 27,00 | 29,00 | 31,00 | 32,00 | 33,00 | 34,00 | 35,00 |
| **Fouling** | 0 | 31,3 | 45,93 | 52 | 52 | 31,3 | 45,93 | 52,00 | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 |
| | 3,00 | 34,30 | 52,93 | 65,00 | 70,00 | 55,30 | 75,93 | 84,00 | 65,30 | 80,93 | 88,00 | 89,00 | 69,30 |
| FR-Coating | | | | | | | | | | | | | |
| **Basis resistance** | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| **Degradation** | 0,00 | 0,00 | 4,00 | 10,00 | 15,00 | 21,00 | 27,00 | 29,00 | 31,00 | 32,00 | 33,00 | 34,00 | 35,00 |
| **Fouling** | 0 | 31,3 | 45,93 | 52 | 52 | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 | 45,93 | 52,00 | 52,00 |
| | 0,00 | 31,30 | 49,93 | 62,00 | 67,00 | 52,30 | 72,93 | 81,00 | 83,00 | 63,30 | 78,93 | 86,00 | 87,00 |
| Hard, Inert Coating | | | | | | | | | | | | | |
| **Basis resistance** | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 |
| **Degradation** | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| **Fouling** | 0 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 |
| | 0,53 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 |
| **Met degradation** | | | | | | | | | | | | | |
| AF-HI | 2,47 | 19,82 | 38,45 | 50,52 | 55,52 | 40,82 | 61,45 | 69,52 | 50,82 | 66,45 | 73,52 | 74,52 | 54,82 |
| FR-HI | -0,53 | 16,82 | 35,45 | 47,52 | 52,52 | 37,82 | 58,45 | 66,52 | 68,52 | 48,82 | 64,45 | 71,52 | 72,52 |
| **Zonder Degradation** | | | | | | | | | | | | | |
| AF-HI | 2,47 | 19,82 | 34,45 | 40,52 | 40,52 | 19,82 | 34,45 | 40,52 | 19,82 | 34,45 | 40,52 | 40,52 | 19,82 |
| FR-HI | -0,53 | 16,82 | 31,45 | 37,52 | 37,52 | 16,82 | 31,45 | 37,52 | 37,52 | 16,82 | 31,45 | 37,52 | 37,52 |
| **Without Degradation** | | | | | | | | | | | | | |
| Biocidal AF-Coating | 3,00 | 34,30 | 48,93 | 55,00 | 55,00 | 34,30 | 48,93 | 55,00 | 34,30 | 48,93 | 55,00 | 55,00 | 34,30 |
| FR-Coating | 0,00 | 31,30 | 45,93 | 52,00 | 52,00 | 31,30 | 45,93 | 52,00 | 52,00 | 31,30 | 45,93 | 52,00 | 52,00 |
| Hard, Inert Coating | 0,53 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 |

| Years | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biocidal AF-Coating | | | | | | | | | | | | | |
| **Basis resistance** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Degradation** | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 |
| **Fouling** | 45,93 | 52,00 | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 | 45,93 | 52,00 | 31,3 | 45,93 | 52,00 | 31,3 |
| | 83,93 | 90,00 | 69,30 | 83,93 | 90,00 | 90,00 | 69,30 | 83,93 | 90,00 | 69,30 | 83,93 | 90,00 | 69,30 |
| FR-Coating | | | | | | | | | | | | | |
| **Basis resistance** | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| **Degradation** | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 | 35,00 |
| **Fouling** | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 | 45,93 | 52,00 | 52,00 | 31,3 |
| | 66,30 | 80,93 | 87,00 | 87,00 | 66,30 | 80,93 | 87,00 | 87,00 | 66,30 | 80,93 | 87,00 | 87,00 | 66,30 |
| Hard, Inert Coating | | | | | | | | | | | | | |
| **Basis resistance** | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 | 0,53 |
| **Degradation** | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| **Fouling** | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 | 13,95 |
| | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 |
| **Met degradation** | | | | | | | | | | | | | |
| AF-HI | 69,45 | 75,52 | 54,82 | 69,45 | 75,52 | 75,52 | 54,82 | 69,45 | 75,52 | 54,82 | 69,45 | 75,52 | 54,82 |
| FR-HI | 51,82 | 66,45 | 72,52 | 72,52 | 51,82 | 66,45 | 72,52 | 72,52 | 51,82 | 66,45 | 72,52 | 72,52 | 51,82 |
| **Zonder Degradation** | | | | | | | | | | | | | |
| AF-HI | 34,45 | 40,52 | 19,82 | 34,45 | 40,52 | 40,52 | 19,82 | 34,45 | 40,52 | 19,82 | 34,45 | 40,52 | 19,82 |
| FR-HI | 16,82 | 31,45 | 37,52 | 37,52 | 16,82 | 31,45 | 37,52 | 37,52 | 16,82 | 31,45 | 37,52 | 37,52 | 16,82 |
| **Without Degradation** | | | | | | | | | | | | | |
| Biocidal AF-Coating | 48,93 | 55,00 | 34,30 | 48,93 | 55,00 | 55,00 | 34,30 | 48,93 | 55,00 | 34,30 | 48,93 | 55,00 | 34,30 |
| FR-Coating | 31,30 | 45,93 | 52,00 | 52,00 | 31,30 | 45,93 | 52,00 | 52,00 | 31,30 | 45,93 | 52,00 | 52,00 | 31,30 |
| Hard, Inert Coating | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 | 14,48 |

