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THESIS

ANALYZING UNDERWATER HULL COATING SYSTEM WEAR FOR SURFACE COMBATANTS

by

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September 1999

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Current hull coating wear models are derived from dry film thickness (DFT) measurements and are only being used on aircraft carriers, less than four percent of the surface fleet. Dry film thickness is a complicated value because it currently encompasses the thickness of both anticorrosive and anti-fouling (AF) layers and is susceptible to paint swelling. An analysis of data taken from surface combatant hulls by hull roughness analyzer is performed to provide a more reliable means of measuring paint wear as a function of paint smoothing. This method provides important insight to ablation rates and initial exploration into a potentially useful model. In 1997, Wimmer performed a least squares regression to develop a model that predicts the total coating system wear on an aircraft carrier's hull using DFT measurements taken in drydock. In 1999, Ellis derived an estimate of the mean thickness of one coat of AF and a simple method for estimating the mean thickness of an aircraft carrier hull's total coating system following two operational cycles. Both models are used to determine their ability to predict hull coating wear for surface combatants and paint application distributions are analyzed to explain some of the variation experienced in their models.

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ANALYZING UNDERWATER HULL COATING SYSTEM WEAR FOR SURFACE COMBATANTS

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ABSTRACT

Current hull coating wear models are derived from dry film thickness (DFT) measurements and are used only on aircraft carriers, less than four percent of the surface fleet. Dry film thickness is a complicated value because it currently encompasses the thickness of both anticorrosive and anti-fouling (AF) layers and is susceptible to paint swelling. An analysis of data taken from surface combatant hulls by hull roughness analyzer is performed to provide a more reliable means of measuring paint wear as a function of paint smoothing. This method provides important insight to ablation rates and initial exploration into a potentially useful model. In 1997, Wimmer performed a least squares regression to develop a model that predicts the total coating system wear on an aircraft carrier's hull using DFT measurements taken in drydock. In 1999, Ellis derived an estimate of the mean thickness of one coat of AF and a simple method for estimating the mean thickness of an aircraft carrier hull's total coating system following two operational cycles. Both models are used to determine their ability to predict hull coating wear for surface combatants and paint application distributions are analyzed to explain some of the variation experienced in their models.

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LIST OF TERMS AND ABBREVIATIONS

AC	Anti-corrosive
AF	Anti-fouling
cdf	cumulative distribution function
DFT	Dry Film Thickness
HRA	Hull Roughness Analyzer
NSWCCD	Naval Surface Warfare Center, Carderock Division
ROV	Remotely operated vehicle

EXECUTIVE SUMMARY

In an attempt reduce drydocking costs, the Navy is investigating ways to extend the lifetime of the underwater hull coating systems of its ships. Current hull coating wear models are used only on aircraft carriers, less than four percent of the surface fleet. The remaining fleet is maintained primarily according to the US Navy hull maintenance policy as stated in the Naval Ships Technical Manual (NSTM). This policy directs that all naval ships receive essentially the same underwater hull coating system, without consideration to the ship's expected duration of operation or its anticipated hull maintenance requirements. Furthermore, significant improvement in the performance of ablative anti-fouling paints, where they remain free of visible fouling for extended periods, directed closer attention to the roughness changes of the anti-fouling paint occurring during service and as an improvement to existing hull coating system wear models which are based on dry film thickness (DFT). This thesis focus on coating systems of surface combatants and on using paint roughness as a reliable measurement for modeling hull coating system wear.

The underwater coating system is comprised of multiple coats of anti-corrosive (AC) paint followed by multiple coats of anti-fouling (AF) paint. Newly painted ships in operation today have systems that consists of 2-3 layers of AC paint followed by 3-4 layers of AF paint. The AF paint is designed to slowly and continuously leach cuprous oxide, a toxin that prevents marine growth from attaching and living on the exterior of a ship's hull. To maintain a high concentration of cuprous oxide on the surface, today's anti-fouling paints are design to slowly wear away or ablate as the ship moves through the water. Monitoring the wear of the coating system in order to determine the layers of AF paint needed to sustain an operational cycle is limited to hull DFT measurements taken while the ship is in drydock. Ellis (1999) shows that a wet film thickness measurement taken while the ship is in the water is an inconsistent means of measuring the effect of an operation cycle. Thus there is not a reliable method to monitor the thickness of the AF layer during the operational cycle.

The ultimate goal for all this research is to more accurately predict hull coating system wear using a measurement taken every year and not just during drydocking periods every three to five years. Using coating surface roughness data collected from the fleet's surface combatants, this analysis aims to increase current model accuracy for predicting the effects of an operational cycle on a hull coating system. The advantage of coating surface roughness data collection is that it can be measured between drydocking events. Additionally the analysis will determine if the two models currently in use for predicting hull coating wear for aircraft carriers can be applied for non-aircraft carrier ships such as surface combatants. Finally an analysis of paint application will add possible explanation for the variation in thickness experienced with paint application and subsequent wear modeling.

