Identifying Alternative Strategies for Controlling Biofouling on United States Coast Guard Sector San Juan Vessels

An Interactive Qualifying Project submitted to the faculty of
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in partial fulfillment of the requirements for the Degree of Bachelor of Science

Sponsoring Agency: United States Coast Guard Sector San Juan

Submitted to:

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Abstract

The United States Coast Guard Sector San Juan sought alternative approaches to combat aggressive biofouling. The goal of this project was to analyze the biofouling control practices used by Sector San Juan, and make recommendations to adjust these practices to save money and increase vessel efficiency. To do this, we proposed the use of a data collection and analysis protocol through which Sector San Juan can calculate potential fuel savings from alterations made to their current hull cleaning schedules. In addition to this, we recommended alternative hull coatings be applied to the vessels and new techniques for conducting hull cleanings.

Acknowledgements

We would like to acknowledge the following individuals who spent countless hours in assisting us with our project; we would not have accomplished this work without their help and guidance. We first would like to thank our sponsor adviser, CDR Robert Hemp, and the rest of the United States Coast Guard Sector San Juan for their assistance while we were in San Juan. The information and guidance that was provided to us was integral in making our final recommendations. We also would like to thank the professors who advised us throughout the project development. We would like to thank Professor Anna Jaysane-Darr for all of her guidance and assistance throughout the preparatory term. Additionally, we would like to thank our project advisers, Professor Frederick Hart and Professor Karla Mendoza-Abarca, as the assistance that they provided while on site proved to be invaluable over the course of the past eight weeks. Finally, we would like to acknowledge our fourth teammate, Lindsay Gurska. Unfortunately, Lindsay suffered an injury during the preparatory term, and as a result, could not travel to Puerto Rico to work on the project. However, the work that she did during the preparatory term was vital to the success of our project; we are all confident that our project would not be nearly as complete without the assistance provided by her this fall.

Executive Summary

Video Overview:

(The image above links to the video overview)

Background:

Biofouling is the accumulation of marine organisms on surfaces submerged in the ocean (Cao et al., 2010). It oftentimes affects the hulls of ships and causes significant drag and thus increased fuel consumption (“Waterborne Underwater Hull Cleaning of Navy Ships”, 2006). Sector San Juan of the United States Coast Guard has faced significant economic losses in fuel costs (Robert Hemp, personal communication, 2015). This is due to the drag induced by biofouling. Due to budgetary constraints, Sector San Juan is only able to provide one in-water hull cleaning per year before having to pull from other budgets around the base (Robert Hemp, personal communication, 2015). One cleaning is insufficient, however, as the biofouling accumulation in Sector San Juan is so aggressive that ships will experience up to a 20% loss in speed in an unacceptable time frame (Robert Hemp, personal communication, 2015).

Our team was tasked with looking at the current hull cleaning schedule and finding where it could be improved in order to save the most money for the Sector in fuel savings. Early in the project we discovered that some of the data necessary to make these schedules was not presently available, so we created a data collection and analysis protocol which recommends how data should be collected, organized, analyzed, and then compared to create the improved hull cleaning schedules. In addition to this, we researched anti-fouling coatings and hull cleaning techniques to make recommendations for the application of a more ecologically appropriate anti-fouling system and alternative hull cleaning technologies for the Sector San Juan vessels.

Methodology:

To accomplish the goal of reducing the economic impact of biofouling in Sector San Juan, we created three primary objectives. They are as follows:

1. Determine an effective hull cleaning interval that reflects the needs of the Sector.
2. Evaluate the effectiveness of current standardized anti-fouling coatings set by the United States Coast Guard and research alternative technologies that may provide better defenses against biofouling.
3. Assess the present cleaning tools and techniques employed in Sector San Juan to combat biofouling accumulation and if appropriate, propose alternative tools and techniques.

To address the first objective, we completed several steps. First, we identified what the current hull cleaning schedule is, and evaluated its effectiveness. Second, we identified what aspects of a ship's performance (engine performance, fuel consumption rates, etc.) were taken into greatest consideration when justifying a hull cleaning. Third, our group assessed how the biofouling issue in San Juan affects the aforementioned performance aspects of a ship. Finally, we searched for data relating to these reasons, such as biofouling accumulation, top speed reduction, distance traveled by each vessel, and consumed fuel amounts. Once these steps were completed, we were able to correlate the factors affecting a vessel with the performance losses experienced. This assessment would then lead to identifying when a vessel should be cleaned in order to avoid these certain performance losses.

To acquire all of this information, we reached out to:

- Commander (CDR) Hemp – the head of the Sector San Juan Logistics Department
- Sam Alvord – the head of the Coast Guard Office of Energy Management
- Several Commanding Officers (COs) and Engineering Petty Officers (EPOs) of the vessels on base.

For the second objective we identified the current hull coating used in Sector San Juan. Following this, we sought to understand the mechanisms by which the coating combats biofouling and how successful it was in the Sector. Furthermore, we researched other coatings available on the market to find one that could better serve the needs of the Sector.

We completed the last objective by identifying the current techniques used by the contracted divers and researching academic literature for proven hull cleaning methods. We then compared our findings and put forth recommendations.

Findings:

- We found that there are four sets of data needed in order to be able to effectively create a new hull cleaning schedule:
    - **Biofouling Accumulation** – Necessary to see how biofouling accumulation accelerates on vessels in Sector San Juan. As harder biofouling begins to

accumulate, the difficulty to remove it from the hulls will increase (Commanding Officer “A”, personal communication, 2015).

  - **Speeds and associated RPM** – Can be used to illustrate how a ship’s operating speeds are impacted over the time that biofouling accumulates. To achieve a vessel’s top speed, an engine needs to input more work which could lead to engine breakdown.
  - **Fuel consumption (burn) and associated distance travelled** – Needed to correlate biofouling accumulation to the increase in fuel consumption (and thus increased costs to operate the ships). This is important because it allows for comparing new schedule options on the basis of potential money saved for the Coast Guard, and will be the definitive data set in deciding upon new schedules.
  - **Gallons per hour consumed** – This data point is an alternative for calculating fuel money saved, as it is more specific and can be correlated to the different speeds a ship travels at.

- We found that the anti-fouling paint currently employed on the vessels in Sector San Juan is a copper ablative biocidal anti-fouling paint (more specifically International Interspeed BRA 640) (Commanding Officer “A”, personal communication, 2015). This type of coating (ablative and copper biocide) is unfit for the conditions of San Juan.
  - Copper is at risk of being legally banned for use in anti-fouling due to the damage it does to marine life (Kaznoff & Rudroff, 2000).
  - Ablative paints intentionally wear down and fall off the hull easily (Commanding Officer “A”, personal communication, 2015). This is unsuitable for San Juan

because the hulls undergo more frequent cleanings in San Juan than in most other USCG Sectors (Robert Hemp, personal communication, 2015).

- Current in-water hull cleanings are very effective at removing macrofouling (the hard, easily visible biofouling), but do not remove the microfouling according to a diver contracted by the Coast Guard to clean hulls (Personal communication, 2015). Microfouling is important to remove, because without it the macrofouling cannot attach well (Cao et al., 2010).
    - Should the frequency of in-water cleanings per vessel increase, it would be wise to have this microfouling cleaned off as well, so that for the next cleaning, the macrofouling would be less abundant and attached less strongly. This would reduce the time needed to clean the hull and make the work to do so easier.
- Our findings and potential recommendations do not put the divers contracted by Sector San Juan at risk of losing in-water hull cleaning contracts. None of our findings support the need, benefit, nor possibility of reducing the number of in-water cleanings conducted within the Sector.

Recommendations:

Based on our findings, we have determined that the information derived from our three objectives would provide the Coast Guard with the necessary protocol to improve their hull cleaning schedule.

Objective 1:

As we analyzed the information mentioned in the findings, we determined the need for a data collection and analysis protocol. In the table seen below, illustrates how Sector San Juan should collect and evaluate the data.

Data Type	Collection Method Recommendations	Importance
Biofouling Accumulation	• Use an underwater camera attached to a retractable pole, while walking around the perimeter of the ship. • This should occur right before the ship goes on patrol (underway), and right after it returns, for ample data points. • By using the Naval Fouling Rating Scale* one can determine the amount of biofouling on the hull upon analysis of the video.	• This process allows for the amount of biofouling to be quantified. • By graphically representing this data, one can determine the amount of biofouling that is removed from each cleaning. This value can correlate to vessel efficiency.
Vessel Speed and Associated Engine RPMs	• Instantaneous vessel speed and engine RPMs are calculated and displayed by computers on board the vessels, and should be recorded from them.	• One can determine the impact that biofouling has on the vessel speed by recording said speed • Additionally, one can correlate how speed changes at constant RPM are affected by biofouling

	• We recommended adding additional columns to the Round Sheets** in order to document this information.	
Fuel Burn	• Fuel burn information for all vessels is collected and documented by the Office of Energy Management.	• By determining the amount of fuel saved by an additional cleaning, one can associate money saved through fuel burn
Distance Travelled	• Information on distance travelled is available on the Operational Summary Sheets***.	• This information, used with fuel burn data, can be used to calculate potential fuel dollar savings from additional cleanings implemented
Gallons/Hour	• As an alternative method, we recommended that gallons/hour information be added to the Round Sheets as well. • This information would be recorded at clutch, mid, and top speeds, to avoid averaging data • This information is also displayed on vessel computers, and could be recorded from them.	• This analysis accomplishes similar results to the analysis of fuel burn and distance travelled data, but is more accurate as it accounts for vessels travelling at different speeds • Fuel saved could be determined for each speed, and then totaled to find the overall fuel cost savings.

*Naval Fouling Rating Scale: This scale was created by the Navy, and is a quantitative measurement of the amount of fouling on the hulls. It is a scale from 0-100 based upon increments of 10. At each increment, a different level of biofouling is described through written descriptions as well as visuals.

**Round Sheets: Round Sheets are documents that are filled out by Coast Guard personnel that document the engine performance and travel information throughout an underway period (Engineering Petty Officer "A", personal communication, 2015).

***Operational Summary Sheets: A document where a travel summary of each underway period can be found (Engineering Petty Officer “A”, personal communication, 2015).

Objective 2:

Concluding interviews with Coast Guard personnel and the contract divers, it has become apparent that a biocidal, copper ablative paint may not be suitable for the needs of Sector San Juan. A better alternative anti-fouling paint for Sector San Juan to employ on their vessels would be a hard fouling release coating. Fouling release paints work by creating a smooth low friction surface on the hull, which makes it difficult for biofouling to attach to. This coating does not easily wear away with cleanings, and does not leach harmful toxins into the surrounding marine environment. We recommended to use a paint of this type after a decisive cleaning interval has been adopted by the Sector.

With a hopeful increase in the amount of cleanings per calendar year, this paint will provide a low friction surface that biofouling may be easily removed from. In addition, Sector San Juan will not have to worry about releasing toxic chemicals that other coatings may use into the environment, helping them achieve the Coast Guard mission of “Marine Environmental Protection.” (Missions: United States Coast Guard, 2014).

Objective 3:

After consulting academic research and the current methods employed by the contract divers, we recommended that the divers implement an additional process to their cleanings known as grooming. Grooming is the process of gentle, repetitive cleaning on the hull, normally with a device that has a low coefficient of friction (Tribou & Swain, 2010). One example would be a nylon brush, as the material is not as abrasive as traditional brushes and is efficient in removing the biofilm present. Additionally, we recommended utilizing circular brushing patterns, as opposed to the traditional, rigorous patterns within these groomings. This method is better at removing the biofilm as well as preserving the anti-fouling coatings on the hulls (Tribou & Swain, 2010). Sector San Juan uses copper ablative coatings, which are very soft and wear away easily (Engineering Petty Officer “B”, personal communication, 2015). This process is very efficient at removing the biofilm on the hull, and lengthens the time interval necessary between cleanings (Tribou & Swain, 2010).

Additionally, there are autonomous hull cleaning techniques that are currently in the developmental stages, and we recommended that the Coast Guard looks further into the development of these technologies. These devices consistently monitor and groom the hulls of the vessels, which prevents the formation of a biofilm and rapidly slows the accumulation of macrofouling.

Authorship List

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1.0 Introduction

The content and recommendations of this report and associated materials do not necessarily reflect the opinions, views, or positions of the United States Coast Guard Sector San Juan.

Navigating the oceans appears to be an effortless task that many ships are able to undertake with ease. Below the crashing waves, however, lies a forceful and rapidly accumulating mass of marine organisms. The attachment of living species to the hulls of vessels severely increases the frictional drag, thereby requiring a greater force to propel the craft through the water. With a demand for additional fuel and engine output to overcome the amassing of organisms, financial losses may arise. In order to be able to maintain a traveling speed of approximately 11 mph after only 6 months at sea, a Navy destroyer would have to increase its fuel consumption by approximately 50% (Woods Hole Oceanographic Institute, 1952). This example illustrates the potential impact of biofouling.

The United States Coast Guard (USCG) has likely been battling this issue since its creation in 1790 (US Coast Guard History: United States Coast Guard, 2015). This problem originates from a biological process known as biofouling, which is defined as the attachment and growth of organisms on submerged surfaces (E.R. Holm, 2012). Currently, Sector San Juan is experiencing heavy performance and economic losses based on increased fuel consumption caused by biofouling attachment to the hulls of ships (Robert Hemp, personal communication, 2015). The Sector would like to see a reduced impact on their budget while maintaining vessel performance (Robert Hemp, personal communication, 2015). A previous investigation into the economic impact of biofouling estimates that marine organism attachment has cost the U.S.

Navy an additional total ranging from $75-$100 million in fuel penalties (Alberte et al., 1992). This issue in Sector San Juan must be dealt with in an efficient and timely manner to prevent the continuation of raised expenditures.

Across Puerto Rico, the USCG plays a major role in maintaining safety and enforcing laws. As biofouling accumulates on USCG vessels, the speed, and therefore efficiency of these vessels drop. Sector San Juan is a part of District 7 of the USCG; on average within this district, there are 22 search and rescue missions performed and 3 lives saved per day (United States Coast Guard: USCG Station San Juan, 2014). Oftentimes, it is only a brief moment that determines whether a mission is a success or a failure; mere seconds could be the difference between life and death.

The current methodology being utilized by the USCG to combat biofouling includes an out-of-water (dry dock) hull cleaning for each vessel, occurring roughly every three years (Commanding Officer "A", personal communication, 2015). In addition, in-water cleanings are conducted once annually and on site whenever the vessel shows a proven speed loss of at least 20% (Robert Hemp, personal communication, 2015). These cleanings do not suffice, however, as the accumulation of biofouling in Sector San Juan occurs more rapidly than it can be removed.

Our team looked into potential alterations in this schedule to improve vessel efficiency. Through an analysis of the current hull cleaning schedule, it was determined that the information necessary to make calculations regarding the enhancement of hull cleaning schedules was not presently available. With this realization, we constructed a data collection and analysis protocol that will form the foundation from which alternative schedules can be created. In addition to this protocol, we proposed alternative anti-fouling coatings and enhanced cleaning techniques to accompany future changes in the cleaning schedule. With these recommendations, we aim to have the smallest impact on the contracted divers, while having the strongest positive effects for the Coast Guard's hull cleaning system. This potential social impact was strongly considered before communicating the proposed solution to the USCG Sector San Juan. More context regarding the Coast Guard and its biofouling issue is available in our background chapter. Details on our investigation and recommendations for the cleaning schedules as well as the anti-fouling coatings and cleaning techniques are available in the methodology section.

2.0 Literature Review

Hull biofouling may be seen as an inconvenience to many boat owners. Biofouling accumulation on the hulls of United States Coast Guard (USCG) vessels, however, can create many functionality and efficiency issues. The USCG implements many satisfactory methods for the prevention and management of biofouling growth. Anti-fouling coatings are applied to ship hulls and different cleaning techniques are practiced across the Coast Guard, in order to curtail biofouling accumulation. Unfortunately, biofouling in Sector San Juan is more aggressive than many other Sectors in the Coast Guard, and as such the standardized methods of biofouling control may have to be modified to maintain vessel efficiency (Robert Hemp, personal communication, 2015).

This chapter will define the process of biofouling and the impacts it poses. Furthermore, it will explain the current hull cleaning schedule and technologies implemented by the United States Coast Guard, as well as the specific negative economic and performance impacts the United States Coast Guard has faced due to biofouling. Finally, the chapter will explore prospective technologies that can be added to the current biofouling prevention and management practices in the Sector and detail the potential social impacts of biofouling in Puerto Rico.

2.1 United States Coast Guard

The United States Coast Guard has a long and respected history of serving America in a variety of ways. The USCG is unique in that it simultaneously serves as a branch of the United States Military as well as a federal law enforcement agency ("US Coast Guard History", 2014). Because of this, it is integral that the Coast Guard is operating at maximum efficiency. See Appendix A for more information.

Sector San Juan of the USCG serves the island of Puerto Rico and the rest of the Eastern Caribbean area ("Sector San Juan", 2010). The Sector was established in 1993, and serves as an integral part of the Coast Guard's District 7 ("USCG Station San Juan", 2014). Sector San Juan possesses the only USCG Search-and-Rescue Station in the entire Caribbean, as well as multiple boats that serve the purposes of homeland security, special operations, and first response ("USCG Station San Juan", 2014).

Figure 1 – Map of Jurisdiction of Sector San Juan

(SECTOR SAN JUAN, 2010)

In Sector San Juan, there are currently three classes of vessels that serve, each specified by their length. The 87' and 110' cutters have served in San Juan for roughly a decade, while the implementation of 154' Fast-Response Cutters (FRC) has very recently began (Robert Hemp, personal communication, 2015). By February 2016, both of the 110' vessels will be decommissioned completely, and there will be one 87' vessel and six 154' vessels in Sector San Juan (Robert Hemp, personal communication, 2015).

Currently, the vessels work on different operational schedules, with the 87' vessel implementing a cycle that includes approximately 2 weeks in port and 2 weeks at sea, whereas the 110' and 154' vessels cycle around 3 weeks in port and 3 weeks at sea (Commanding Officer "B", personal communication, 2015). However, these schedules are subject to change upon the different needs of the Coast Guard (Commanding Officer "B", personal communication, 2015). All USCG vessels (also known as cutters) are manufactured by Bollinger Shipyards in Lockport, LA, where the remaining FRCs will be manufactured and sent to San Juan (Bollinger Shipyards

LLC: Military and Government Vessels, 2015). On each cutter there is a hierarchy of order. The Commanding Officer (CO) is in charge of the daily operations of each cutter, while maintaining operational standards falls under the responsibilities of the Engineering Petty Officer (EPO) (Commanding Officer "A", personal communication. 2015).