Figure B.7: The calculations for the additional shaft power depending of the start resistance, stages of fouling and the degradation of the vessel's hull.

Finally two graphs are made: the graph of estimated additional shaft power depending on fouling and begin resistance (Figure B.9) and one graph of estimated additional shaft power depending on fouling, begin resistance and degradation of the hull (occurs when hull is not properly maintained) (Figure B.10). The degradation is based on the Hull Roughness vs age of ship for Biocidal AF-Coatings and FR-coating (Figure B.8). This is added in the graph each year. Only the Hard, Inert coatings is immune from general degradation. (MAREX , 2013)




*7.9* Increased average hull roughness with ship age and effect on powering.

Figure B.8: Hull roughness vs age of ship (The Hydrex Group, 2012)

From the graph B.9, we can see that the Biocidal AF-Coating and the FR-Coating loses ±45% of their fuel consumption efficiency based on start friction and fouling resistance. And the Hard, Inert coating loses ±15% fuel consumption.

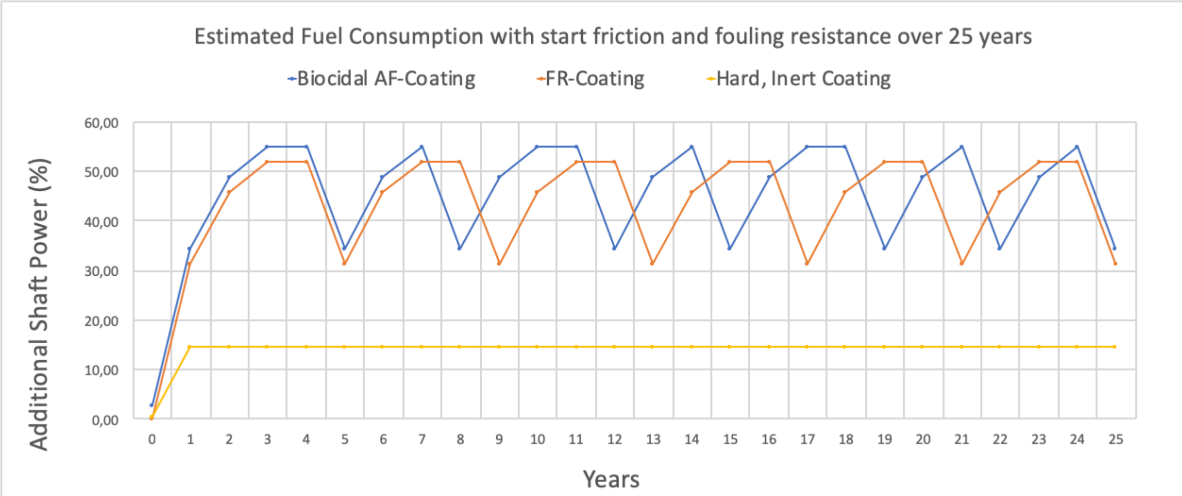



Figure B.9: Estimated Fuel Consumption Efficiency between the three coating systems

From the graph B.10, we can see that the Biocidal AF-Coating and the FR-Coating loses ±75% of their fuel consumption efficiency based on start friction, fouling resistance and degradation of the hull (if badly maintained). And the Hard, Inert Coating loses ±15%.