2.2 Biofouling

Biofouling is the accumulation of living marine organisms on hard, wetted surfaces (Railkin et al., 2003). This biological process has several steps, and these steps can be impacted by numerous variables altering the rate at which these steps occur. Dependent on this rate of progression is the incurred economic effects that a ship owner may experience. This section highlights specific information regarding the biofouling process, variables that may impact it and, the economic effects caused by biofouling.

2.2.1 Biofouling as a Process

The accumulation of biofouling species occurs as a gradual process. In dealing with marine organisms, the navy has outlined a Naval Fouling Rating Scale that is able to quantify the different progressions within the biofouling process ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). As seen in Table 1, the scale works on a 0-100 rating, with unit increments of 10 ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). A rating of 0 corresponds to a clean surface that is free of biofouling, and a score of 100 relates to a term known as composite biofouling, where a larger portion, if not all, of the vessel is covered ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). In general, two classes of biofouling exist: microfouling and macrofouling. Microfouling is a slimy film of bacteria that coats the ship hull ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). This is followed by macrofouling, which consists of a variety of soft and hard marine species like algae and marine invertebrates (Yebra & Kiil, 2003). Below in Table 1 is an example of the scale, and each rating's corresponding description. The Navy also has outlined example photographs of each rating, providing visual cues that make the categorization process simple to follow. Parts of this scale and their provided pictures are used to help explain the biofouling process in five steps.

Table 1 – Naval Fouling Rating Scale

Type	Fouling Rating (FR)	Description
Soft	0	A clean, foul-free surface; red and/or black AF paint or a bare metal surface.
Soft	10	Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.
Soft	20	Slime as dark green patches with yellow or brown colored areas (advanced slime). Bare metal and painted surfaces may by obscured by the fouling.
Soft	30	Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in color; or soft non calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand.
Hard	40	Calcareous fouling in the form of tubeworms less than ¼ inch in diameter or height.
Hard	50	Calcareous fouling in the form of barnacles less than ¼ inch in diameter or height.
Hard	60	Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.
Hard	70	Combination of tubeworms and barnacles, greater than ¼ inch in diameter or height.
Hard	80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, ¼ inch or less in height. Calcareous shells appear clean or white in color.
Hard	90	Dense growth of tubeworms with barnacles, ¼ inch or greater in height; Calcareous shells brown in color (oysters and mussels); or with slime or grass overlay.
Composite	100	All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth.

("Waterborne Underwater Hull Cleaning of Navy Ships", 2006)

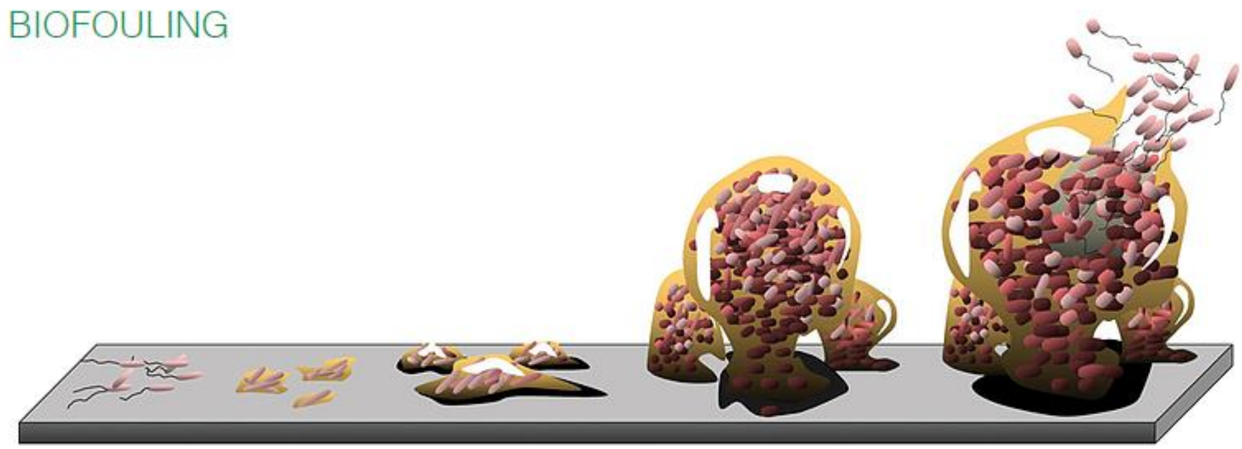

Figure 2 – Qualitative Biofouling Description

1. The first step of biofouling involves abundant organic material in the water that comes into contact with a submerged surface (Cao et al, 2010). This step occurs rapidly, and is not quantified within the Naval Fouling Rating Scale.
2. From here, formation of the biofilm begins. The biofilm is a microorganism layer that changes the chemical condition of the surface (Global Invasive Species Programme, 2008). This begins as a reversible clinging to the prior-established organic coating, and makes it more favorable for the attachment of macrofouling species (Global Invasive Species Programme, 2008).

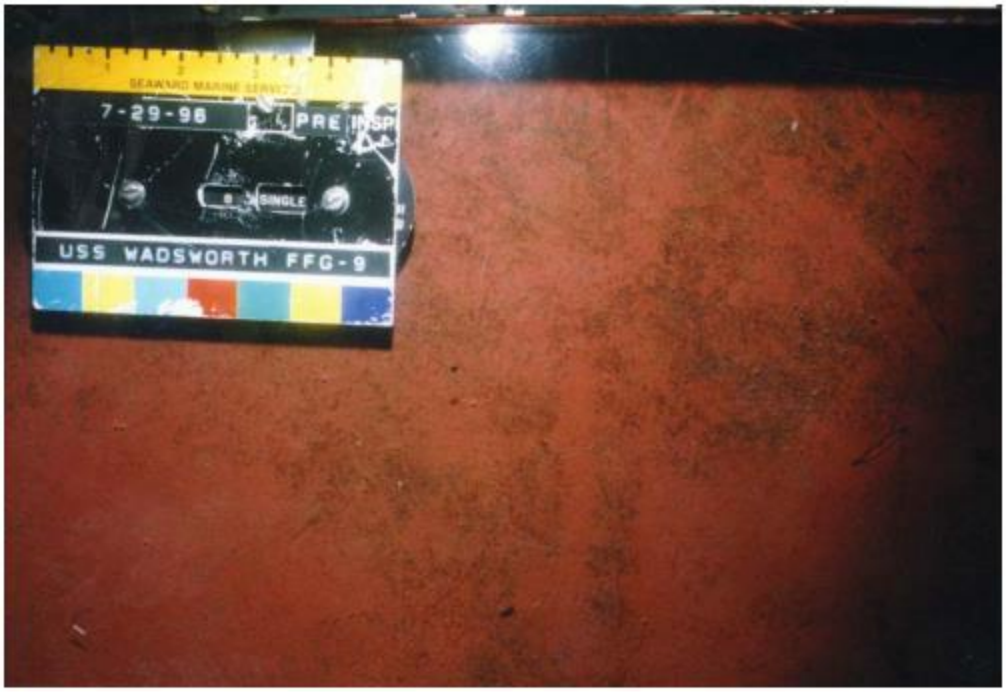

Figure 3 – Light Biofilm Coverage: FR-10

(“Waterborne Underwater Hull Cleaning of Navy Ships”, 2006)

The biofilm layer accumulation develops into a more permanent adhesion than the initial clinging. Its stronger attachment is due to biochemical effects (Cao et al, 2010).

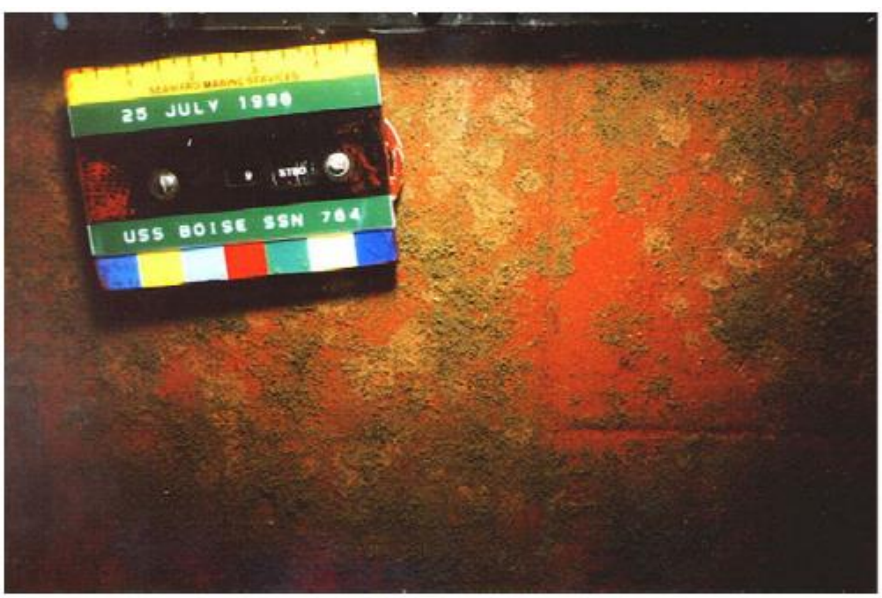

Figure 4 – Biofilm Establish on Roughly 80% of Surface: FR-20

(“Waterborne Underwater Hull Cleaning of Navy Ships”, 2006)

3. After the completion of the biofilm layer (microfouling), larger species may begin to attach such as barnacle larvae, tubeworms and algae (macrofouling) (Cao et al, 2010).

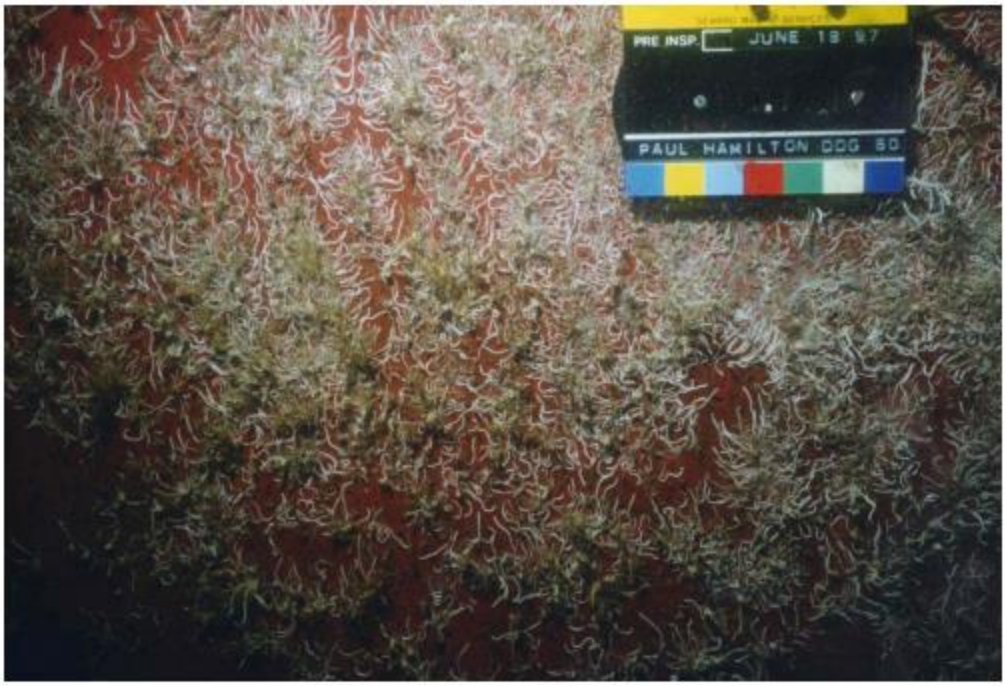

Figure 5 – Predominantly Tubeworms are Abundant on the Hull: FR-40

("Waterborne Underwater Hull Cleaning of Navy Ships", 2006)

4. Once macrofouling species begin to attach, they then move to maturity and become much more visible, eventually growing to mask the surface if left untouched (Cao et al, 2010).

Figure 6 – Composite Biofouling with Many Different Species: FR-100

("Waterborne Underwater Hull Cleaning of Navy Ships", 2006)

As seen through Figure 1 and Figure 2, microfouling is difficult to distinguish as species, and is therefore referred to as the biofilm or slime layer. Macrofouling species are more commonly associated with biofouling, as they can be seen easily by the human eye in Figure 3 through Figure 6.

Figure 7 - Biofouling off of Sector San Juan Vessels

2.2.2 Important Variables Regarding Biofouling

There are many factors that marine industries must take into consideration when assessing the effects of a biofouling accumulation on a vessel. The extent of surface cleaning, for example, as well as how often this cleaning takes place, is important when evaluating the biofouling accumulation.

Another factor is the presence or absence of an effective anti-fouling coating, as those surfaces not protected with such a coating will accumulate greater levels of biofouling (The National System for the Prevention and Management of Marine Pest Incursions, 2009). The status of such an anti-fouling coating should also be considered. These factors include its age, type, and its suitability to the specific vessel and surface type, as anti-fouling paints are designed for different vessels of varying function (The National System for the Prevention and Management of Marine Pest Incursions, 2009).

The amount of stationary or low speed working periods for a vessel is also crucial to analyze, as the accumulation of biofouling is highest during periods of inactivity. This factor ties closely to the type of anti-fouling coating chosen, as some paints are not intended for such low speed/activity vessels because they rely on the vessel speed to remove biofouling species (The National System for the Prevention and Management of Marine Pest Incursions, 2009).

In addition to the characteristics of the ship, many environmental parameters can contribute to biofouling accumulation. An environment's water temperature, salinity, depth, and amount of sunlight are major factors that impact the likelihood of a marine species to adhere to and grow on the surface of a vessel (The National System for the Prevention and Management of Marine Pest Incursions, 2009). Assessing the variables impacting biofouling accumulation is an important piece in combating it, as understanding these factors and how to react accordingly can lower the amounts of biofouling accumulating.

2.2.3 Economic Effects of Biofouling

The most well-known effect of biofouling is the economic impact. Shipping and coastal industries have found that biofouling increases fuel costs, as organism accumulation can cause drag which decreases the overall speed of the vessel. This speed loss ranges anywhere from a ten to forty percent speed decrease (Global Invasive Species Programme, 2008). Additionally, since biofouling on a ship's hull increases the hydrodynamic drag and thus lowers the movement and speed of the vessel, the fuel consumption will increase (Global Invasive Species Programme, 2008). Thus, industries are often forced to take the vessel out of commission in order to clean the surface and get their ships back up to speed.

Oftentimes, hull damage can occur during the cleaning process. Removing the biofouling can also remove anticorrosive and anti-fouling coatings present on the vessels (Commanding Officer “A”, personal communication, 2015). The removal of a vessel from the workforce for a period of time is detrimental to the industry, as the daily functioning of such a vessel cannot go on. The cleaning and repair costs are also expensive for the Coast Guard. Preventative measures of biofouling, including anti-fouling technologies, have become more popular. According to James Ward, the USCG point of contact for hull paints, the incorporation of such technologies and paints is expensive (James Ward, personal communication, 2015). The economic impact of biofouling also affects third party anti-fouling cleaning companies, vessel workers, and other affiliated laborers.

2.3 Anti-fouling Methods

In order to prevent biofouling on ships, various anti-fouling measures have been created. Anti-fouling exists in several forms and is a technology which serves the purpose of preventing the accumulation of biofouling on submerged surfaces (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). Several types of anti-fouling paint exist for commercially and industrially coating hulls. A list of the different types of anti-fouling that will be discussed in this section can be viewed below in Table 2.

Table 2 – Summary of Anti-fouling Paints

Technology	**Description**	**Types/Examples**
Biocidal Paint	Utilizes chemicals to kill biofouling as it attaches to ship hulls.	• Tributyltin • Copper (Cuprous Oxide)
Fouling Release Paint	Creates a low-friction surface on ship hulls so that biofouling has difficulty rooting into the paint.	• Fluoropolymer • Silicone
Biomimetic Coating	Biomimetic coatings are "mimick" the skin of other ocean creatures. Biomimetic coatings are similar to fouling release in that they prevent the initial settlement of biofouling.	• Sharklet
Active technologies	Relies on powered systems actively protecting the hull of a ship.	• Ultrasonic Transducer

For many years, a coating known as tributyltin (TBT) was used as the first line paint to keep one's ship clean of biofouling (Yebra & Kiil, 2003). According to Yebra and Kiil (2003), an estimated 70% of vessels in the world utilize this paint to combat biofouling (as of 2003). While highly effective and economically accessible, the paint has been discovered to be highly toxic and prone to accumulate within mammals as well as deform other marine life (Yebra & Kiil, 2003). This is due to the presence of the heavy metal tin within the paint (Chambers et al., 2006). Fortunately, TBT was banned internationally by the International Maritime Organization in 2003 (Chambers et al., 2006).

Since the discovery of the adverse marine health effects of metal-based anti-fouling paints, many different companies have rushed to fill the void with paints that were cheaper, safer, and equally as effective as TBT (Yebra & Kiil, 2003). The majority of these paints utilize some chemical mechanism to kill biofouling that attaches itself to the ship (Yebra & Kiil, 2003). These paints are known as biocidal paints. The issue that biocides present, according to Yebra & Kill

(2003), is that these types of paint are still toxic to varying extents when present in the environment. Copper is a common ingredient in these alternative biocide coatings, and while not as damaging as TBT, it can still kill marine life aside from the biofouling on the ship (Chambers et al., 2006). The US Navy made plans to halt future use of copper anti-fouling in 2000, as it had anticipated a future ban on copper-based biocides (Kaznoff & Rudroff, 2000).

Within biocidal paints exists a subsection of coatings known as ablative paints. Ablative coatings combine either biocide or foul release mechanisms with the addition of shedding itself from the surface it covers to improve anti-fouling effectiveness (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). In combination with biocides, ablative coatings release biocide into the water at a more steady rate and uses up less biocide than a typical non-ablative biocide paint (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). The downside is that part of the anti-fouling mechanism for these paints is the sacrifice of the paint layers. The paint is incredibly soft, and thus is easily damaged by in-water cleanings. The vessels in San Juan are currently coated with a copper ablative paint (SFLC Standard Specification 6310, 2014).

An alternative to these biocide paints is a foul release paint, which stops biofouling by preventing fouling from sticking to the vessel's hull by creating an incredibly smooth surface layer (Chambers et al., 2006). Any fouling that does stick to the surface will fall off once a ship hits a certain speed (Chambers et al., 2006). This type of paint is very effective at preventing larger biofouling (macrofouling), but makes it much harder for the microfouling to be removed from the hull (Chambers et al., 2006). Additionally, foul release coatings can't remove biofouling from ships when sitting in port. According to the head diver contracted to conduct hull cleanings, this allows for biofouling to adhere more strongly to the surface, so once these ships get up to speed, they may not shed the biofouling (Personal Communication, 2015). Thus, a foul release coating is usually ideal with ships constantly in motion.

In a similar vein to the foul release paint, "biomimetic" surfaces have been heavily researched as another means to keep biofouling from sticking to hull surfaces. Biomimetic skins are hull surface applications that mimic the skin/shells of various marine life that has shown resistance to biofouling (Chambers et al., 2006). These various organisms modeled for biomimetic skins have evolved to exhibit either chemical or physical anti-fouling properties on their shells and skins (Chambers et al., 2006). According to Chambers et al. (2006), the surfaces of crabs, mussels, and dogfish have been tested and exhibited varied amounts of success in repelling biofouling. The skin of sharks has also been widely researched, particularly by the Navy (New Hull Coatings Cut Fuel Use, Protect Environment, 2009). One material, known as Sharklet, was created by Professor Anthony Brennan at the University of Florida, under a research grant from the Office of Naval Research (New Hull Coatings Cut Fuel Use, Protect Environment, 2009). An image of the Sharklet material can be seen in the middle picture of Figure 8, featured next to images of actual shark skin. This technology, unfortunately, is not yet on the market nor being employed for the large scale surfacing of ship hulls as it has only recently become the focus of anti-fouling research (Chambers et al., 2006).

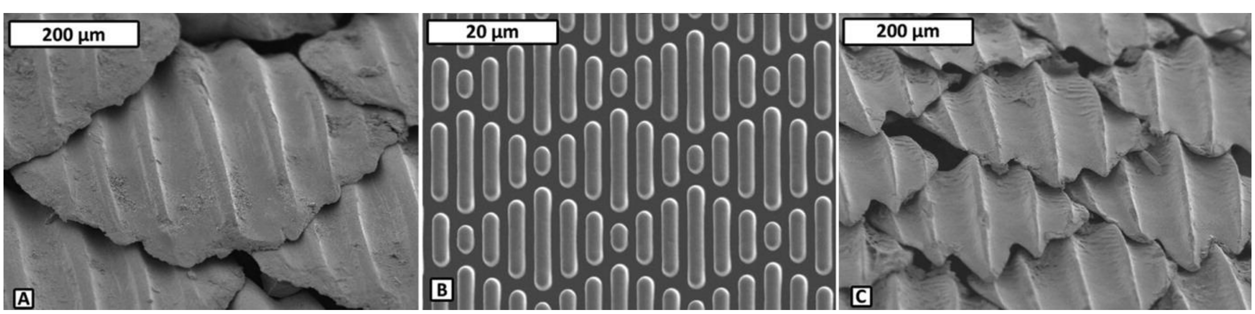

Figure 8 – Microscopic View of Sharklet Technology

(Scardino et al., 2011)

Aside from coating technologies, there are active systems available to prevent biofouling. One such system is the ultrasonic transducer, which send out pulses of sound waves to discourage marine life settlement. The company, Howell Labs, currently produces ultrasonic transducer anti-fouling for private boats. Throughout the length of a ship's hull, both port and starboard sides, several transducers are placed facing outwards (UltraSonic ANTI-FOULING, Ltd, 2015). Figure 9 illustrates such placement.

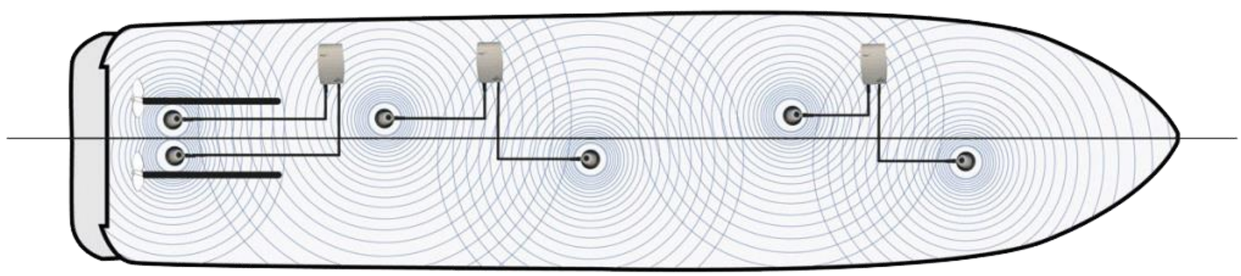

Figure 9 – Ultrasonic Transducer Schematic

(UltraSonic ANTI-FOULING, Ltd, 2015)

These transducers send out specific frequency sound waves that discourage marine life settlement near the source of the sound, i.e. the ships' hulls. The Coast Guard is currently looking into implementing ultrasonic transducers from Howell Labs. The current plan, which is still awaiting funding, involves having one transducer placed externally on each side of a ship only while it is in port. The transducer is unfortunately not officially funded for testing as of now, but given the success of case studies of private ships using this technology, the Coast Guard may be able to reduce the biofouling issue in Puerto Rico with just a few of these transducers (UltraSonic ANTI-FOULING, Ltd, 2015).

2.3.1 Regulations on Anti-Fouling

Many of the established methods for anti-fouling can cause serious damages to the environment and the community, and must be monitored closely ("Anti-Fouling System", 2015).

Early implementations of anti-fouling included the utilization of chemicals, such as arsenic, to prevent the formation of a biofilm on the afflicted ships ("Anti-Fouling Systems", 2015). This worked with moderate success, but the negative environmental impact that it posed was far greater than any efficiency created for the vessels ("Anti-Fouling Systems", 2015). Because of the general lack of regulation, the International Maritime Organization established rules and regulations in regards to anti-fouling ("Anti-Fouling Systems", 2015). This was completed through the International Convention on the Control of Harmful Anti-Fouling Systems on Ships, to implement a system for regulation on potentially dangerous coatings ("Anti-Fouling Systems", 2015).

Adopted on October 5, 2001, the convention outlines many practices that are required for vessels that utilize international waters ("Anti-Fouling Systems", 2015). The convention requires that biocides cannot be used as coatings on the hulls of ships, and that any ship over 400 gross tonnage must undergo an inspection to earn an International Anti-Fouling System Certificate before the voyage (Anti-Fouling Systems: International Maritime Organization, 2015). Additionally, a list of banned coating substances is listed by the International Maritime Organization, which is updated regularly. With the United States Coast Guard being a significant international maritime force in the world, they are held to these strict regulations. Thus they must work towards implementing a system for anti-fouling that is effective, economically sound, and safe for the ocean environment.

2.3.2 USCG Anti-fouling Methods

The accumulation of biofouling, especially in tropical waters such as those of Puerto Rico, causes a large reduction in efficiency and therefore safety as well. USCG vessels operating with as much as a 20% reduction of speed creates a situation of compromised ability to function (Robert Hemp, personal communication, 2015). The Coast Guard budgets for one out-of-water cleaning every three years and one in-water cleaning a year. During the out-of-water cleaning, the hull is blasted to clean and remove the present coatings, then the hulls are recoated with paints according to the standard spec 2310. At this time, there are six standardized anti-fouling paints employed by the Coast Guard for initial coatings and re-coatings across all districts (SFLC Standard Specification 6310, 2014). The cutters presently located in Sector San Juan are classified as having "Steel Hulls (Up to 12 Years), in Salt Water". For these hulls, the anti-fouling paint employed is a copper-based ablative biocide known as International Interspeed BRA 640 (See section 4.2. for more information).

As for in-water cleanings, the annual cleaning takes place immediately before the mandated annual inspection in order to get the hull prepared for the inspection (Commanding Officer "A", personal communication, 2015). As part of the inspection, forms known as Maintenance Procedure Cards (MPC's) are filled out, and detail the amount of fouling on a scale of 0 to 100 (See Appendix A). Additional cleanings are done when the above 20% reduction in speed is proven when the ship is underway (not sitting in port) (Robert Hemp, personal communication, 2015). Due to this protocol that Sector San Juan has in place, the cleaning of each vessel is not regimented, but only conducted on an as-need basis. This leads to sporadic ship maintenance, and no concrete plan that is able to be evaluated.

To conduct the in-water cleanings, the USCG hires divers from a local third party company. During the cleanings, divers chip away the accumulation of biofouling with flat metal scrapers (Robert Hemp, personal communication, 2015). This method, however, cannot remove the all the fouling from off of the hull, as much of it is rooted in the anti-fouling paint according to the diver who does the cleanings (Personal communication, 2015). Attempting to remove the deeply rooted macrofouling would result in chipping the anti-fouling paint and expose unprotected sections of the hull that will allow fouling much quicker (Diver, personal communication, 2015).

The conditions of Puerto Rico, and specifically San Juan Bay on which the Coast Guard base is located, are incredibly favorable to biofouling growth. Lots of sunlight, consistently high temperatures, and high salinity all contribute to aggressive biofouling (Yebra & Kiil, 2003). Due to this, macrofouling build-up on the vessels returns rather quickly; occasionally as frequently as 1-2 months (Robert Hemp, personal communication, 2015). As previously stated, the most effective way to remove biofouling is through out-of-water cleanings, as all of the biofouling is detached. Unfortunately, the cost of fuel just to get the San Juan ships to travel to Florida for dry-docking is roughly the cost of 3 in-water cleanings, so additional out-of-water cleanings are unfeasible (Engineering Petty Officer “A”, personal communication, 2015).

2.4 Defouling Methods

While anti-fouling is important, the methods utilized to clean off the biofouling that does stick are equally worthy of investigation. The removal of biofouling on ships, referred to as defouling, occurs through in-water cleanings and out-of-water cleanings. In-water cleanings involve having divers go down to the vessel hull and manually scrape off biofouling (Robert Hemp, personal communication, 2015). This is dangerous to do on ships with anti-fouling coatings, however, as the paint can be easily chipped and enter the water thus poisoning local marine life (The National System for the Prevention of Management of Marine Pest Incursions, 2009). The chipping in the anti-fouling paint also reduces the hulls ability to resist regrowing biofouling (The National System for the Prevention of Management of Marine Pest Incursions, 2009). Overall, in-water cleanings are less thorough and can damage the vessel’s coating, but cost significantly less and are easier to execute logistically (the ship is not taken out of commission, it doesn't have to be scheduled as far in advance as an out-of-water cleaning, etc.) than out-of-water cleanings (Commanding Officer "A", personal communication, 2015).

Divers must be careful when executing in-water cleanings however, as oftentimes the anti-fouling and anticorrosive paints are chipped in the cleaning process. Although out-of-water cleanings are more effective, the cost of them is exponentially higher, making further implementation unreasonable. The Coast Guard in San Juan currently use in-water cleanings due to the aforementioned benefits of the technique (Robert Hemp, personal communication, 2015). Out-of-water (dry-dock) cleanings, where abrasive-blasting is employed, are conversely more thorough and less damaging (The National System for the Prevention of Management of Marine Pest Incursions, 2009). Another benefit of dry docking ships is that over a period of roughly seven days, exposure to oxygen and sunlight will kill much of the remaining fouling left after abrasive cleaning (The National System for the Prevention of Management of Marine Pest Incursions, 2009).

2.5 Social Impacts of Biofouling and Anti-fouling

After the economic recession from 2007 to 2011 in the United States, the economy has been steadily recovering. Unfortunately for Puerto Rico, which was also impacted by the recession, the economy has comparatively declined (Ehrenfreund, 2015). This economic downturn has had many effects on Puerto Rico. The island has experienced rising unemployment, mass emigration, and low wages reaching below the federally mandated minimum wage (Ehrenfreund, 2015). Overall, the unemployment rate in Puerto Rico is exorbitant (Ehrenfreund, 2015). Currently, the San Juan Coast Guard contracts out to a local company to complete the in-water hull cleanings (Robert Hemp, personal communication, 2015). Diving is likely to be the only source of income for these individuals, and certain outcomes of this project could lead to less/no work for these locals.

One reason at large for these economic conditions is an archaic law known as the Jones Act (Ehrenfreund, 2015). The Jones Act restricts Puerto Rican businesses to shipping through the US Merchant Marines, leading to more expensive import/exportation (Ehrenfreund, 2015). Puerto Rico has had a history of tension with the US Military; for over 60 years, the US Navy used the eastern part of the island of Vieques, off the coast of Puerto Rico, to test air-to-land and sea-to-land artillery strikes (Canedy, 2003). Only recently in 2003 did the Navy agree to halt bombings, but in their wake left the island contaminated with undetonated explosives and a damaged landscape (Canedy, 2003). With the combination of the Merchant Marines' Jones Act and the Navy's testing in Vieques, tension between the people of Puerto Rico and the United States military may very well cause issues with the Coast Guard. In light of this, the team aims to handle the issue of effectively defouling the Coast Guard's vessels with caution. Our final plans intend to incorporate evaluating the possibility of keeping local contracted workers employed by the Coast Guard during these poor economic times.

2.6 Summary

Although biofouling may seem like a relatively simple and harmless occurrence, many factors throughout San Juan and other tropical climates can pose a significant impediment to many different functions. The United States Coast Guard has a large role in maintaining the safety and security of Sector San Juan, and any impediment to their functions could create serious safety concerns. Additionally, inefficiencies in terms of fuel consumption and time loss provide additional dangers for the USCG, making biofouling a process that creates hazards throughout the entire district, and financial losses throughout the Coast Guard. Over the duration of this project, we implemented a strategy to combat the accumulation of this biofouling, in hopes of creating a more efficient and economically sound Sector San Juan.

3.0 Methodology

The United States Coast Guard (USCG) Sector San Juan has been attempting to combat excessive biofouling on their vessels due to its negative economic impact (Robert Hemp, personal communication, 2015). To accomplish the goal of reducing the economic impact of biofouling in Sector San Juan, we determined the need to solve the three following objectives:

1. Analyze the current hull cleaning schedule implemented by the United States Coast Guard, and investigate areas where the schedule can be improved.
2. Evaluate the effectiveness of current standardized anti-fouling coatings set by the United States Coast Guard and research alternative coatings that may provide better defenses against biofouling.
3. Investigate the current cleaning tools and techniques implemented by Coast Guard contract divers, while concurrently researching academia to find alternative and effective cleaning techniques and technologies.

The necessary tasks completed to accomplish the objectives listed is illustrated in the flowchart below in Figure 10.

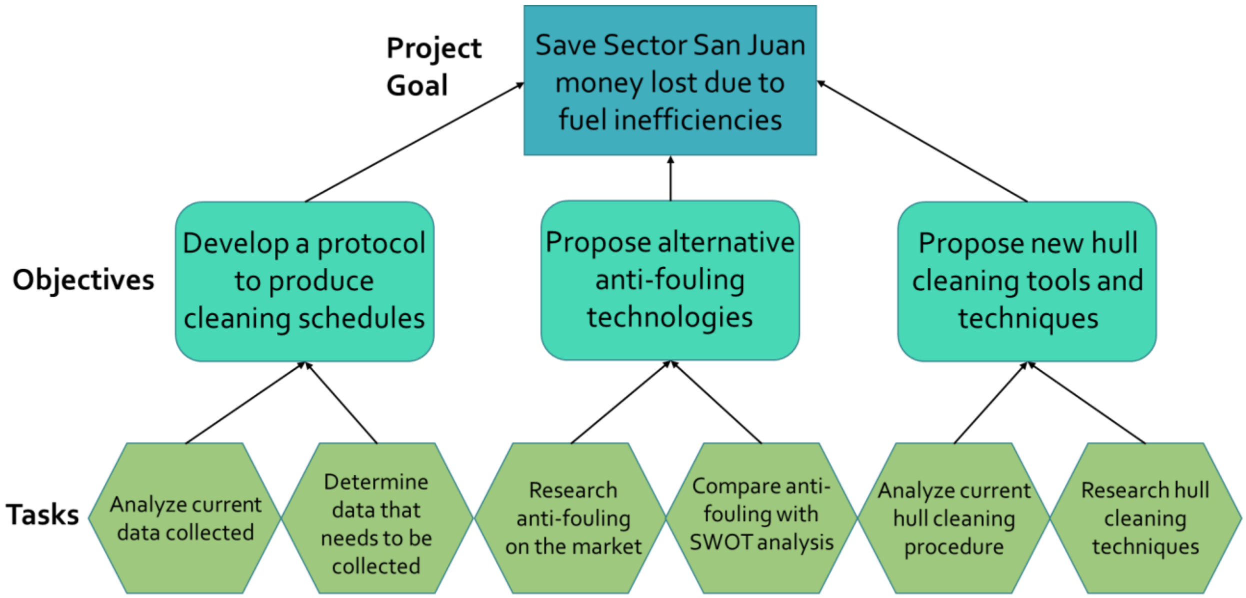

Figure 10 – Methodology Flowchart

In addition to the project objectives, we will take into account the possible social impacts that schedule and hull cleaning recommendations could have on the contracted divers and that coating recommendations could have on the environment surrounding Sector San Juan. We feel it is vital to address these potential impacts in a constructive manner, and, as such, have developed a methodology to ensure that throughout the project we are working to minimize these possible impacts.

3.1 Objective 1 – Develop an Effective Cleaning Interval

To begin the research into our first objective of determining an effective cleaning interval for Sector San Juan, our team identified the following necessary steps:

1. Identify the current hull cleaning schedule
2. Identify what aspects of ship performance are taken into greatest consideration when justifying a hull cleaning (fuel efficiency, speed the ship achieves, etc.)
3. Identify how biofouling accumulation affects these aforementioned performance aspects
4. Search for data relating to the aspects that affect performance

5. Create a new schedule through analysis of this data

The above steps enabled us to pinpoint what factors go into deciding when a hull cleaning is scheduled for a ship. From an analysis of these factors, we were able to demonstrate how biofouling accumulation impacts the ship's performance. From this we could also demonstrate how the removal of this biofouling would positively impact the ship's performance. These two demonstrations allowed for us to make calculations that would lead to finding better cleaning intervals. To begin finding these better cleaning intervals, we looked for whether the data needed to make the calculations was available, and where it could be found.