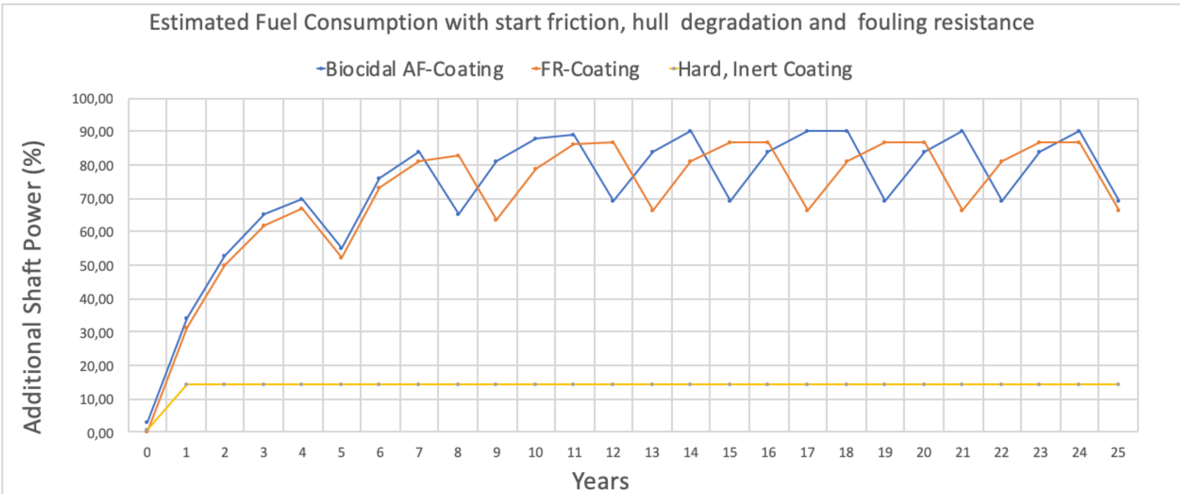



Figure B.10: Estimated Fuel Consumption Efficiency between the three coating systems

# C

# MSDS Coatings

## 1. Biocidal AF-Coating

**SECTION 3: Composition/information on ingredients**

**3.2 Mixtures** : Mixture

| Product/ingredient name | Identifiers | % by weight | Classification 67/548/EEC | Classification Regulation (EC) No. 1272/2008 [CLP] | Type |
|---|---|---|---|---|---|
| dicopper oxide | EC: 215-270-7<br>CAS: 1317-39-1<br>Index: 029-002-00-X | >=25 - <35 | Xn; R22<br>N; R50/53 | Acute Tox. 4, H302<br>Aquatic Acute 1, H400<br>Aquatic Chronic 1, H410 | [1] |
| zinc oxide | REACH #: 01-2119463881-32<br>EC: 215-222-5<br>CAS: 1314-13-2<br>Index: 030-013-00-7 | >=2.5 - <25 | N; R50/53 | Aquatic Acute 1, H400<br>Aquatic Chronic 1, H410 | [1] |
| rosin | REACH #: 01-2119480418-32<br>EC: 232-475-7<br>CAS: 8050-09-7<br>Index: 650-015-00-7 | >=5 - <10 | R43 | Skin Sens. 1, H317<br>Aquatic Chronic 4, H413 | [1] [2] |
| xylene | REACH #: 01-2119488216-32<br>EC: 215-535-7<br>CAS: 1330-20-7<br>Index: 601-022-00-9 | >=5 - <10 | R10<br>Xn; R20/21, R65<br>Xi; R36/37/38 | Flam. Liq. 3, H226<br>Acute Tox. 4, H312<br>Acute Tox. 4, H332<br>Skin Irrit. 2, H315<br>Eye Irrit. 2, H319<br>STOT SE 3, H335 (Respiratory tract irritation)<br>Asp. Tox. 1, H304 | [1] [2] |
| Solvent naphtha (petroleum), light arom. | REACH #: 01-2119455851-35<br>EC: 265-199-0<br>CAS: 64742-95-6<br>Index: 649-356-00-4 | >=2.5 - <10 | R10<br>Xn; R65<br>Xi; R37<br>R66, R67<br>N; R51/53 | Flam. Liq. 3, H226<br>STOT SE 3, H335 and H336 (Respiratory tract irritation and Narcotic effects)<br>Asp. Tox. 1, H304<br>Aquatic Chronic 2, H411 | [1] [2] |
| bis(1-hydroxy-1H-pyridine-2-thionato-O, S)copper | EC: 238-984-0<br>CAS: 14915-37-8 | >=3 - <5 | T+; R26<br>Xn; R22<br>Xi; R41<br>N; R50 | Acute Tox. 4, H302<br>Acute Tox. 2, H330<br>Eye Dam. 1, H318<br>Aquatic Acute 1, H400<br>Aquatic Chronic 1, H410 | [1] |
| ethylbenzene | REACH #: 01-2119489370-35<br>EC: 202-849-4<br>CAS: 100-41-4<br>Index: 601-023-00-4 | >=1 - <3 | F; R11<br>Xn; R20, R48/20, R65<br>Xi; R36/37/38 | Flam. Liq. 2, H225<br>Acute Tox. 4, H332<br>Skin Irrit. 2, H315<br>Eye Irrit. 2, H319<br>STOT SE 3, H335 (Respiratory tract irritation)<br>STOT RE 2, H373 (ears) (inhalation)<br>Asp. Tox. 1, H304 | [1] [2] |
| | | | **See Section 16 for the full text of the R-phrases declared above.** | **See Section 16 for the full text of the H statements declared above.** | |

*Date of issue/Date of revision* : *27/08/2015.*
*Version : 1.02* *3/18*

*YBC100* *Micron 99 Dover White*

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment, are PBTs or vPvBs or have been assigned a workplace exposure limit and hence require reporting in this section.