To identify the hull cleaning schedule currently used in the Sector (step 1 above), we interviewed our main point of contact, Commander (CDR) Robert Hemp. CDR Hemp is in charge of the logistics division within the Sector, and his department is responsible for the upkeep and maintenance of the Sector's vessels. As such, the department oversees the cleanings and are knowledgeable in the process. To determine how biofouling impacted ship performance and to find data on this (steps 2 – 4), we reached out to the Commanding Officers (CO's) and their Engineering Petty Officers (EPO's) of all present vessels and inquired about their experiences on their ships. For security purposes, the COs and EPOs will be referred to as CO "A", CO "B", EPO "A", and EPO "B" throughout the rest of the report. The interview questions for the COs and EPOs and the interview transcripts for Sam Alvord, can be found in Appendix B, Appendix C, and Appendix D, respectively. CO's direct their vessel's actions and have a thorough understanding of how it is operating. EPO's are responsible for overseeing the engine and the functionality of the vessel. To accomplish steps 2 – 4 above, we asked several CO's and EPO's the questions listed in Appendix B and Appendix C.

From the responses of both CDR Hemp and the vessel CO's and EPO's, we considered what data was available on ship performance and where it could be located. Following this, we then began to formulate schedule recommendations.

3.2 Objective 2 – Evaluation of Current and Alternative Anti-fouling Coatings

To address the second objective, our team looked to research and evaluate the types of anti-fouling coatings that are used on vessels. Specifically, we sought to identify the coatings that were utilized on Coast Guard ships, and learn about their strengths and weaknesses. Additionally, we researched other types of anti-fouling coatings that are commercially produced to find one that would work most effectively within the climate and conditions of the Sector.

Across the entire Coast Guard, anti-fouling coatings are standardized for specific ship types (SFLC Standard Specification 6310, 2014). In Sector San Juan, all ships have underwater surfaces classified as "Steel Hulls (Up to 12 Years), in Salt Water" and only copper ablative anti-fouling paints are applied on the hulls of the vessels (SFLC Standard Specification 6310, 2014). Ablative paints intentionally wear away with attached biofouling as a mechanism to remove it from the hull (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). Our primary intention regarding this coating was to better understand the ablative process and its role in combating biofouling, and to establish the level of success of copper ablative paints in Sector San Juan.

Along with the task of analyzing the current anti-fouling coating used in the Sector, our team researched alternative coatings that are available on the market. In the case that the currently used, copper ablative paint does not meet the needs of Sector San Juan, our group wanted to suggest a coating that could meet those needs. To accomplish this, several tasks were completed:

1. Scheduled interviews with the contract divers on site to talk about their experiences in cleaning the hulls. The divers interact with the coatings directly, and thus have a good chance in understanding their characteristics.
2. Reached out to the COs of the vessels, as well as relevant ship personnel. In this case, it was most often the ship's Engineering Petty Officer (EPO). For both parties, we asked for their experiences with the vessel and its anti-fouling coating.
3. Comparatively analyzed the coatings using a Strength, Weakness, Opportunity, and Threat (SWOT) analysis (Goodrich, 2015). From here, we used the analyses to decide which coatings fit the needs of Sector San Juan.

3.2.1 Alternative Anti-fouling Coating Research

While the current paint used in the Sector was being evaluated, we researched other coatings available. We wanted to know the strengths other types had, and if they could provide a better defense against biofouling. Our mission was to distinguish a category of anti-fouling coatings that would be better at combating biofouling within Sector San Juan. Once this was accomplished, we were then able to look further into individual product candidates within this specific category.

Research was separated by categories of anti-fouling coatings. As is stated in the background, anti-fouling exists in two main types: biocidal and non-biocidal. The non-biocidal category is dominated by a type of coating known as fouling release coatings. Within the biocidal realm lies further categories, with the most common being ablative.

As we anticipated for a lack of findings on specific coatings, research was conducted mainly through manufacturer provided sources. These included case studies, Material Safety Data Sheets and Product Data Sheets. Additional sources for research included peer reviewed literature that discussed or compared the effectiveness of given coatings, or externally provided case studies such as those produced through official boating publications.

3.2.2 Anti-fouling Coating Analysis

Each anti-fouling coating has different qualities that affect its price, effectiveness, and ecological impact. In order to compare these coatings, we employed a SWOT analysis on each coating in question. The internal parameters, which are strengths and weaknesses, are for analyzing the good and bad aspects of a coating pertaining to how it combats biofouling (Goodrich, 2015). The external parameters, which are opportunities and threats, apply to the coating's external impacts (Goodrich, 2015). These include the environmental and social effects that the coating could produce. The external aspects of opportunities and threats will help our sponsor to see the project on a larger scope, and take the health, ecological, and social impacts into consideration. Shown below in Table 3 is an example of how the SWOT chart will be formatted:

Table 3 – SWOT Analysis Chart

Paint	HELPFUL	HARMFUL
I N T E R N A L	Strengths	Weaknesses
E X T E R N A L	Opportunities	Threats

Once all of the categories of coatings researched were analyzed using a SWOT analysis, we looked at the charts to determine which ones that best fits the needs of Sector San Juan. From this, we were able toss compile a list of products that fell within the most promising category and have had commercial use.

3.3 Objective 3 – Analyze Alternative Hull Cleaning Techniques

When combating biofouling, hull cleanings are integral. A complete cleaning can increase the performance of a vessel appreciably (Tribou & Swain, 2010). We believed that the current cleaning protocols are sufficient for other parts of the United States, but could be altered to increase the performance of the vessels in San Juan. By exploring different methods of cleaning, we suggest to implement these methods to receive a more complete cleaning, thus saving the Coast Guard time and money.

The process of cleaning the hull of a Coast Guard vessel is a delicate balance; one must be careful to remove as much of the fouling as possible while simultaneously taking care not to damage the anti-fouling coatings on the outermost layer of the hull. Our team evaluated the methods that are currently used in the hull cleaning process and planned to suggest alternative methods, if appropriate. In working towards this objective, our team formulated tasks, and utilized different resources to offer comprehensive recommendations. Our two tasks were as follows:

1. Interviewed the diving company that the Coast Guard contracts and learned about the current cleaning process.
2. Conducted research into the academic world, seeking case study information from experts regarding the cleaning processes of hulls.

3.3.1 Contracted Diving Company

In order to learn about the cleaning strategies that are utilized on the Coast Guard vessels, it was necessary to talk to the people that perform these cleanings, and to learn as much as possible regarding the tools and practices used in the biofouling removal process. We spoke with the diving company that is contracted by the Coast Guard to learn the methods in which they clean and the tools that they utilize. During the interview, we asked the questions that are outlined further down in section 3.4.1, with the goal of learning the techniques and tools used. We additionally saw a live cleaning; by seeing the tools that this company uses, as well as how they use them, we gained a better understanding of their cleaning practices. In the interview, we sought to find out if they were aware of the anti-fouling coating mechanisms, and if they were knowledgeable of different methods of cleaning the hulls. By learning what is done and what is not done, we began to formulate new methods of cleanings; however, more information and research will be needed before tangible, specific recommendations can be made.

3.3.2 Academic Research

Once our team determined the current hull cleaning protocol, we looked to the academic world, attempting to find the most effective and efficient methods of cleaning. With the information from the contract divers as a reference, we researched specific anti-fouling case studies, and determined if the methods that the divers utilized coincided with the information found in the academic field.

In comparing the new techniques to the ones currently in use, we were able to communicate these recommendations to the divers and the Coast Guard. Additionally, our team sought to find alternative tools for hull cleanings. With the current methods used by the divers as a reference, we looked to see if there were tools that would clean the hulls better, while still keeping the anti-fouling coatings intact. Finally, we attempted to establish points of contact with the experts who have done research on the anti-fouling process. With the experts as a resource, we utilized their knowledge, to make supported recommendations.

3.4 Social Impact

Due to the possibility of job loss and the potential for damage to local marine life, it is important that we take particular caution in the concluding recommendations we make in this project. To properly gauge the impacts of our recommendations for the implementation of anti-fouling coatings, we were diligent in our research. Material safety data sheets for individual anti-fouling products provided us with the chemical toxicity and ecological effects for each paint that we considered. Any potentially harmful aspects of these paints were noted in their respective SWOT analyses. These harmful aspects weighed against those paints when it came to creating the final anti-fouling recommendations.

Conducting an interview with the diving company contracted for the current in-water-cleanings gave us a perspective regarding the importance of Coast Guard employment to the divers' livelihoods. Had our recommendations reduced the number of cleanings, we were prepared to use information from these interviews to make plans for having the divers contracted for other work on base.

3.4.1 Contract Diver Interviews

In interviewing the contract divers, we went about asking questions in a sensitive manner. CDR Robert Hemp helped us to establish contact, and we interviewed the head diver. Since we were asking about livelihood and careers to some extent, we ensured that the diver was comfortable answering these questions, or was comfortable in refusing them. It was our responsibility to minimize the risk present to the subject. We conducted the interview in the Sector San Juan engineering building. This provided a central and well-known location for the interview to take place. It was also important that as we asked these questions, we did not give the impression that our recommendations and our project may put the divers out of work. This would have caused undue stress for the participants we were working with. In order to ensure the personal and emotional safety of the participants, we have protected their anonymity. To accomplish this, no personal identifying data was recorded with their responses, which was only to be viewed by the students in the project team. Refer to Appendix E for the interview questions that we asked. From these questions, we were able to evaluate the role that these cleaning contracts have in supporting the livelihood of the divers.

3.5 Summary

Our main goal was distinct: make recommendations to save Sector San Juan money in their hull cleaning processes. Through a combination of interviews with Coast Guard personnel, research into anti-fouling and hull cleaning procedures, and analysis of the current practices used in the Sector, we created a methodology that focused on three objectives. These objectives were to produce cleaning schedules, propose alternative anti-fouling technologies and recommend new hull cleaning tools and techniques. Through these objectives, we were able to gather knowledge that developed into our findings.

4.0 Findings

Through our scheduled interviews with coast guard personnel and contract divers, we encountered the following findings relating to Sector San Juan's hull cleaning schedule, the current anti-fouling coating applied to the vessels, and diver's cleaning techniques:

- **There are four sets of data needed to effectively create a new hull cleaning schedule:**
    - Biofouling Accumulation
    - Speeds and associated RPM
    - Fuel consumption (burn) and associated distance travelled
    - Gallons per hour consumed

We found these data points to be necessary in evaluating the current cleaning schedule, and creating alterations to better suit the Sector

- **The anti-fouling coating currently employed on the vessels in Sector San Juan is a biocidal, copper, ablative anti-fouling paint (more specifically, International Interspeed BRA 640) and is unfit for the conditions within this Sector** (Commanding officer "A", personal communication, 2015).

Copper is at risk of being legally banned for use in anti-fouling due to the damage it does to marine life (Kaznoff & Rudroff, 2000). Ablative paints intentionally wear down and fall off the hull easily (Commanding Officer "A", personal communication, 2015). This is unsuitable for Sector San Juan because the hulls undergo frequent cleanings. (Robert Hemp, personal communication, 2015).

- **Microfouling is important to remove, because this prevents macrofouling from attaching well** (Cao et al., 2010).

Current in-water hull cleanings are very effective at removing macrofouling (the hard, visible biofouling), but do not remove the microfouling (hard to see, slime and film-like biofouling that acts as a surface for macrofouling to accumulate upon) (Diver, personal communication, 2015). Should the frequency of in-water cleanings per vessel increase, it would be wise to have this microfouling cleaned so future macrofouling would be less abundant and attach less strongly.

- **Our recommendations for Sector San Juan do not put the contracted divers at risk of losing in-water hull cleaning contracts.**

None of our findings support the need, benefit, nor possibility of reducing the number of in-water cleanings conducted within the Sector.

4.1 Objective 1 – Data Necessary to Create Effective Hull Cleaning Intervals

Our first objective with this project was to improve Sector San Juan's hull cleaning schedule. Before we could improve upon it, we needed to determine the factors that are most important in deciding when in-water hull cleanings should occur. To accomplish this we spoke with the following personnel:

- **Commander (CDR) Robert Hemp** (our main sponsor contact and head of Sector San Juan Logistics Department)
- Several of the ships' **Commanding Officers** (COs) and their **Engineering Petty Officers** (EPOs).
- The head of the Energy Management Office for the Coast Guard, **Sam Alvord**.

In talking to CDR Hemp about the cleaning process, we learned that all ships in Sector San Juan are budgeted for one in-water hull cleaning per year (Robert Hemp, personal communication, 2015). This specific cleaning is typically performed before each ship undergoes its mandated annual inspection (Robert Hemp, personal communication, 2015). Should a ship need an additional cleaning within the year, which is nearly inevitable, it needs to quantitatively prove that it has experienced a 20% loss in its top speed (Robert Hemp, personal communication, 2015). Under this policy, roughly 3 cleanings occur throughout a calendar year for each vessel in the Sector (Robert Hemp, personal communication, 2015). Once a vessel proves this speed loss, money from external budgets is used to pay for an additional cleaning (Robert Hemp, personal communication, 2015). Additionally, CDR Hemp helped to establish our contact with a few COs of the ships stationed in the Sector, as well as Sam Alvord. He informed us that the COs would be able to articulate important data in restructuring the cleaning schedules, and where we could find it. CDR Hemp stated that Sam Alvord would be able to speak towards the vessels' fuel consumption, which played into the larger goal of tying additional cleanings to total fuel cost savings.

The Commanding Officers, alongside their Engineering Petty Officers, were helpful with advising our team on what vessel data is collected. Based on our interviews with the COs, EPOs, and Sam Alvord (found in Appendix D) we developed the following list of data necessary to determine cleaning schedules:

- **Biofouling accumulation**
- **Speeds and associated RPM**
- **Fuel consumption (burn) and associated distance travelled**
- **Gallons per hour consumed**

The flowchart in Figure 11 illustrates the data from above and general sources of where these data sets can be found.

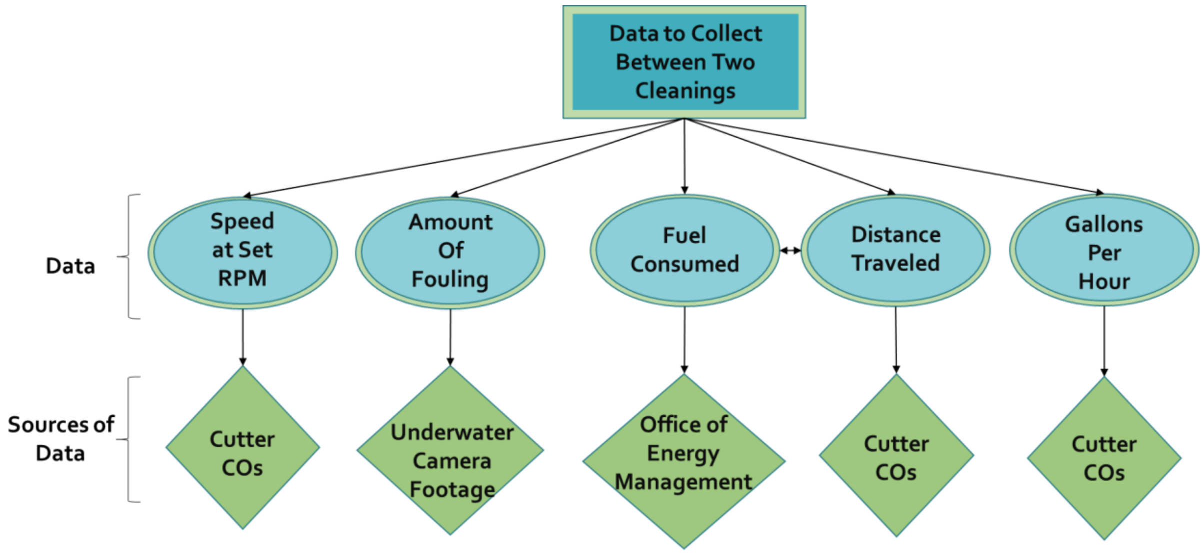

Figure 11 – Data Collection Flowchart

4.1.1 Data Collection – Biofouling Accumulation

Data on biofouling accumulation currently is only recorded in the in-water hull cleaning reports filled out by the contracted diving company (Commanding Officer "A", personal communication, 2015). These reports are completed for every in-water hull cleaning, and consist of a brief paragraph written by the head diver that describes the type of biofouling and a percentage cover on the hull.

Unfortunately, the hull cleaning reports are the only instances where biofouling accumulation is recorded. This means that each report gave roughly the same descriptions of the same types and amounts of biofouling, since the cleanings were conducted after roughly the same time period of biofouling accumulation. Consequently, these data could not be used to illustrate the true nature of biofouling accumulation, as each data point was for maximum fouling right before a cleaning, or minimum fouling right after one. To address this data gap, we devised a plan to collect quantitative data on biofouling in the time between two in-water hull cleanings.

First, we needed to determine how to get the same view of the hull as a diver does, but without having to actually hire a diver. We theorized that one could potentially obtain the same view as a diver with a pole and an attached camera. More information on our recommendation to collect the data can be seen in the recommendations section 4.1.1. Seen in Figure 12 is an illustration of what such a device would look like. From preliminary measurements, each ships' hull on base reaches roughly 6 feet under water, and 2 feet above the water. Additionally, we assumed a person would hold the pole 3 – 4 feet comfortably above the ground. Therefore, the pole for the recording device needs to be at least 10 feet long. See the Appendix F for more details on the design of the recording device.