Type

[1] Substance classified with a health or environmental hazard
[2] Substance with a workplace exposure limit
[3] Substance meets the criteria for PBT according to Regulation (EC) No. 1907/2006, Annex XIII
[4] Substance meets the criteria for vPvB according to Regulation (EC) No. 1907/2006, Annex XIII
[5] Substance of equivalent concern

Figure C.1: MSDS Biocidal AF-Coating: Composition/information on ingredients product (AkzoNobel, 2015)

2. FR-Coating

## SECTION 3: Composition/information on ingredients

**3.2 Mixtures** : Mixture

| Product/ingredient name | Identifiers | % by weight | Classification Regulation (EC) No. 1272/2008 [CLP] | Nota (s) | Type |
|---|---|---|---|---|---|
| pentane-2,4-dione | EC: 204-634-0<br>CAS: 123-54-6<br>Index: 606-029-00-0 | ≥38 - <50 | Flam. Liq. 3, H226<br>Acute Tox. 4, H302<br>Acute Tox. 3, H311<br>Acute Tox. 3, H331 | - | [1] |
| dioctyltin dilaurate | EC: 222-883-3<br>CAS: 3648-18-8 | ≥5 - <10 | Repr. 2, H361fd (Fertility and Unborn child)<br>STOT RE 2, H373<br>Aquatic Chronic 3, H412 | - | [1] [2] |
| | | | **See Section 16 for the full text of the H statements declared above.** | | |

*Date of issue/Date of revision* : *26/07/2016*
*Version : 2* *2/14*

*FXA983* *Intersleek 970 Part C*

## SECTION 3: Composition/information on ingredients

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment, are PBTs or vPvBs or have been assigned a workplace exposure limit and hence require reporting in this section.

Type

[1] Substance classified with a health or environmental hazard
[2] Substance with a workplace exposure limit
[3] Substance meets the criteria for PBT according to Regulation (EC) No. 1907/2006, Annex XIII
[4] Substance meets the criteria for vPvB according to Regulation (EC) No. 1907/2006, Annex XIII
[5] Substance of equivalent concern

Occupational exposure limits, if available, are listed in Section 8.

Figure C.2: MSDS FR-Coating: Composition/information on ingredients product (AkzoNobel, 2016)

# 3. Hard, inert coating

#### 4.2.2. Toxicity/oestrogen effects leaching samples

In the table given below, the results of the toxicity tests are summarized.[3] Hardly any effects are observed. Only in the test with the crustacean *Acartia tonsa* a very, very small effect (EC50 94,1%) is noticed. Because of the fact that there is already some effect in the blank seawater, one can assume that the shown effect is nil. This means that the leached components don't lead to any shown effects. These samples are harmless compared to similar tests of some industrial discharges.

This means in real terms that when a ship will be launched after 24 hours, it is out of the question that one can find toxic effects because of leaching components. It should be mentioned that the hardening of the coating happened very fast due to the high outside temperatures[4]

| | unit | blank seawater | 2 plates in seawater | 1 plate in seawater |
|---|---|---|---|---|
| Leaching time | hours | 168 | 168 | 168 |
| Lab code | | 107107 | 107106 | 107111 |
| Toxicity tests | | | | |
| Microtox (bactery-test) | | | | |
| EC20 | % vol. | >50 | >50 | >50 |
| EC50 | % vol. | >50 | >50 | >50 |
| *Acartia tonsa* | | | | |
| EC50 | % vol. | >100 | 94,1 | >100 |
| NOEC | % vol. | 32 | 10 | 100 |
| *Phaeodactylum tricornutum* | | | | |
| EC50 | % vol. | >100 | >100 | >100 |
| NOEC | % vol. | 100 | 100 | 100 |
| Oestrogen effects | | | | |
| ER Calux | pg EEQ/l | <LOQ (72) | 82 | Not set |

Figure C.3: Information Hard, Inert Coating: Composition/information on ingredients product (A. Wijga, 2008)

**GENERAL INFORMATION**

| | |
|---|---|
| Toxicity | Nil<br>100 % tin free<br>100 % copper free<br>100 % biocide free |
| VOC – 1998 compliant | 1990 EPA-PG6/23(97) Clause 20(d) – industrial<br>1990 EPA-PG6/23(97) Clause 20(e) – marine |

Figure C.4: General Information Hard, Inert Coating (Subsea Industries, 2018)

| | unit | Water toxicity before polishing | Water toxicity after polishing |
|---|---|---|---|
| Leaching time | uur | 168 | 168 |
| Lab code | | 107111 | 107110 |
| Toxicity test | | | |
| Microtox (bacterialtest) | | | |
| EC20 | % vol. | >50 | >50 |
| EC50 | % vol. | >50 | >50 |
| *Acartia tonsa* | | | |
| EC50 | % vol. | >100 | >100% |
| NOEC | % vol. | 100 | 100 |
| *Phaeodactylum tricornutum* | | | |
| EC50 | % vol. | >100 | >100 |
| NOEC | % vol. | 100 | 100 |
| Oestrogenic effects | | | |
| ER Calux | pg EEQ/l | 192 | 104 |

The results of the oestrogenic tests are also presented in the table. De oestrogenic activity is slightly decreased after polishing. The demonstrated activity is low and below the level that effects are observed in studies on fish.

Figure C.5: The toxicity tests before and after polishing. (A. Wijga, 2008)

# D

# Calculation Time Efficiency

**Biocidal AF-Coating:**
8 times visit dry dock / 25 year
First visit is at the beginning of the lifetime of the vessel, so this one does not count in the time efficiency while operating.
The inspection is done during the (re-)application of the paint.
Average time in dry dock is 2,5 weeks

7 times visit dry dock / 25 year * 2,5 weeks = 0,56 weeks spent each year
= 4,9 days spent each year
= **117,6 hours** spent each year on dry docking (=4,9 days)

**FR-Coating:**
7 times visit dry dock / 25 year
First visit is at the beginning of the lifetime of the vessel, so this one does not count in the time efficiency while operating.
The inspection is done during the (re-)application of the paint.
The average time in dry dock is 2,5 weeks

6 times visit dry dock / 25 year * 2,5 weeks = 0,6 weeks spent each year
= 4,2 days spent each year
= **100,8 hours** spent each year on dry docking (=4,2 days)

**Hard, Inert Coating:**
5 times visit dry dock / 25 year for inspection
Average time in dry dock is 4 days.

5 times visit dry dock / 25 year * 4 days = 0,8 days spent each year
= 19,2 hours spent each year on dry docking

- Cold water: 37,5 times cleaning / year of ±6 hours = 9,4 hours spent each year on cleaning
- Warm water: 225 times cleaning / year of ±6 hours = 56,25 hours spent each year on cleaning

Total time for cleaning and dry docking:

- Total time spent cold water: 19,2 + 9,4 = **28,6 hours** (=1,19 days)
- Total time spent warm water: 19,2 + 56,25 = **75,45 hours** (=3,14 days)

| Type Coating | Visit Dry dock / 25 Year | Duration Visit | Cleaning / 25 year | Time Cleaning | Total Time Spend / Year |
|---|---|---|---|---|---|
| Biocidal AF-Coating | 7 times | 2,5 weeks | 0 times | 0 hours | 4,9 days |

| Type Coating | Visit Dry dock / 25 Year | Duration Visit | Cleaning / 25 year | Time Cleaning | Total Time Spend / Year |
|---|---|---|---|---|---|
| FR-Coating | 6 times | 2,5 weeks | 0 times | 0 hours | 4,2 days |

| Type Coating | Visit Dry dock / 25 Year | Duration Visit | Cleaning / 25 year | Time Cleaning | Total Time Spend / Year |
|---|---|---|---|---|---|
| Hard, Inert Coating | 5 times | 4 days | Cold water: 37.5 times | 6 hours | 1,19 days |
| | | | Warm water: 225 times | | 3,14 days |

Figure D.1: Time Efficiency based on lifetime scheme 4.1

# E

# In-water cleaning

In-water cleaning of a Biocidal AF-Coating causes a pulse discharge of biocides and greatly depletes the coating. The toxic compounds will accumulate at the ports where the vessels are cleaned.

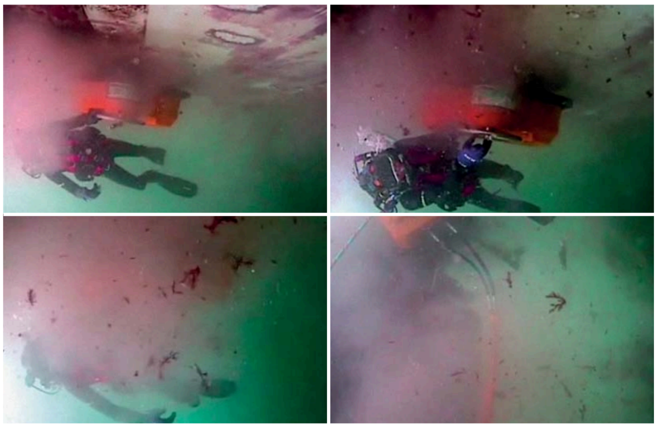


Figure E.1: Video clip screen shots showing the effects on the water of in-water cleaning on a hull coating with a copper-based biocidal AF-coating (Report, 2013)

In-water cleaning of a Hard, Inert Coating is very efficient if the right tools are used for the job (as seen in figure E.2). The coating is hard and will not deplete while cleaning with brushes. No toxic compounds will be released. Fuel costs will be reduced.