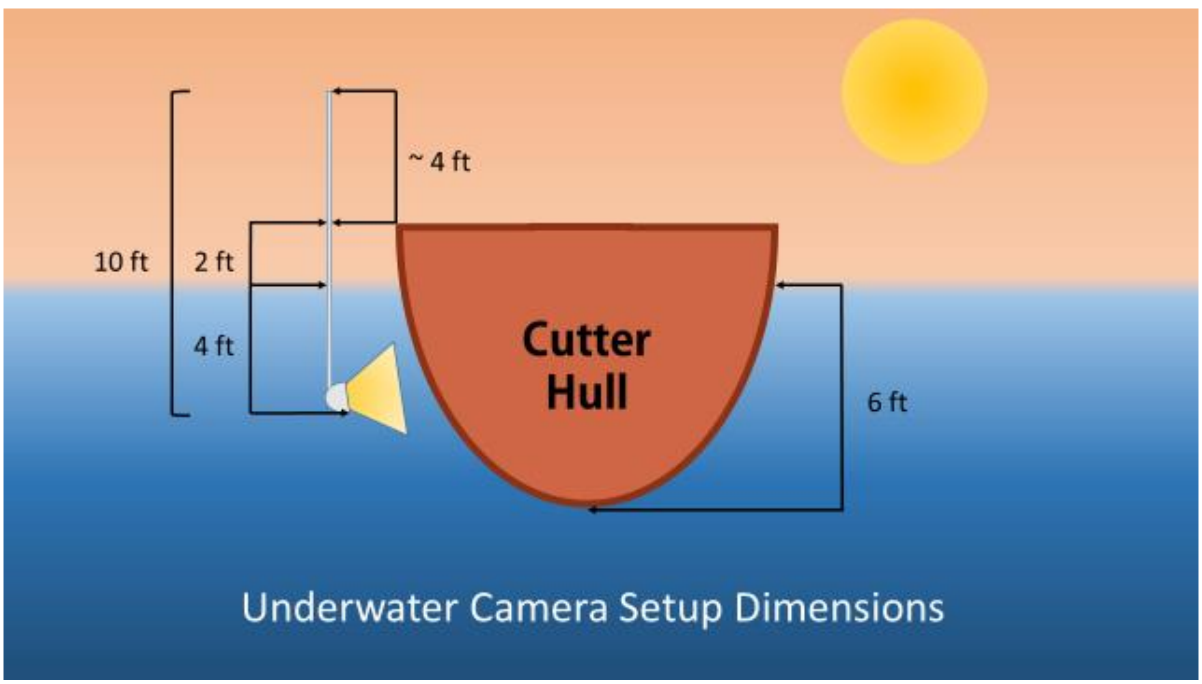

Figure 12 – Underwater Camera Setup Dimensions

Once the hull is recorded, the data needs to be effectively analyzed. As previously mentioned, the Navy employs a Fouling Rating (FR) system using values from 0 to 100, with increments of 10. This scale can be seen in Table 1. One can analyze the videos recorded and compare them with the FR scale, then record the data. To make this process easier, Sam Alvord directed us towards Chapter 081 of the Naval Ships' Technical Manual ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). Chapter 081 outlines each numerical amount of biofouling accumulation visually by providing pictures that correspond to the scale ratings ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). Overall, this recording technique is a simpler and less expensive alternative compared to hiring a diver just to do hull inspections.

Once the data is collected, it can be plotted over time according to Figure 13 below. Based upon the process of biofouling, we anticipate that the actual chart will show an exponential growth/acceleration of the biofouling accumulation. From this chart, one can set a "sliding" cleaning interval, and see at a given time (using integration of the area under the curve) how much biofouling accumulation can be avoided with an added cleaning.

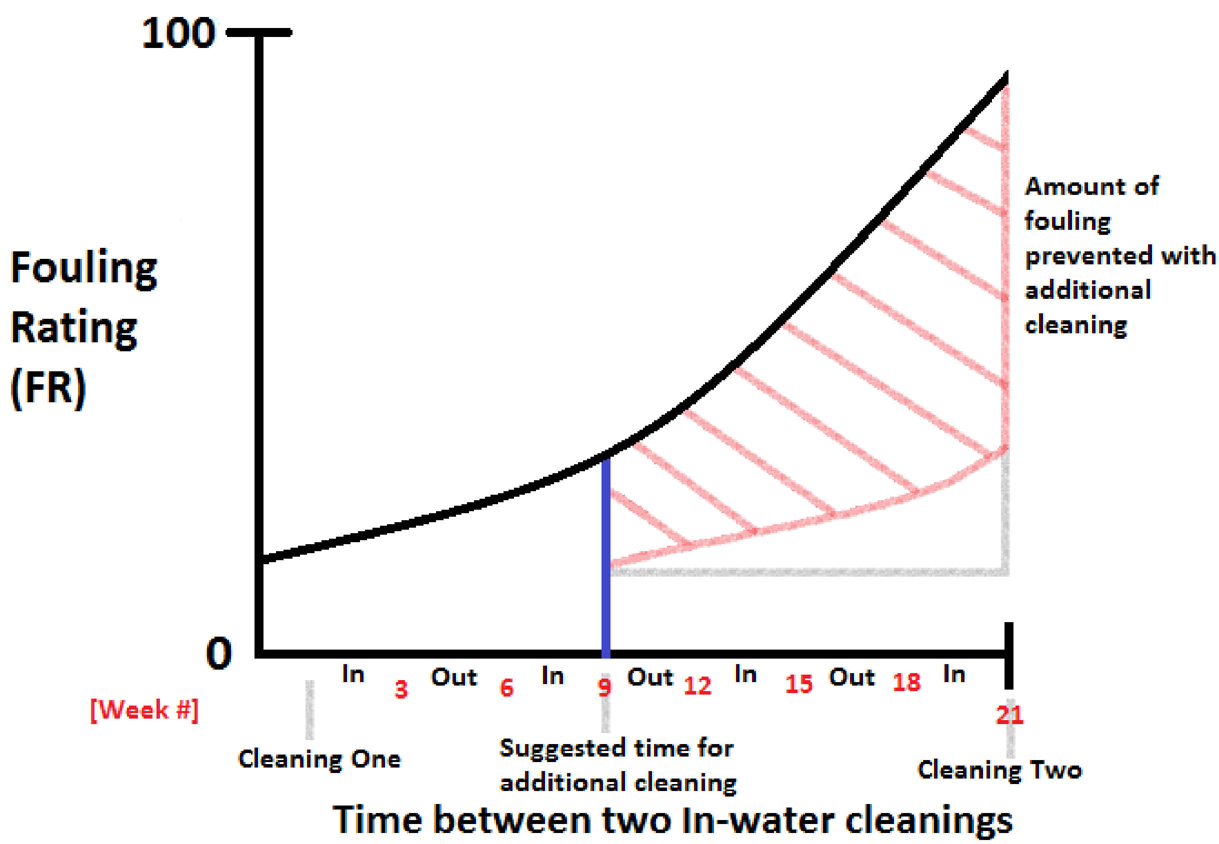

Figure 13 – Biofouling Accumulation Graph

4.1.2 Data Collection – Speed & Associated RPM

Through conversations with the several COs and EPOs, we learned that both speed and engine RPM data could be viewed live (while a ship is operating), but only engine RPM was recorded. Engine RPM is recorded in "round sheets", which are maintenance sheets filled out every hour of every day while a ship is operating. A sample round sheet can be seen below in Figure 14. The speed is not recorded in these sheets, however, even though it is just as easy to record as engine RPM's (both are available as live readings).

USCGC (Insert Name and #)																
#1 MDE LOG																
	ENG RPM	SHAFT RPM	ENG L/O PSI	ENG L/O TEMP	R/G L/O PSI	R/G L/O TEMP	R/G CONT PSI	J/W TEMP	SHAFT SEAL	OIL LEVEL	R/G OIL LEVEL	GOV OIL LEVEL	OIL ADDED	FUEL RACK POS	J/W LEVEL	INIT.
LOW																
HIGH																
0000																
0100																
0200																
0300																
0400																
0500																

Figure 14 – Sample Round Sheet

If the speed and RPM data were to exist over a sufficient sample period, speed divided by RPM could be plotted over time. Since biofouling accumulation over time causes ship drag, it is reasonable to assume that a ship's engine will need to work harder to maintain a standard speed. Thus, at a set engine RPM output, the ships speed will decrease over time. Similarly to the biofouling accumulation chart above, a "sliding" cleaning interval can be used in analyzing this chart. One could set an additional cleaning interval and see how a ship's speed recovers and the ship's ability to maintain top speed stays more consistent over a set period of time (since traveling at top speed is vital to the Coast Guard's missions).

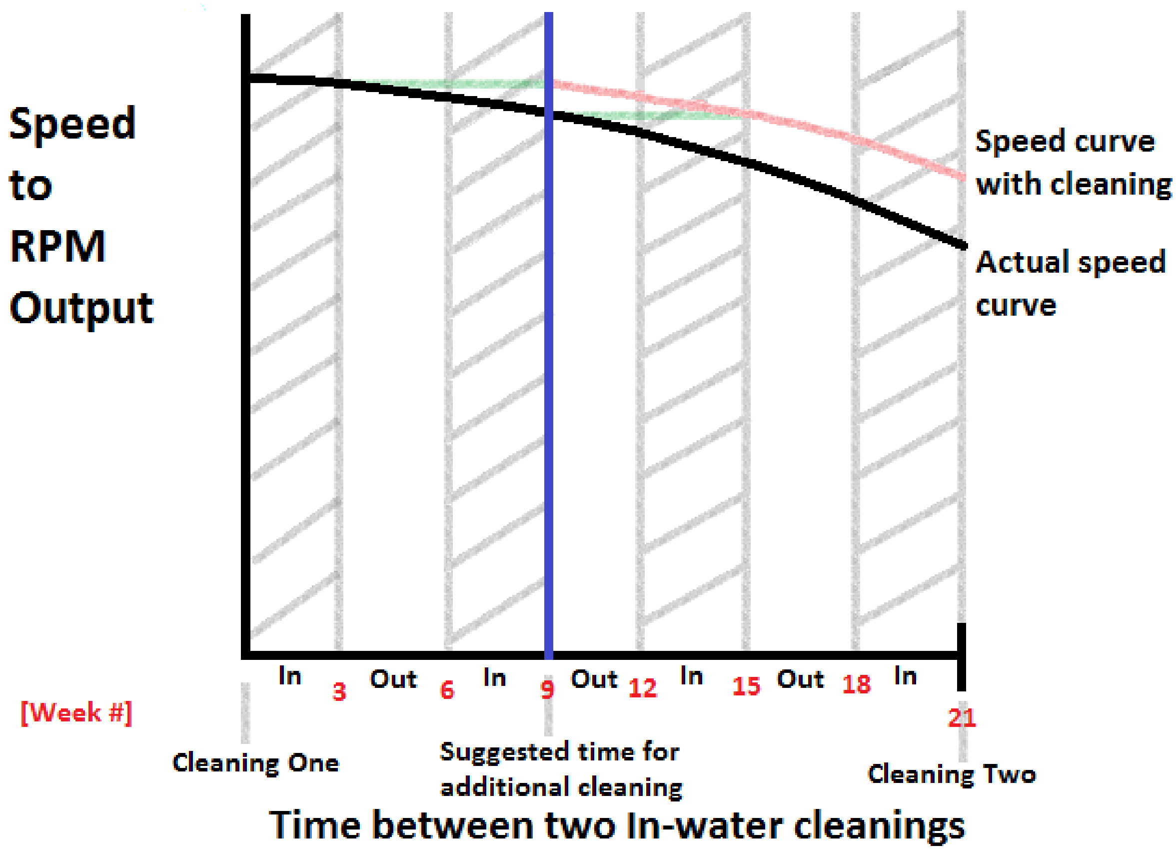

Figure 15 – Speed to RPM Graph

4.1.3 Data Collection – Fuel Consumption & Associated Distance Traveled

In our conversation with Sam Alvord, we discovered that the USCG Office of Energy Management files fuel consumption, also known as fuel burn, logs for all of the ships in Sector San Juan. From these we can see how much fuel a ship used over a period of time, and how many hours that ship was operating during that same period. Additionally, in our conversation with the CO's and EPO's, we learned that distance data was recorded in a similar fashion to engine RPM data. Distances traveled every several hours are recorded daily while a ship is underway in the "Weather Observation and Operational Summary Sheet".

The fuel burn and distance data can be analyzed by dividing corresponding fuel consumption numbers with distances traveled. This division will create new data points, Gallons to the Nautical Mile, which can then be plotted over time. Similarly to the Speed to RPM data, as biofouling accumulates on a ship, the ship will need to spend more fuel to travel a set distance. The trend of this plot is expected to be an increase in the curve's slopes over time, as visualized below in Figure 16. Using the same sliding cleaning interval as mentioned above, it is possible to see how much money can be saved when a new cleaning is set. This is done by redrawing the initial gallon/nautical mile curve trend at the "new" cleaning (the blue line in Figure 16 below), then integrating between the top (actual) and bottom (hypothetical cleaning) curves. This will give you data that can be calculated into total gallons of fuel saved from the implementation of the new cleaning(s), which can then be translated into money saved.

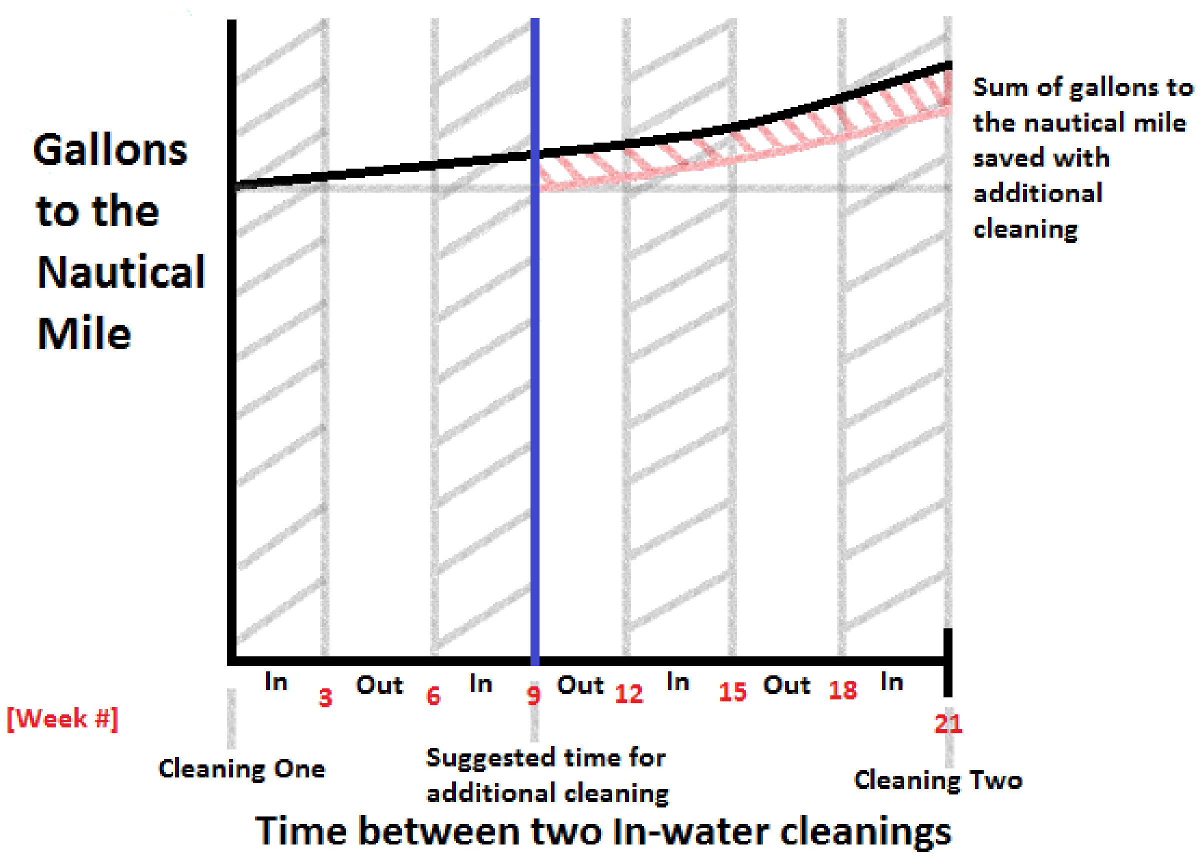

Figure 16 – Fuel Efficiency Graph

4.1.4 Data Collection – Gallons Per Hour Consumed

As an alternative to using distance and fuel burn data to calculate the fuel money saved with additional cleanings, we also discovered that gallons per hour data could be used. As we learned through the COs, gallons per hour is a live data point similar to speed and rpm output. What this means is that it could be just as easily recorded in addition to speed data on the same round sheet as the rpm data Table 6 in section 5.1.2.

As an alternative, gallons per hour can be directly correlated to travelling speed because the engines will consume different rates of fuel depending on what speed the vessel is traveling at. As a vessel is on patrol, it does not travel at one consistent speed. It will move at a low “clutch” speed, a range if middle speeds, or its top speed (Commanding Officer “A”, personal communication, 2015). As the vessel is travelling at different speeds, it will be consuming fuel at different rates (Commanding Officer “A”, personal communication, 2015). While a fuel burn/distance analysis will not account for the different speeds, gallons per hour can account for this. To do this, gallons per hour could be plotted over time on three separate curves: one for top speed, one for the range of middle speeds, and one for clutch speeds. The anticipated trend is that each of these curves will have a slight exponential increase, since biofouling accumulation and increased drag over time will cause the engines to consume more gallons of fuel per hour. To find fuel money saved from this plot, integrating under each separate speed curve and adding the results would produce one number for fuel saved with an additional cleaning (represented by the blue line on Figure 17). This fuel amount can then be converted to total fuel dollars saved.