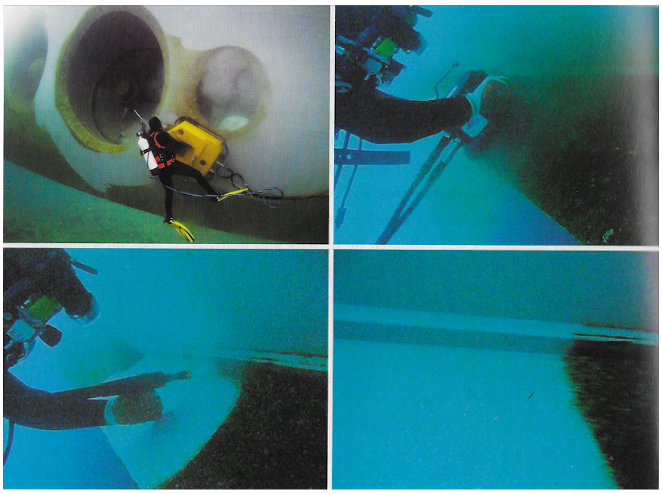


Figure E.2: Footage showing the in-water cleaning on a hull coating with hard, inert coating (Rompay, 2012)

# F
# Explanation Criteria

Each criterion is explained in detail:

**1. Public Health:**
This parameter measures how harmful the various coating systems can be to public health. The toxic substances are released throughout the ocean, ports and shipyards. This allows people to come into direct contact with the toxic water. People can also indirectly come into contact because these toxic substances enter the food chain through the marine organisms that may be poisoned. The coating system whereby the least number of people come into contact with harmful substances gets a higher rating.

**2. Protection and Longevity:**
The protection and the longevity of the coating is examined. The longer a coating lasts without being replaced and repaired, the higher the rating.

**3. Time Efficiency:**
This criterion looks at the time efficiency of the different coating systems. If a ship spends more time on cleaning and repairing, this will only cost more money for the shipping industry. The coating system with the best time efficiency, receives a higher rating.

**4. Initial and Lifetime Costs:**
The costs can be seen as two parts. The initial costs of the coating and the operational costs during the lifetime of the ship. The costs for the various coatings must remain as low as possible. This applies to the coating itself, the initial application, maintenance and fuel savings. The coating system with the lowest total costs gets a higher rating.

**5. Environmental Problems:**
This parameter looks at which coating system is the less harmful for the environment. Coatings that cause environmental problems such as the release of toxic substances that damage the environment, the contamination of sediment and the NIS-problem that can disturb ecosystems get a lower rating. Coatings that cause the least damage to the environment logically gets a higher rating.

**6. Fuel Efficiency:**
In this criterion, we examine which coating system has the lowest fuel loss. This can save a lot of money on the entire world fleet and avoid unnecessary exhaust gases. The coating system with the least fuel loss gets a higher rating.

# G
# Multi-Criteria Analysis

| Effect table | Biocidal AF-coating | FR-coating | Harde, Inerte coating |
|---|---|---|---|
| Public Health | - - | - | + + |
| Longevity | 3,125 years | 3,57 years | + 25 years |
| Protection | - | - - | + + |
| Time Efficiëntcy | 117,6 hours | 100,8 hours | (28,6 + 75,45)/2 = 52 hours |
| Initial Costs | 25 € / m^2 | 50 € / m^2 | 45 € / m^2 |
| Lifetime Costs | 5,1 million € | 5,4 million € | 2,3 million € |
| Environmental Concerns | - - | - | + + |
| Fuel Consumption Effiency | 45 % inefficienct resistance | 45 % inefficient resistance | 15% inefficient resistance |

Figure G.1: Effect table

| Standardized Effect table | Biocidal AF-coating | FR-coating | Harde, Inerte coating |
|---|---|---|---|
| Public Health | 0 | 0,25 | 1 |
| Longevity | 0,125 | 0,1428 | 1 |
| Protection | 0,25 | 0 | 1 |
| Time Efficiëntcy | 0 | 0,344 | 1 |
| Initial Costs | 1 | 0 | 0,2 |
| Lifetime Costs | 0,11 | 0 | 0,42 |
| Environmental Concerns | 0 | 0,25 | 1 |
| Fuel Consumption Effiency | 0,55 | 0,55 | 0,85 |