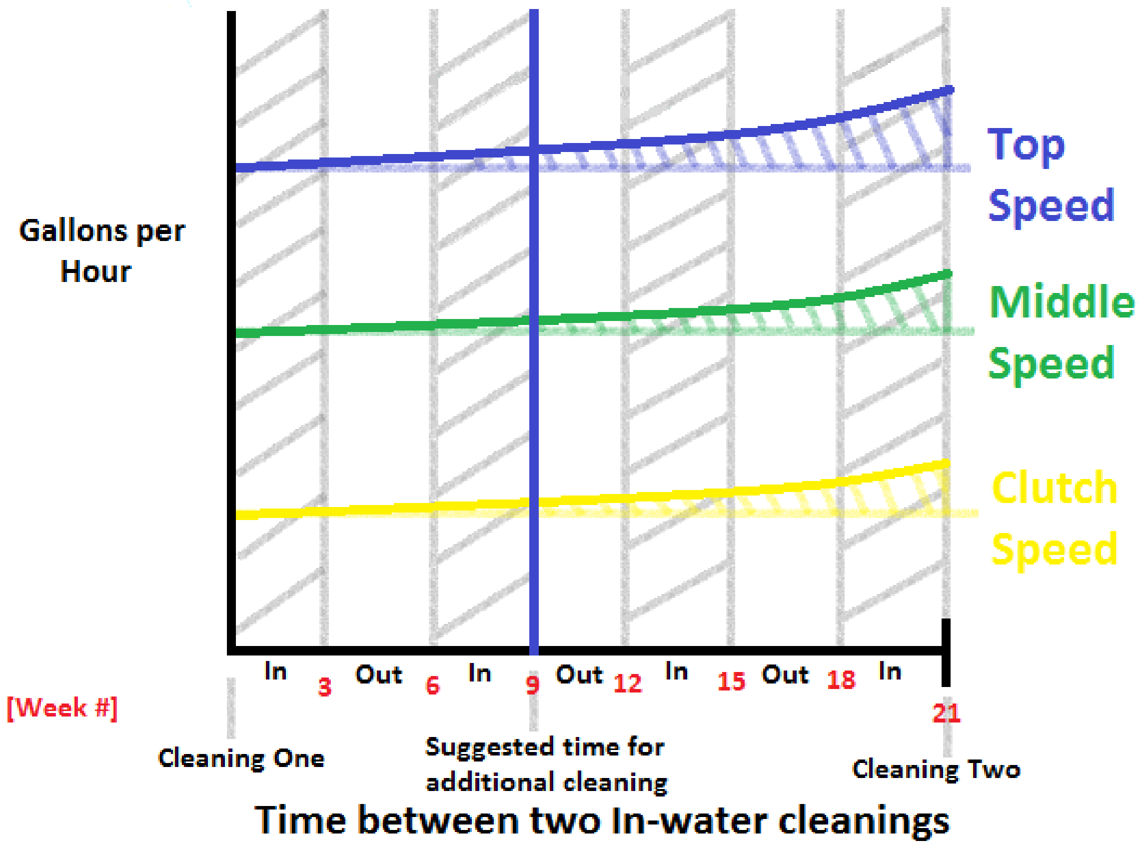

Figure 17 – Gallons per Hour Graph

4.2 Objective 2 - Evaluation of Current and Alternative Anti-fouling Technologies

Through interviewing Coast Guard personnel, we discovered that International Interspeed BRA 640 is the anti-fouling paint currently used on vessels in Sector San Juan. This paint utilizes the ablative mechanism as previously mentioned, confirming our research in how this coating combats biofouling. Concerning a vessel's CO, it was a general consensus that this paint is unable to meet the needs of Sector San Juan. As for the divers, the paint can be soft and may wear away excessively when submitted to thorough cleanings. Due to this, we believe that a harder paint may better suit Sector San Juan, such as a foul release coating.

International Interspeed BRA 640 is a biocidal, copper-based, ablative paint that wears away when the vessel is traversing the sea (for more information on this coating, refer to background section 2.3.1). We were able to locate its material safety data sheet and product data sheet and gathered more specific information. From here, we determined what the coating is and the process by which it works. The paint is designed to wear away as a vessel is cutting through the water, but in conversing with many of the COs, we found that cutters may sit in port for periods of up to two to three weeks (Commanding Officer “A”, personal communication, 2015). This may be an issue if the vessel is stationary and therefore not creating an environment in which the paint is designed to work. The biofouling accumulation after a period of 2 months was referred to as a “vegetable garden” towing behind the vessel, providing evidence that this coating may not be suitable for the Sector (Commanding Officer “A”, personal communication, 2015).

A supporting opinion was expressed by the diver contracted by the Sector. This paint is delicate and can be removed while cleaning the hull (Diver, personal communication, 2015). The divers have traditionally not encountered an issue like this, as previous vessels employed the use of a different, harder coating (Diver, personal communication, 2015). Over the course of several cleanings, the excessive wearing of the paint will decrease the lifetime of the coating and prevent it from being able to deliver an effective defense against biofouling (Diver, personal communication, 2015).

Additionally, it is worth mentioning that copper-based biocidal coatings may be dismissed for future application by the Navy (Kaznoff & Rudroff, 2000). They fear copper-based coatings may be banned from use, similar to the banning of a tin based system in previous years

(Hearin et al, 2015). From these aforementioned reasons, we believe it may be beneficial to utilize a different type of anti-fouling paint.

After exploring different types of coatings and assessing their qualities with a SWOT analysis, we were able to compare what each coating category could offer for Sector San Juan. Appendix G provides these SWOT charts. Table 4 shows the results of our research, listing the type of paint and breaking into respective Strengths, Weaknesses, Opportunities and Threats. Note the undesirable environmental impacts that may result if a coating containing biocides is enacted, whereas this may be avoided with a foul release coating. Additionally, the contact leaching paint may also increase maintenance costs for the owner of the vessel. Most notable is that the foul release type can withstand cleanings of the hulls to resolve the excessive wearing issue current divers are facing. With this in mind, we believe the niche for a foul release coating in Sector San Juan has presented itself.

Table 4 – Summarized Results of SWOT Analysis

Paint Type	Strength	Weakness	Opportunity	Threat
Contact Leaching	+ Releases biocides constantly using diffusion	- Coatings build up over time and crack, increasing maintenance costs	+ Hard outer coating that can be cleaned	- Utilizes biocides that are typically metal-based
Self-Polishing	+ Chemically reactive surface to release biocides dependent on environment	- N/A	+ N/A	- Heavily tin-based leading to the harm of marine organisms in surrounding environment
Controlled Depletion	+ Slow release of biocide with the intention that the layer will wear away and remove biofouling with it	- Thorough cleanings may excessively wear away paint reducing its effectiveness	+ N/A	- Biocides may still diffuse in worn away paint affecting the surrounding environment
Foul Release	+ Provide a smooth surface to more readily remove the biofouling	- Does not actively combat marine organism attachment	+ Does not employ use of biocide with no adverse effect on environment + Designed to benefit from cleanings	- N/A

4.3 Objective 3 – Alternative Hull Cleaning Techniques

Through talking with the contract divers currently employed by the Coast Guard, researching the science community, and consulting experts in the field of anti-fouling, we have found that there are methods and technologies that can better remove biofouling accumulation for longer periods of time. We believe that there are current practices that can be implemented immediately for these purposes. Additionally, we also trust that the development of new hull cleaning technologies may also have an impact on biofouling accumulation. By adopting these techniques and technologies, in addition to the other deliverables, we have developed a protocol that positively affects the impact of the cleanings.

In preliminary discussions with the Coast Guard contract diver, we learned that hard biofouling accumulates thoroughly on the hulls of the ships in between cleanings. Because of this, the biofouling is deeply rooted into the paint of the hull, and requires scraping tools for removal (Diver, personal communication, 2015). As a result, portions of the paint are removed in addition to the coating, which is unavoidable once the biofouling becomes deeply rooted into the hull. Additionally, this makes for arduous cleanings, as the team of divers must work delicately yet forcefully to remove the hardened growth (Diver, personal communication, 2015). This makes the removal of the macrofouling difficult and time consuming. Although we cannot disclose the specifics of the techniques that the contract divers use to clean the ship hulls, it is clear that this process is only able to remove the macrofouling. The biofilm does not get completely removed. The presence of the layer of biofilm serves as the base for the accumulation of hard fouling, and must additionally be removed for a fully effective cleaning (Cao et al, 2010). With this information recorded, we then turned to consulting scientific research in an attempt to devise a more efficient and effective method of cleaning.

When beginning our research on hull cleaning methods and techniques, we first made contact with Dr. Geoff Swain of Florida Institute of Technology. Dr. Swain studies the effects of biofouling accumulation and the methods of removal, and has published many scientific papers regarding biofouling removal. He provided the team with studies and publications, specifically regarding biofouling accumulation and its removal in different environments. Throughout Swain's works, there were several techniques and methods that were proven to greatly reduce fouling accumulation on submerged surfaces. One method known as grooming could easily be applied to Coast Guard vessels. In this process, the hull of the ship is cleaned in a gentle, repetitive motion (Hearin et al., 2015). This is performed after the macrofouling is removed, and targets the layer of biofilm, which as previously discussed, provides the environment for hard macrofouling to accumulate (Hearin et al., 2015). Additionally, Swain recommended the utilization of softer brushes, such as ones with nylon bristles to perform these groomings (Tribou & Swain, 2015). This is shown to not only remove the biofilm more thoroughly, but to also protect softer anti-fouling paints (Tribou & Swain, 2015).

Dr. Swain has also researched the possibility of implementing autonomous hull cleanings. By consistently grooming the hull of a vessel, the biofilm is unable to accumulate; therefore, the macrofouling that attaches to the biofilm will not accumulate as severely (Hearin et al., 2015). These technologies would be programmed to perform groomings at specified intervals. Many of these technologies are years away from being affordable or practical, though it is a good window for future research.

It should be noted that there were some differences between the conditions of the locations in which Dr. Swain's experiments were performed and the conditions of Sector San Juan. Dr. Swain's studies took place in Port Canaveral, Florida, which naturally has a slightly different climate and different salinity and biofouling species from San Juan (Hearin et al., 2015). In one of Swain's experiments, groomings were performed at 3, 6, 12, and 24 day intervals (Tribou & Swain, 2010). At the 3 day grooming interval, biofouling on both a copper ablative surface (the paint type currently used on Sector San Juan hulls) and a foul release surface was limited to minimal microfouling coverage with no macrofouling (Tribou & Swain, 2010). Implementing such a short cleaning interval would be unfeasible for Coast Guard vessels, however, as it would cost a lot of money to pay for divers to clean at that frequency (Personal communication, Robert

Hemp, 2015). More reasonably, with a 24 day grooming interval, biofouling on a copper ablative surface was still limited to only biofilm (Tribou & Swain, 2010). This illustrates how useful implementing some form of grooming in Sector San Juan could be.

4.4 Social Impact

In gauging the potential social impact, we interviewed the owner and head diver of the company contracted to conduct in-water cleanings. One major finding was that the company mainly works contracts from the Coast Guard (Diver, personal communication, 2015). We concluded that if these contracts were terminated for whatever reason, the company and its employees would suffer from a lack of work.

Fortunately, based upon our findings in the previous sections, it appears that recommendations will not decrease the number of cleanings. Instead, pending what results come from following the cleaning schedule protocol we laid out, the diving company will likely receive a marked increase in work contracts from the Coast Guard. Furthermore, by May of 2016, the Sector will increase its fleet size from 5 ships to 7 ships (Robert Hemp, personal communication, 2015). This means that even without additional cleanings implemented for each ship, the contract diving company will still be receiving more cleaning contracts for the two additional ships. Overall, the outcomes and findings from our project will benefit the contract divers with the potential for more cleaning contracts.

5.0 Conclusions and Recommendations

The current hull cleaning schedule and practices implemented by the Coast Guard are not able to keep up with the excessive biofouling rates in the USCG at maximum operational efficiency. We believe that the application of our three deliverables will lead to more efficient and economic cleaning practices for the Coast Guard. Our team is confident that the application of our recommendations can save the Coast Guard operational time and a significant amount of money that is normally lost in fuel inefficiency expenses. Over the course of the project, we created the following deliverables:

1. A protocol for the determination of hull cleanings, based upon information gathered from Coast Guard personnel.
2. An examination of the current anti-fouling coatings implemented by the Coast Guard, followed with recommendations of alternative anti-fouling coatings to apply.
3. Recommendations of different hull cleaning techniques and procedures to be employed by the contract divers in the Sector.

Based upon these deliverables, the following sections will contain recommendations for the implementation of the information that we gathered.

5.1 Objective 1 – Recommendations to Develop an Effective Cleaning Interval

As previously stated in the findings, the collection of certain data from Coast Guard personnel is necessary to formulate conclusions regarding money saved through additional cleanings. In order for the data collection protocol to work, the proper information must be acquired, organized, and analyzed. Submitted with the final report is a spreadsheet that we have created to allow for the input and analysis of the data we have found necessary for developing an effective cleaning interval. Without the collection of this data, quantitative evaluations of the impacts of biofouling accumulation cannot be made. By collecting and graphically analyzing the following data, as was demonstrated in the findings section, the number of gallons of fuel saved with shortened cleaning intervals can be calculated. Additionally, amounts of biofouling and speed loss avoided may also be calculated. For these calculations to be completed, however, the following information is necessary:

1. Biofouling Accumulation
2. Speed and Associated RPM
3. Fuel Burn
4. Distance Travelled
5. Gallons per Hour

As a means to organize, visualize, and analyze the data collected above, we have created a data collection and analysis spreadsheet. It allows for the input of all the above data and simultaneously graphs the data for user analysis. This is part of the first deliverable and is included with our final submission.

5.1.1 Biofouling Accumulation

In order to quantify the amount of biofouling on the hull of the vessels, we recommend that underwater footage to visualize the hull is collected and analyzed. Anyone may do this recording, though we recommend that it be a member of the engineering department of each vessel, as they are involved in hull maintenance of their ship (Commanding Officer "B", personal communication, 2015). To do this, a camera with underwater capabilities attached to long pole should be moved along the perimeter of the deck of each ship. More information on the design and procedures for this footage collection may be seen in Appendix F. Our team recommends that this occurs between two typical in-water hull cleanings, every time directly before a vessel goes underway (out to sea), and right after it returns. With this information, the footage can be analyzed through the Naval Fouling Rating Scale (Table 1).

This scale was created by the Navy, and is a quantitative measurement of the amount of fouling on the hulls ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). It is a scale from 0-100 based upon increments of 10 ("Waterborne Underwater Hull Cleaning of Navy Ships", 2006). At each increment, a different level of biofouling is described through written descriptions as well as visuals. Once quantified, we recommended inputting the ratings into a Biofouling Inspection Card that we have designed. An example can be seen in Appendix H. Similar to the Maintenance Procedure Card used by the Coast Guard before a cleaning (as seen in Appendix I), this document can quantify the amount of fouling on the hulls, leading to a better understanding of the growth of the fouling.

After the period between two in-water hull cleanings has concluded, we recommend that whoever was in charge of recording and analyzing the footage now take the data from the biofouling accumulation forms and input it into the data analysis spreadsheet earlier described. The sheet for biofouling accumulation data input is shown in Table 5 below. As can be seen, each individual hull section as described in the biofouling inspection form (Appendix H) has its own section for accumulation data. These are all plotted, and we recommend that these individual section accumulations be taken into consideration when looking into the option of setting shorter cleaning intervals, because there is the option of conducting partial cleanings of only the sections most fouled (Robert Hemp, personal communication, 2015). Continuing, the individual section fouling data is averaged to produce the "Average Biofouling Rating", which is also shown in Table 5. This average biofouling rating is also plotted and can be analyzed as per outlined in findings section 4.1.1.

Table 5 – Biofouling Accumulation Data

Biofouling Amounts	Week	Inspection Date	Average Biofouling Rating	Avg Propellor FR	Avg Shaft FR	Avg Rudder/Stab Fins FR	Avg Sea Chest FR
Post-Cleaning Inspection	0		#DIV/0!				
Before U/W	3		#DIV/0!				
After U/W	6		#DIV/0!				
Before U/W	9		#DIV/0!				
After U/W	12		#DIV/0!				
Before U/W	15		#DIV/0!				
Pre-Cleaning Inspection	18		#DIV/0!				
		Week	Inspection Date	Avg Bow FR	Avg Bottom FR	Avg Stern FR	Avg Transom FR
		0					
		3					
		6					
		9					
		12					
		15					
		18					

One potential limitation with the biofouling accumulation data analysis is the subjective nature of the analysis. We recommended that the Naval Fouling Rating Scale be followed as closely as possible, and that both the written descriptions and visuals are used in the analysis of the hull footage. Additionally, the same Coast Guard personnel should be in charge of analyzing all of the hull footage within one trial. In this way, subjectivity can be minimized within the video analyses.

5.1.2 Speed and Associated RPM

To collect speed data and associated engine RPMs, our team recommended an addendum to the “Round Sheet” utilized by vessels while underway as is visualized in Table 6 below. Round Sheets are documents that are filled out by personnel that document the engine performance and travel information. We recommend that a column for vessel speed be added to the Round Sheet. Data is collected every hour of every day that a ship is operating. With engine RPMs and vessel speed documented on the sheet, which is all information that can be gathered as live readings on various vessel displays, the correlation between biofouling accumulation and changes in engine output could be illustrated (Commanding Officer “B”, personal communication, 2015). Throughout an underway period, we recommend that the speed data is collected as often as the other data (including engine RPM) is collected in the Round Sheet. The data can be input and analyzed by the Engineering Petty Officer or another member of the ship's engineering department in the data collection and analysis spreadsheet when the vessel is in port.

Table 6 – Round Sheet with Column Added (Speed)

USCG Cutter (Name & Number)									
#1 MDE LOG									
	ENG RPM	SHAFT RPM	SPEED	GAL/HR	ENG L/O PSI	ENG L/O TEMP	R/G L/O PSI	R/G L/O TEMP	R/G CONT PSI
LOW									
HIGH									
0000									
0100									
0200									
0300									
0400									
0500									
0600									
0700									

5.1.3 Fuel Burn

We recommended that the fuel burn data be collected from the Office of Energy Management, which stores this information for all of the Coast Guard vessels. By doing this, the Coast Guard will be able to track the amount of fuel burned by each vessel throughout an underway period. This data can allow for the tracking of fuel efficiency as biofouling accumulates on the hull, and is a major component in determining fuel money saved with additional hull cleanings.

5.1.4 Distance Travelled

Additionally, we recommend that the distance travelled for each cutter is recorded for an underway period. This information is stored in the "Operational Summary Sheets", where a travel summary of each underway period can be found. With this information, along with the fuel burn data acquired from the Office of Energy Management, a savings figure can be derived from the amount of fuel saved by implementing additional cleanings. The process of fuel burn and distance travel data input and analysis is further described in Appendix J.

5.1.5 Gallons/Hour

As an alternative method to calculate fuel money saved with smaller cleaning intervals, we recommended that the gallons/hour figure be added to the round sheets as well. This is visualized below in Table 7. The information can be collected live on an engine display. We recommend that the same engineering department personnel that collects the speed and engine RPM data record the gallons per hour data on the amended Round Sheet. This method is a valid alternative, as the information is not averaged between all of the speeds; rather, savings can be calculated separately for each of the travelling speeds of the vessels and then summed for total savings.

Table 7 – Round Sheet with Column Added (Gallons/Hour)

USCG Cutter (Name & Number)									
#1 MDE LOG									
	ENG RPM	SHAFT RPM	SPEED	GAL/HR	ENG L/O PSI	ENG L/O TEMP	R/G L/O PSI	R/G L/O TEMP	R/G CONT PSI
LOW									
HIGH									
0000									
0100									
0200									
0300									
0400									
0500									
0600									
0700									

5.2 Objective 2 - Alternative Anti-fouling Coating Recommendations

The current anti-fouling coating used on vessels in Sector San Juan (a copper ablative biocide) may not be an appropriate choice of an anti-fouling coating. This is because of two reasons:

- Ablative paints are soft and wear away in the water similar to a bar of soap under a running faucet (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). With the number of in-water cleanings that ships in the Sector require, the ablative paint will wear away more quickly, decreasing its planned life cycle, or being removed in the cleaning process.
- Copper based biocides are at risk of being internationally banned, and thus the ships would need to be recoated anyway should the ban go through (Kaznoff & Rudroff, 2000). Even if it is not banned in the near future, Coast Guard vessels may be banned from entering international ports that do not allow copper coatings of a certain percentage. (Robert Hemp, Personal Communication, 2015)

In place of the copper ablative biocide (specifically International Interspeed BRA 640), we recommended replacing the coatings on the Sector San Juan vessels with a foul release anti-fouling coating. Foul release coatings contain no biocides and thus, have no adverse effects on the surrounding environment. This would keep the coating safe from being banned in the future, while simultaneously providing an effective defense against biofouling.

Foul release paints prevent biofouling by creating a low-friction surface on the ship. This surface makes it more difficult for biofouling organisms to take hold on the hull (Anti-fouling

101: A Comprehensive Guide from Interlux, 2012). Additionally, foul release paints have harder coating surfaces than ablative paints. As our cleaning schedule protocol anticipates, the Sector will most likely implement additional cleanings throughout the year. With additional cleanings, this coating will be more effective, as a foul release paint is designed to handle cleanings, thus removing any attached marine organisms (Anti-fouling 101: A Comprehensive Guide from Interlux, 2012). Decreased cleaning intervals will result in the biofouling being rooted less strongly than before, due to the smoother hull surface.

Because we recommended foul release coatings, we also looked into specific products for further recommendation. Based upon our research, we have identified the following three products as candidates for USCG Sector San Juan to further investigate.

- **PPG SigmaGlide 1290**
- **International Intersleek 700**
- **International Intersleek 900**

We reached this conclusion though research centered on International (the company) based coatings. The current anti-fouling paint for Sector San Juan is provided by International (Engineering Petty Officer “B”, personal communication, 2015). Due to this, most research was conducted on marketed products through this company, along with similar results while searching commercial sites. Therefore, we narrowed our search to only include foul release coatings and have discovered these products. All of the paints are foul release coatings, with differences in chemical composition and manufacturing processes.

5.3 Objective 3 – Recommendations for Alternative Hull Cleaning Methods and Technologies

After consulting academic research and the current methods employed by the contract divers, we recommend that the divers implement a cleaning process called grooming in addition to the cleanings performed by contract divers. Grooming is the process of gentle, repetitive cleaning on the hull, normally with a device that has a lower coefficient of friction. This process is normally done after macrofouling has been removed, is most effective in removing the microfilm from the hull of a vessel. By disrupting the formation of a biofilm, the reproduction of macrofouling is significantly hindered. One example of a grooming technology would be a brush with nylon bristles, as the material is not as abrasive as traditional brushes and is efficient in removing the biofilm.

Additionally, we recommended utilizing new brushing techniques, with one example being circular brushing patterns. As opposed to the traditional, linear patterns, this method is better in removing the microfilm as well as preserving the anti-fouling coatings on the hulls. In some cases, such as the copper ablative coatings used on Coast Guard vessel hulls, the hull coatings are very soft to begin with. This process is very efficient in removing the microfilm on the hull, and lengthens the time necessary in between cleanings.

However, it is important to note that many of the findings from the academic research are not directly applicable to Sector San Juan. Throughout many of Swain's experiments, groomings were able to be performed at very frequent intervals. This is not feasible on a Coast Guard vessel, and it is likely that macrofouling will accumulate on the hulls in between cleanings. Therefore, we recommend that groomings are done after the macrofouling is removed from the hulls. By doing this, the macrofouling will not return to the hulls for a longer period of time, maximizing the efficiency of the vessel while still utilizing the work of the contract divers.

Finally, research has shown that there are autonomous hull cleaning techniques that are currently in the developmental stages, and we recommend that the Coast Guard looks into the further development of these technologies. Some of these technologies include using ultrasonic transducers on the hulls of vessels, or using an autonomous grooming machine to constantly groom the hulls. These processes consistently monitor and groom the hull of the vessels, which prevents the formation of a biofilm and rapidly slows the accumulation of macrofouling. However, most of these technologies are either too expensive to implement immediately, or not yet ready for military implementation. Therefore, we recommended that the Coast Guard remains aware of these technologies for future implementation, but utilizes grooming methods in the immediate future.

5.4 Conclusion

The goal of this project was to analyze the biofouling control practices used by Sector San Juan, and to adjust these practices to save money. We found that these current practices are unable to sufficiently combat the aggressive biofouling rates present in Sector San Juan. To improve the current practices, we have created a data collection protocol to help determine a better cleaning interval, while also providing a list of more suitable antifouling coatings and cleaning techniques. By following these recommendations and utilizing the materials we have provided to improve their practices, Sector San Juan has the potential to decrease the amount of money lost due to biofouling accumulation. We hope that our protocol and suggestions can be applied more broadly across the USCG to aid in reducing fuel consumption and improving vessel efficiency.

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Appendix A Coast Guard History and Overview

Established on August 4, 1790 by President George Washington, the Coast Guard has served a myriad of purposes throughout the history of the United States, and has been present in many defining moments for the country. The USCG has humble roots; originally there were only ten vessels that were constructed to regulate international tariffs and to enforce international law on the Atlantic Ocean (US Coast Guard History: United States Coast Guard, 2014). However, the USCG has grown into a multifaceted and global force over the course of American history, becoming a recognized force in both military endeavors and law enforcement.

The USCG is unique in that it simultaneously serves as a branch of the United States Military as well as a federal law enforcement agency (US Coast Guard History: United States Coast Guard, 2014). During times of peace, the USCG serves under the Department of Homeland Security, and some of the responsibilities carried out by them include the enforcement of international maritime law, aiding in search and rescue missions, and preserving the environment and ecology of the area in which they inhabit. Alternatively, during times of war, the Coast Guard serves under the United States Navy, or at the discretion of the Commander-in-Chief (US Coast Guard History: United States Coast Guard, 2014). There are 17 districts throughout the United States as well as the territories, and the San Juan Sector of the Coast Guard falls under District 7. Because of the organization of the Coast Guard, in addition to its presence across the country, the USCG has an impact at every level, from the local and regional levels all the way to the international level.

USCG Missions

The Coast Guard is a regimented, goal-oriented institution, with their eleven missions clearly outlined (Missions: United States Coast Guard, 2014). They are ranked in terms of modern prevalence, though they all carry significant importance. Their missions are as follows:

1. Ports, Waterways, and Coastal Security
2. Drug Interdiction
3. Aids to Navigation
4. Search and Rescue
5. Living Marine Resources
6. Marine Safety
7. Defense Readiness
8. Migrant Interdiction
9. Marine Environmental Protection
10. Ice Operations
11. Other Law Enforcement

Whether it is during times of war or peace, the Coast Guard plays an integral role in the lives of Americans across the country. Consequently, the ships and boats that the USCG deploys must operate at a high efficiency: oftentimes it is a matter of minutes that can determine the success or failure of a majority of these missions.

Appendix B CO and EPO 1 Interview

How long have you been on this ship?

Since July 31, 2015

Over this period at time, have you noticed any changes in the amount of accumulation of materials on the ship's hull?

Yes, currently it's like a small vegetable garden

Have there been any dredgings or cleanings in this bay recently that you know of?

Yes, there was one but not sure when

Do you think those have affected the amounts of biofouling on the ship's hull?

Yes, believe the biofouling did decrease after the dredging

Do you know what kinds of coatings are used on this ship's hull?

Both steel an aluminum hull, but primer is put on then an anti-fouling coating
Don't know the specific coating

What is the ship's cleaning schedule? (How often is it cleaned, for how long is it cleaned)

In San Juan, recommended for one but get at least three annually

How often is the ship out of port vs. static in the water?

This vessel works approximately on a 2 weeks out 2 weeks in cycle

What are the ship's operating speeds?

Typically move at clutch speed, very rarely top speed

Have you noticed any hull damage as a result of the biofouling or the hull cleanings?

Sometimes the calcareous (hard, barnacle) fouling will leave a calcified layer that may remove he paint when scraped off. If not scraped off, regrowth may occur

How long is the vessel out of commission for in water cleanings?

About a two day cleaning process

How long is the vessel out of commission for dry-dock cleanings?

About 3 months, where a dockside is heavy maintanence that lasts for about 6 weeks

What would you note as the main differences in this bay as compared to the other areas of the island (weather patterns, temperature, contamination)?

Very contaminated around these waters, much trash

What about other Coast Guard Sectors?

No visible oil sheen in the water – present elsewhere

Appendix C CO and EPO 2 Interview

How long have you been on this ship?

Over this period at time, have you noticed any changes in the amount of accumulation of materials on the ship's hull?

Since Sep 28th, 2015

Have there been any dredgings or cleanings in this bay recently that you know of?

Do you think those have affected the amounts of biofouling on the ship's hull?

No and unsure

Do you know what kinds of coatings are used on this ship's hull?

Intertuff Red and Light Gray, then anti-fouling coatings of International BRA 640

How often is the ship out of port vs. static in the water?

Works in general cycles of 3 weeks on and 3 weeks off

What are the ship's operating speeds?

Should be 28 knots, but currently slower

Have you noticed any hull damage as a result of the biofouling or the hull cleanings?

No

Appendix D Mr. Samuel Alvord Interview (11/4)

Mr. Samuel Alvord - Chief of Office of Energy Management (Nov 4)

Are there any resources available to us that may be relevant to vessel cleanings?

There is Chapter 081 of the Naval Ships Technical Manual
This outlines the progression of biofouling on a naval ship and has pictures that correlate with the progression

Do you have any advice when approaching the how often to clean a hull?

It is beneficial to keep these in mind:

- Must take into account the schedule of the vessel
  - If one cutter is always in maintenance, how will it be cleaned?
  - If the cutter is in for three weeks, you may clean it often, but be careful to not remove the coating
- You may clean just the propeller or the whole ship
- When cutters are unable to reach a top speed, does this require a cleaning?
- Also important to keep the diver in mind:
  - They may clean quickly or in full length depending on what they want to charge
  - The diver has his own schedule to work with
  - Do you tell them vessels to service, or just have them show up certain days and clean what is available?

(Dec 2)

Would an outlined data collection method to better quantify biofouling and its vessel performance impacts be useful? – don't know if should make mention of the types of data

The Coast Guard budgets money by the hour, so hourly data would be useful
This would be helpful in determining if an hour is always well spent at sea
It should include nautical miles since last report if you are asking to collect distance covered
The fouling scale can be subjective when addressing biofouling accumulation

- Might be helpful to train personnel or have a balance check
- Could be beneficial to have a second person assess the accumulation to make it less subjective to an individual and average the scoring
- Consistency is important with this aspect

Might be beneficial to have a future group do the analysis

Would an underwater camera be suitable to capture the biofouling accumulation?

Yes, keep it simple
Can just use PVC piping which should be capped so it will float

Appendix E Contract Diver Interview Questions

Can you talk to us about the cleaning process / biofouling process?

Have you noticed an increase in biofouling in the past 1 to 5 years?

What are the methods you use to clean the ships?
If brushes, what types do you use?

Do you see any damages that are caused by biofouling?

How often do you clean the hulls and on which ships do you clean the hulls?

How often do you think the ships should be cleaned?

Can you describe the conditions of the San Juan Bay?

Do you work other contracts or jobs in the diving industry?

Do you work other jobs outside the diving industry?

Appendix F Biofouling Recording

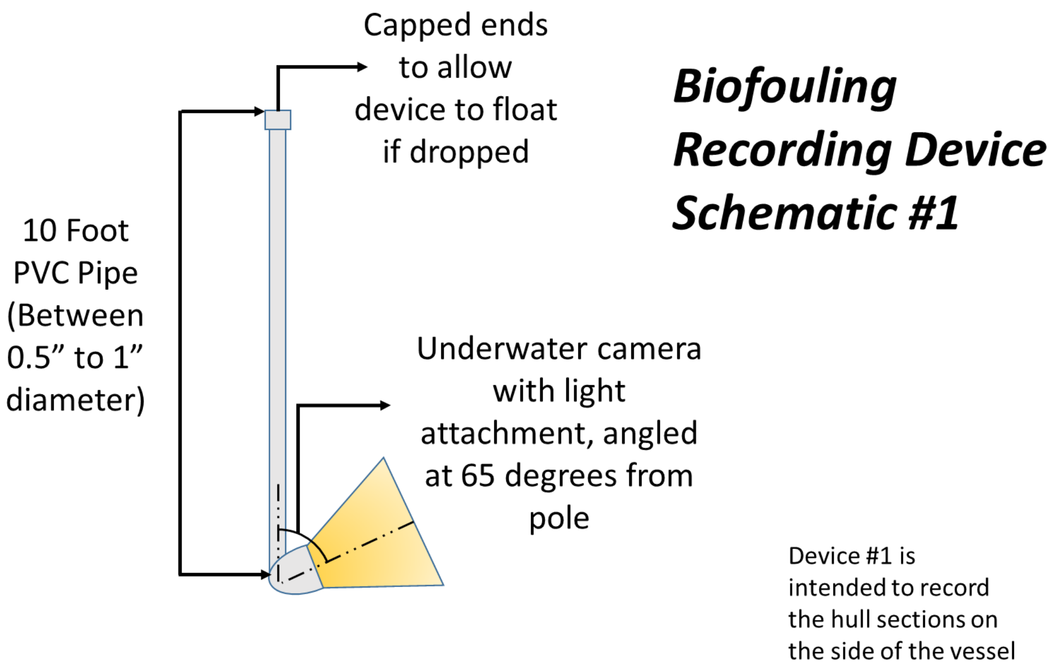


Figure 18 – Biofouling Recording Device Schematic #1

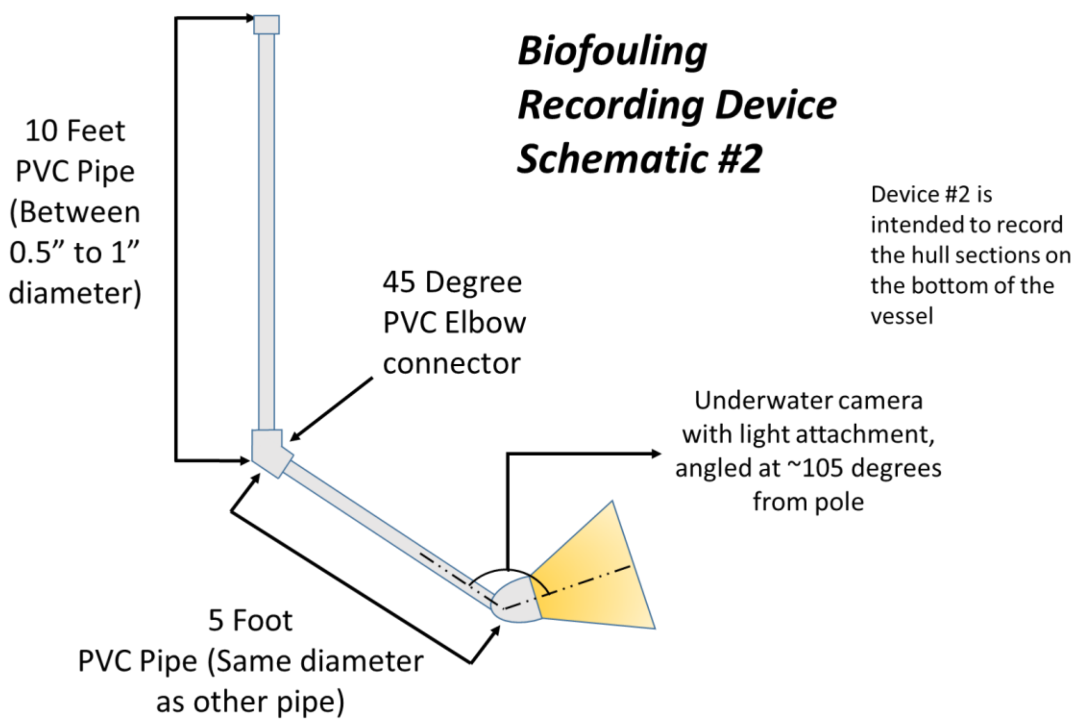


Figure 19 – Biofouling Recording Device Schematic #2

Recommended “Other” Materials

- GoPro Hero
- GoPro Standard Waterproof Housing
- GoPro Handlebar/Seatpost/Pole Mount
- Underwater GoPro Light and Mount
- More information on recommended materials may be found at:

http://gopro.com/

Device #1 Measurement procedure

- Submerge the device from the deck of the ship
- Hold device perpendicular to the surface of the water and at arm’s length
- Walk along the port, starboard, and the stern of the ship with the device held as described above. Move the device upwards and downwards (~1 foot in each direction) to record the hull according to the general pattern below. This will allow for maximum coverage of the ship’s hull

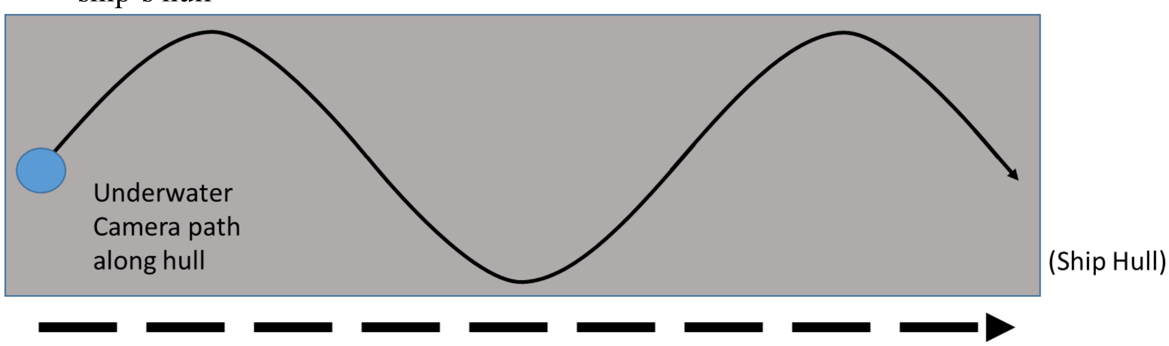


Figure 20 – Motion to Record the Hull

Device #2 Measurement procedure

- Submerge the device from the deck of the ship
- Hold device perpendicular to the surface of the water and at arm’s length
- Ensure that the device has reached under the hull by looking into the water
- Walk along the port, starboard, and the stern of the ship with the device held as described above. Unlike the procedure for device #1, device #2 should be held at a constant depth and distance from the hull