Figure G.2: Standardized effect table

| Shipyard | Public Health | Protection and longevity | Time Efficiëntcy | Initial Costs | Lifetime Costs | Environmental Concerns | Fuel Consumption Effiency | Total score |
|---|---|---|---|---|---|---|---|---|
| Public Health | - | 2 | 2 | 4 | 3 | 3 | 2 | 16 |
| Protection and longevity | 8 | - | 6 | 8 | 7 | 7 | 6 | 42 |
| Time Efficiëntcy | 8 | 4 | - | 8 | 7 | 6 | 7 | 40 |
| Initial Costs | 6 | 2 | 2 | - | 8 | 6 | 4 | 28 |
| Lifetime Costs | 7 | 3 | 3 | 2 | - | 6 | 3 | 24 |
| Environmental Concerns | 7 | 3 | 4 | 4 | 4 | - | 6 | 28 |
| Fuel Consumption Effiency | 8 | 4 | 3 | 6 | 7 | 4 | - | 32 |

| Shipping company | Public Health | Protection and longevity | Time Efficiëntcy | Initial Costs | Lifetime Costs | Environmental Concerns | Fuel Consumption Effiency | Total score |
|---|---|---|---|---|---|---|---|---|
| Public Health | - | 4 | 4 | 3 | 1 | 5 | 1 | 12 |
| Protection and longevity | 6 | - | 6 | 5 | 3 | 8 | 5 | 9 |
| Time Efficiëntcy | 6 | 4 | - | 4 | 3 | 8 | 3 | 9 |
| Initial Costs | 7 | 5 | 6 | - | 4 | 8 | 4 | 11 |
| Lifetime Costs | 9 | 7 | 7 | 6 | - | 8 | 5 | 42 |
| Environmental Concerns | 5 | 2 | 2 | 2 | 2 | - | 2 | 2 |
| Fuel Consumption Effiency | 9 | 5 | 7 | 6 | 5 | 8 | - | 5 |

| Coating company | Public Health | Protection and longevity | Time Efficiëntcy | Initial Costs | Lifetime Costs | Environmental Concerns | Fuel Consumption Effiency | Total score |
|---|---|---|---|---|---|---|---|---|
| Public Health | - | 5 | 7 | 7 | 5 | 5 | 5 | 5 |
| Protection and longevity | 5 | - | 8 | 8 | 5 | 6 | 5 | 5 |
| Time Efficiëntcy | 3 | 2 | - | 4 | 3 | 3 | 2 | 3 |
| Initial Costs | 3 | 2 | 6 | - | 3 | 2 | 2 | 3 |
| Lifetime Costs | 5 | 5 | 7 | 7 | - | 5 | 4 | 33 |
| Environmental Concerns | 5 | 4 | 7 | 8 | 5 | - | 5 | 5 |
| Fuel Consumption Effiency | 5 | 5 | 8 | 8 | 6 | 5 | - | 6 |

Figure G.3: Weight tables Shipyard, Shipping Company, Coating Company

| Criteria | Row Total | Weights |
|---|---|---|
| Public Health | 33 | 0,09 |
| Protection and longevity | 56 | 0,16 |
| Time Efficiëntcy | 52 | 0,14 |
| Initial Costs | 42 | 0,12 |
| Lifetime Costs | 99 | 0,28 |
| Environmental Concerns | 35 | 0,10 |
| Fuel Consumption Effiency | 43 | 0,12 |
| | **360** | |

Figure G.4: Weight of criteria

| **Standardized Weight Effect table** | Biocidal AF-coating | FR-coating | Harde, Inerte coating | |
|---|---|---|---|---|
| Public Health | 0,00 | 0,02 | 0,09 | 0,09 |
| Longevity | 0,02 | 0,02 | 0,16 | 0,16 |
| Protection | 0,04 | 0,00 | 0,16 | 0,16 |
| Time Efficiëntcy | 0,00 | 0,05 | 0,14 | 0,14 |
| Initial Costs | 0,12 | 0,00 | 0,02 | 0,12 |
| Lifetime Costs | 0,03 | 0,00 | 0,12 | 0,28 |
| Environmental Concerns | 0,00 | 0,02 | 0,10 | 0,10 |
| Fuel Consumption Effiency | 0,07 | 0,07 | 0,10 | 0,12 |

| | Biocidal AF-coating | FR-coating | Harde, Inerte coating |
|---|---|---|---|
| Score | **0,3** | **0,2** | **0,8** |
| Ranking | 2 | 3 | 1 |

Figure G.5: Weights from figure F.4 multiplied with the criteria. A ranking is received from the analysis.

# H

# Underwater Footage

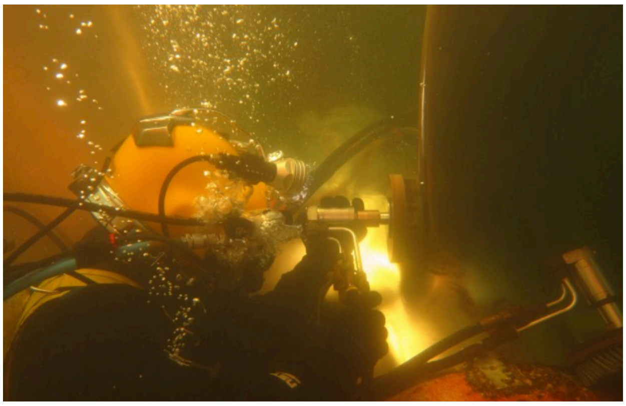


Figure H.1: Working with The Hand Unit (Subsea Industries, 2018)

Figure H.2: Working with The Pod Unit (Subsea Industries, 2018)

Figure H.3: Working with The Twin Brush Unit (Subsea Industries, 2018)

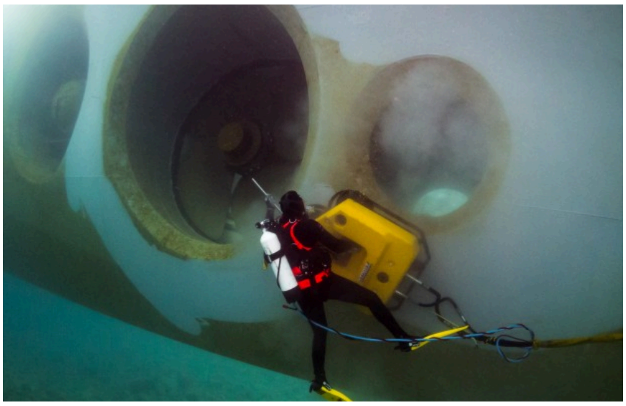


Figure H.4: Working with The Four-Wheel Drive Unit (Subsea Industries, 2018)

# Calculation Energy Use Cleaning

The specifications of the Hydraulic Units are shown in figures I.1 and I.2 below.

Specifications:

- Dimensions:
  - Oil flow:
    - 20 l.p.m. at 1800 r.p.m.
    - 40 l.p.m. at 3600 r.p.m.
  - Working pressure: Nominal 140 bar
  - Engine:
    - Vanguard 2-cylinder
    - 18 HP (13,4 KW)
    - 4 stroke petrol
  - Dimensions (LxWxH): 805x625x695 mm
  - Weight: 105 kg

Figure I.1: Specifications PP018 Hydraulic power unit (Sub. Ind., 2018)

Specifications:

- Dimensions:
  - Oil flow:
    - 20 l.p.m. - 80 l.p.m.
  - Working pressure: Nominal 140 - 160 bar
  - Engine:
    - Kubota 4-cylinder
    - 104 HP (78 KW)
    - Diesel
  - Dimensions (LxWxH): 1600x1000x1720 mm
  - Weight: 1400 kg

Figure I.2: Specifications PP100 Hydraulic power unit (Sub. Ind., 2018)

Figure I.3: The PP018 Hydraulic Power Unit (Sub. Ind., 2018)

Figure I.4: The PP100 Hydraulic Power Unit (Sub. Ind., 2018)

We choose a ship with a hull area of 9.000 square meters.
The calculations on the energy costs can be shown beneath.

**The Hand Unit:**
This tool is used for small surfaces and niche areas.
The other tools are used for the cleaning of the whole surface of the hull.
This is why it is difficult to calculate the energy consumption for a certain surface.

**The Pod Unit/The Twin Brush Unit/The Four-Wheel Drive Unit**

The efficiency of the different cleaning units are:

- The Pod Unit cleans 300 square meters/hour.
- The Twin Brush Unit cleans 450 square meters/hour.
- The Four-Wheel Drive Unit cleans 1.500 square meters/hour.

Cleaning 9000 square meters will be done in:

- The Pod Unit: 30 hours
- The Twin Brush Unit: 20 hours
- The Four-Wheel Drive Unit: 6 hours

The power of the PP018 hydraulic power unit is 13,4 kW (18HP). This power unit will be connected to the pod and twin brush unit. The fuel consumption is 6 liters each hour. (Vanguard, sd) One liter of fuel is nowadays around €1,78. (ANWB, 2018)

The power of the PP100 hydraulic power unit is 78 kW (104HP). This will be connected to the four-wheel drive unit because more power is needed. The fuel consumption is 17.04 liters each hour. (Barrington Diesel Club, 2016) One liter of diesel is nowadays around €1,48. (ANWB, 2018)

This multiplied with the time of cleaning gives for each cleaning unit the work in kilowatt and the costs in euros for cleaning a ship with a 9.000 square meters hull:

| | Time [Hours] | Work [kWh] | Energy Costs (€) |
|---|---|---|---|
| **The Pod Unit** | 30 | 402 | 320,4 |
| **The Twin Brush Unit** | 20 | 268 | 213,6 |
| **The Four-Wheel Drive Unit** | 6 | 468 | 151,31 |

Table I.1: Cleaning energy consumption of a 9.000m2 hull with the different cleaning units

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