Appendix G SWOT Analysis Charts

Table 8 – Contact Leaching SWOT Analysis

Contact Leaching	HELPFUL	HARMFUL
I N T E R N A L	**Strengths** **+ Releases biocides constantly using diffusion**	**Weaknesses** **- Coatings build up over time and crack, increasing maintenance costs**
E X T E R N A L	**Opportunities** **+ Hard outer coating that can be cleaned**	**Threats** **- Utilizes biocides that are typically metal-based**

Table 9 – Self-Polishing SWOT Analysis

Self-Polishing	HELPFUL	HARMFUL
I N T E R N A L	**Strengths** **+ Chemically reactive surface to release biocides dependent on environment**	**Weaknesses** **- N/A**
E X T E R N A L	**Opportunities** **+ N/A**	**Threats** **- Heavily tin-based leading to the harm of marine organisms in surrounding environment**

Table 10 – Controlled Depletion SWOT Analysis

Controlled Depletion	HELPFUL	HARMFUL
I N T E R N A L	**Strengths** **+ Slow release of biocide with the intention that the layer will wear away and remove biofouling with it**	**Weaknesses** **- Thorough cleanings may excessively wear away paint reducing its effectiveness**
E X T E R N A L	**Opportunities** **+ N/A**	**Threats** **- Biocides may still diffuse in worn away paint affecting the surrounding environment**

Table 11 – Foul Release SWOT Analysis

Foul Release	HELPFUL	HARMFUL
I N T E R N A L	**Strengths** **+Can withstand normal cleanings** **+Provides weak platform for organisms to attach to**	**Weaknesses** **-More frequent use of vessel yields better anti-fouling results** **-Does not actively prevent biofouling**
E X T E R N A L	**Opportunities** **+No biocide use** **+More frequent cleanings will contribute to success of coating**	**Threats** **-N/A**

Appendix H Biofouling Inspection Datasheet

BIOFOULING INSPECTION DATA					
VESSEL NAME		HULL TYPE/ NUMBER	LOCATION (CITY)		DATE (mm/dd/yy)
PRODUCT LINE		DATE			
UNDERWATER PHOTOGRAPHS TAKEN	YES	NO	VIDEO TAKEN	YES	NO
COMPONENTS	VALUES MUST MIMIC THE FOULING INDEX SCALE: 0 -100 RATING	ADDITIONAL COMMENTS			AVERAGE OF EACH PORTION
PROPELLER					PROPELLER
CENTERLINE					#DIV/0!
PORT OUTBOARD					
PORT INBOARD					
STARBOARD INBOARD					
STARBOARD OUTBOARD					
SHAFT					SHAFT
CENTERLINE					#DIV/0!
PORT OUTBOARD					
PORT INBOARD					
STARBOARD INBOARD					
STARBOARD OUTBOARD					
RUDDER/STAB FINS					RUDDER/STAB FINS
CENTERLINE					#DIV/0!
PORT					
STARBOARD					
SONAR DOME					SONAR DOME
PORT SIDE					#DIV/0!
STARBOARD SIDE					
SEA CHEST					SEA CHEST
TYPICAL					#DIV/0!
BOW					BOW
PORT					#DIV/0!
STARBOARD					
BOTTOM					BOTTOM
PORT					#DIV/0!
STARBOARD					
STERN					STERN
PORT					#DIV/0!
STARBOARD					
TRANSOM					TRANSOM
PORT					#DIV/0!
STARBOARD					
TOTAL SHIP RATING			#DIV/0!		
SIGNATURE (SHIP'S ENGINEER):					

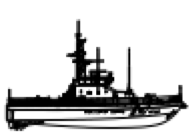
Appendix I Sample Maintenance Procedure Card

U.S. COAST GUARD ASSET COMPUTERIZED MAINTENANCE SYSTEM	WPB-87 B10020.D REV'D 05/15/15

PRE-CLEAN BIOFOULING INSPECTION DATA

VESSEL NAME:	HULL TYPE/ NUMBER:	LOCATION (CITY):	DATE (mm/dd/yy):
PRODUCT LINE:	INSPECTING ACTIVITY:		VISIBILITY (ft):
LOCATION OF LAST DRYDOCKING:			UNDOCKING DATE:
LOCATION OF LAST PAINTING:			DATE:
PAINT TYPE:	ANTIFOULING:	ANTICORROSION:	
UNDERWATER PHOTOGRAPHS TAKEN YES NO		VIDEO TAKEN YES NO	

COMPONENTS	(CHECK IF)		(PERCENTAGES MUST ADD UP TO 100)		
	N/A	NOT INSPECTED	FOULER RATING	FOULER RATING	FOULER RATING
PROPELLER					
CENTERLINE			FR- %	FR- %	FR- %
PORT OUTBOARD			FR- %	FR- %	FR- %
PORT INBOARD			FR- %	FR- %	FR- %
STARBOARD INBOARD			FR- %	FR- %	FR- %
STARBOARD OUTBOARD			FR- %	FR- %	FR- %
SHAFT					
CENTERLINE			FR- %	FR- %	FR- %
PORT OUTBOARD			FR- %	FR- %	FR- %
PORT INBOARD			FR- %	FR- %	FR- %
STARBOARD INBOARD			FR- %	FR- %	FR- %
STARBOARD OUTBOARD			FR- %	FR- %	FR- %
RUDDER/STAB FINS					
CENTERLINE			FR- %	FR- %	FR- %
PORT			FR- %	FR- %	FR- %
STARBOARD			FR- %	FR- %	FR- %
SONAR DOME					
PORT SIDE			FR- %	FR- %	FR- %
STARBOARD SIDE			FR- %	FR- %	FR- %



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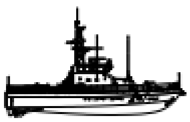
U.S. COAST GUARD
ASSET COMPUTERIZED MAINTENANCE SYSTEM

WPB-87
B10020.D
REV'D 05/15/15

COMPONENTS	(CHECK IF)		(PERCENTAGES MUST ADD UP TO 100)		
	N/A	NOT INSPEC-TED	FOULER RATING	FOULER RATING	FOULER RATING
SEA CHEST					
TYPICAL			FR- %	FR- %	FR- %
BOW					
PORT			FR- %	FR- %	FR- %
STARBOARD			FR- %	FR- %	FR- %
BOTTOM					
PORT			FR- %	FR- %	FR- %
STARBOARD			FR- %	FR- %	FR- %
STERN					
PORT			FR- %	FR- %	FR- %
STARBOARD			FR- %	FR- %	FR- %
TRANSOM					
PORT			FR- %	FR- %	FR- %
STARBOARD			FR- %	FR- %	FR- %
SIGNATURE (SHIP'S ENGINEER):					
SIGNATURE (DIVING SUPERVISOR):					

PRE-CLEAN BIOFOULING INSPECTION DATA
Form 1



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Appendix J Example Calculations Using Self-Generated Data

This shows an example of how the data collection protocol spreadsheets attached with the final report may be utilized for a final calculation of how much money may be saved when deciding a cleaning interval. For the purpose of this example, all data and figures have been self-generated, and picked for ease of calculation, and do not reflect actual values specific to the Coast Guard or their vessels. Units used are KTS, which stands for Knots, and nm, which stands for nautical miles.

For this data, we chose a time sample of 50 days. The following numbers would be calculated through addition of each respective category over the 50 days:

Table 12 – Fuel Burn Information

Operating hours	200 hours
Total fuel cost	$10,000
Fuel burned	5000 gallons

After these numbers had been calculated, we created an average speed that the vessels will travel at by using a weighted average of the time spent at each speed:

Table 13 – Vessel Speeds

Throttle Position	Average Speed (KTS)	Average Time Spent at Speed
Top	20	40% (0.4)
Mid	15	30% (0.3)
Clutch	10	30% (0.3)

0.4* 20KTS = 8KTS
0.3* 15KTS = 4.5KTS
0.3* 10KTS = 3KTS

Adding the three weighted speeds yields:

8KTS + 4.5KTS + 3KTS = 15.5KTS

For this example, this value represents the average underway speed of a cutter while underway.

Now that all pertinent information has been calculated, calculations regarding the use of our spreadsheet may begin. Assume rounding to significant digits for all calculations and 50 is an exact number of days. The time frame of 50 days was used to gain information regarding averages of the relevant data in terms of "per day." These numbers were then applied to an 18 week progression. This is our example for the time in between two cleanings..

With the above mentioned data, the following was calculated:

Fuel burn / operational hour = 5,000gal / 200 hrs = 25 gal/ operational hr
Operating hrs / day = 200 hrs / 50 days = 4 operational hrs / day
Fuel burned / day = 5,000 gal / 50 days = 100 gal / day

From here, we estimated a vessel to be completely free of biofouling, as a cleaning has just occurred. The beginning start speed is what was calculated above: 15.5KTS. Assumed: a general loss of 20% that has culminated by the end of the 18 weeks, Also, over this time frame, we have assumed a 20% loss in top speed, and a 20% loss in average traveling speed for the simplicity of calculations. We have also assumed this decrease in speed occurs at an average linear pace over the duration of 18 weeks. This results in an average loss in traveling speed per day of:

15.5KTS * 0.2 = 3.1KTS / (18 weeks * 7 days/week) = 2.460317 * 10^{-2}KTS loss / day

Thus starting at an average traveling speed of 15.5KTS, this will result in a slower final speed at the end of 18 weeks: 15.5KTS – 3.1KTS = 12.4KTS. 12.4KTS is what is calculated to be the average traveling speed at the end of an 18 week period.

Assumed: the average fuel burned / day figure to be what is mentioned above: 100 gal and this value stays constant throughout the duration of the 18 weeks.

With the fuel burned / day figure remaining constant, and using the two speeds as beginning and end points for the 18 week period, we can calculate the distance traveled per day. As average speed decreases, a similar trend will appear in the distance traveled per day. Using similar logic with the speed reduction, an upper and lower bound are calculated:

Starting: 15.5KTS * 4 operational hrs / day = 62 nm traveled on the first day
Ending 12.4KTS * 4 operational hrs / day = 49.6 nm traveled on last day

From here, the average decreasing speed was multiplied by the average operational hours / day (4) to create a similar decreasing trend for the distance traveled / day. As fuel burned / day was held constant, distance traveled / day decreases over the 18 weeks steadily in this model. To calculate distance traveled per day, the calculation is as follows:

15.5KTS – [2.460317 * 10^{-2}KTS loss / day * (number of days since cleaning)] = average traveling speed (ats)

Then,

ats * 4 hours / operational day = number of nms traveled that day.

For example, on the 21st day, the calculation would be as follows:

15.5KTS – [2.460317 * 10^{-2}KTS loss / day * (21)] = 15.12KTS

Then,

15.12KTS * 4 hours / operational day = 60.48 nm traveled

Using this number of nm traveled per day, and knowing how much fuel is consumed per day (100gal), a fuel efficiency value can be calculated:

Distance traveled (nm) / fuel consumed (gal) = a specific day's nm/gal figure

Similarly, the inverse of this can be calculated by reciprocating to:
Fuel consumed (gal) / Distance traveled (nm) = a specific day's gal/nm figure

This resulting data was then extrapolated for the 18 week period and filled into a pre-made excel sheet that will simultaneously graph the data and insert trend lines. From these trend lines, integration can be utilized to calculate the fuel savings that would be expected if a known price of fuel is at hand, and when a cleaning would be set.

To generate such a graph, the data is recorded in a pre-labeled spreadsheet that will also be shown (Table 14). Typically, the chart would be filled out for three different speeds, but for this example, a single chart is used and speeds have been averaged. Due to this, an additional column has been added to see the average speed and its decrease. The labels cover: Fuel burned (gal); Average Speed (KTS); Distance Traveled (nm); Fuel Efficiency (nm/gal); and Gallons/Nautical Mile. Below, an example of this chart may be seen:

Table 14 – Data Collection Table

Date (Week)	Averaged Speed				
	Fuel Burn (gal)	Avg Speed KTS	Distance Travelled (nmi)	Fuel Efficiency	Gallons/Nautical Mile
0.142857143	100	15.5	62	0.62	1.612903226
0.285714286	100	15.47539683	61.90158732	0.619015873	1.615467459
0.428571429	100	15.45079366	61.80317464	0.618031746	1.618039859
0.571428571	100	15.42619049	61.70476196	0.61704762	1.620620465
0.714285714	100	15.40158732	61.60634928	0.616063493	1.623209315
0.857142857	100	15.37698415	61.5079366	0.615079366	1.625806449
1	100	15.35238098	61.40952392	0.614095239	1.628411908
1.142857143	100	15.32777781	61.31111124	0.613111112	1.631025731
1.285714286	100	15.30317464	61.21269856	0.612126986	1.633647958
1.428571429	100	15.27857147	61.11428588	0.611142859	1.63627863
1.571428571	100	15.2539683	61.0158732	0.610158732	1.638917789
1.714285714	100	15.22936513	60.91746052	0.609174605	1.641565475
1.857142857	100	15.20476196	60.81904784	0.608190478	1.644221729
2	100	15.18015879	60.72063516	0.607206352	1.646886594
2.142857143	100	15.15555562	60.62222248	0.606222225	1.64956011
2.285714286	100	15.13095245	60.5238098	0.605238098	1.652242321
2.428571429	100	15.10634928	60.42539712	0.604253971	1.654933269
2.571428571	100	15.08174611	60.32698444	0.603269844	1.657632997
2.714285714	100	15.05714294	60.22857176	0.602285718	1.660341547
2.857142857	100	15.03253977	60.13015908	0.601301591	1.663058963
3	100	15.0079366	60.0317464	0.600317464	1.665785289
3.142857143	100	14.98333343	59.93333372	0.599333337	1.668520568
3.285714286	100	14.95873026	59.83492104	0.59834921	1.671264844
3.428571429	100	14.93412709	59.73650836	0.597365084	1.674018163
3.571428571	100	14.90952392	59.63809568	0.596380957	1.676780569
3.714285714	100	14.88492075	59.539683	0.59539683	1.679552106
3.857142857	100	14.86031758	59.44127032	0.594412703	1.682332821
4	100	14.83571441	59.34285764	0.593428576	1.685122759

As this information is recorded daily (when operating) the graph will input the data points and a trend may be visible. For this example, an exponential trend line was chosen for a "best fit" curve for the data.

To actually calculate fuel savings, several steps must be completed. For starters, the trend line must be translated to the point where a cleaning would be set. For this example, it is set at the 9 week mark, over a time frame of 18 weeks. Therefore, the original trend line starts at zero days to show what will happen without a cleaning, and then the same trend line is translated to begin at 9 weeks assuming a similar, if not the same trend will be recorded post-cleaning. Also, The trend line equations have been chosen as exponential, and are calculated by Excel's trend line option (see Figure 21 below for a visual).

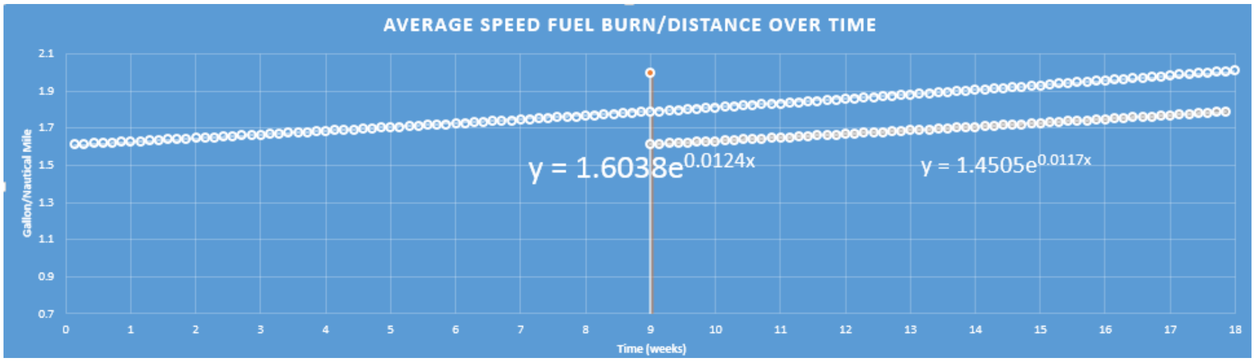

Figure 21 – Sample Fuel Burn Graph

Once all the data has been recorded, the "Gallons / Nautical Mile" figure is calculated by dividing the fuel burned that day by the distance traveled that day. Then, this figure is plotted as it changes over the 18 weeks (see graph above).

In this example, we will analyze what may occur with a new cleaning set at the 9 week mark (red vertical midline).

To begin, integrate the equation output by excel that reflects the trend line from when the new cleaning is set (here it is 9 weeks) to the end of the time frame (18 weeks)

The original equation: $y = 1.6038e^{0.0124x}$
The new cleaning equation: $y = 1.4505e^{0.0117x}$

The integrations is as follows:

Integrating $y = 1.6038e^{0.0124x}$ from 9 to 18 = 17.0734 gal*week/nm
Integrating $y = 1.4505e^{0.0117x}$ from 9 to 18 = 15.2953 gal*week/nm

Then, subtract these values: 17.0734 – 15.2953 = 1.7781 gal*week/nm
This figure represents the gallons * week / nautical mile saved with an additional cleaning which is a bit of a confusing label, but this will make more sense soon.

From here, the total nautical miles must be summed within the time frame being analyzed (9 to 18 weeks). For this calculation, it has been estimated at 3,379.10 nm.

Now, you are ready to calculate the actual amount of fuel expected to be saved over this time frame (9 to 18 weeks). The calculation multiplies the gal*week / nm and the total nautical miles traveled, and then divides by the total number of weeks in the time frame (18 weeks – 9 weeks = 9 weeks). Example provided below:

[(1.7781 gal*week/nm) * (3,379.10 nm)] / (9 weeks) = 667.6 gallons (approximately)

This gallons figure represents the total fuel expected to be saved over the current time frame of 9 weeks. If a price for fuel is known, then the dollar amount can be realized by simply multiplying the two figures. At the beginning of the example, if total fuel cost is divided by total fuel consumed, then the price per gallon would be $2.00. For simplicity's sake, we will remain with this value. Example:

$2.00 per gallon * 667.6 gallons = $1,335 saved by implementing a cleaning at the 9 week mark.

This figure takes many assumptions into account that are previously listed. The main purpose of this document is to explain thoroughly how the data collection protocol may be utilized to its fullest potential, as it can analyze the recorded values and ultimately create a dollar amount that may be used to support the need of a cleaning. This figure **does not** take into account the cost of a cleaning, but simply shows how the spreadsheet and values may come together for a tangible example.