One benefit from collecting roughness data is that the amount of variability in the hull roughness measuring device is significantly less than that of the paint thickness probe. Ellis (1999) in her analysis of measurement taken by underwater remotely operated vehicles (ROV) discussed the difficulties of positioning the probe of the thickness gauge perpendicular to the hull of the ship in order to get an accurate measurement of paint thickness. Since the ROV is submerged and maneuvered remotely from a pier, it is very difficult to determine if the probe is perpendicular to the surface of the ship, especially when maneuvering around the curves of the hull. Thus, some of the measurements retrieved are not accurate representations of hull paint thickness and could potentially present an incorrect picture of the overall hull coating thickness. Another benefit is that the roughness model immediately yields a more precise coefficient of paint lost due to one operational cycle and will further increase the accuracy of the Wimmer (1997) and Ellis (1999) models. Finally, by incorporating this research with past advancements in wear modeling, future surface combatant hull maintenance procedures will be planned and performed on more quantitatively-based estimations.

I. INTRODUCTION

Ship overhauls are an increasing burden on the Navy both operationally and financially. The Navy currently maintains a fleet of 323 ships with 81 ships deployed (25%), another 122 ships (37%) underway involved in any one of 14 exercises or working up for a deployment and the remaining 120 ships (38%) either in-port or in various shipyards (Navy Office of Information, 1999). Expenditures for hull preservation and maintenance total approximately $80 million annually and continually increasing budget constraints apply pressure (Naval Surface Warfare Center, 1995). In an attempt to reduce drydocking costs, the Navy is investigating ways to extend the lifetime of the underwater hull coating systems of its ships. Current hull coating wear models are used only on aircraft carriers, less than four percent of the surface fleet. The remaining fleet is maintained primarily according to the US Navy hull maintenance policy as stated in the Naval Ships Technical Manual (NSTM). This policy directs that all naval ships receive essentially the same underwater hull coating system, without consideration to the ship's expected duration of operation or its anticipated hull maintenance requirements. Furthermore, significant improvements in the performance of ablative anti-fouling (AF) paints enable painted surfaces to remain free of visible fouling for extended periods and can allow for closer attention to be directed to the roughness changes of the AF paint occurring during operational service. Analyzing these changes may improve existing hull coating system wear models, which are currently based on dry film thickness (DFT). This thesis focus on coating systems of surface combatants and on using paint roughness as a reliable measurement for modeling hull coating system wear. The ultimate goal for all this research is to more accurately predict hull coating system wear using a measurement taken every year and not relying solely on measurements during drydocking periods every three to five years.

The underwater coating system is comprised of multiple coats of anti-corrosive (AC) paint followed by multiple coats of anti-fouling (AF) paint. Newly painted ships in operation today have systems that consists of 2-3 layers of AC paint followed by 3-4 layers of AF paint. The AF paint is designed to slowly and continuously leach cuprous oxide, a toxin that discourages marine growth from attaching and living on the exterior of a ship's hull. To maintain a high concentration of cuprous oxide on the surface, today's anti-fouling paints are designed to slowly wear away or ablate as the ship moves through the water. Monitoring the wear of the coating system in order to determine the layers of AF paint needed to sustain an operational cycle is done primarily using hull DFT measurements taken while the ship is in drydock and wet film thickness measurements taken while the ship is in the water.

Using coating surface roughness measurements collected from the fleet's surface combatants, this analysis aims to increase current model accuracy of predicting the effects of operational cycle on a hull coating system. Additionally, the analysis will investigate if the two models currently in use for predicting hull coating wear for aircraft carriers can be applied for non-aircraft carrier ships such as surface combatants.

A. BACKGROUND

1. Hull Coating System Roughness

Understanding hull roughness is achieved by first the acceptance that applied AF paint is not smooth or of uniform thickness. The surface is marked by imperfections such as rises and falls, ridges, protuberances and projections on the minute level. Several causes of initial surface roughness can be attributed but not limited to paint structure, poor application standard, and environment. The demand by the marine industry for shorter time in drydock has led the paint manufacturers to seek a compromise between cohesive paints which will spray smoothly, but sag easily and thixotropic paints which tend to roughen the surface but may be applied in thicker coats. The result is that for higher volumetric throughput, unless carefully controlled, modern paints tend to ripple the surface resulting in severe overspray. This careful control of paint application and the single most important factor in hull roughness is attributed to the man who applies the paint. This is a highly skilled job, which unfortunately, usually attracts lower quality labor. The training of such personnel is a priority item. It includes application in windy, humid, or cold conditions and limited dimensions of the drydock relative to the ship (Byrne, 1979). The ultimate concern with hull roughness is intuitive; smoother hulls sail faster and cheaper.

Marine biofouling growing on ship hulls also significantly affects speed and fuel consumption. Increased hydrodynamic drag from fouling organisms requires more power to push a hull through the water. The best efforts of naval architects to maximize efficiency of hull form are for naught when fouling is allowed to roughen the underwater hull (Bohlander, 1984). Paint roughness is measured using a Hull Roughness Analyzer (HRA), manufactured by British Maritime Technology. The Mark III HRA uses a stylus mounted on a trolley to measure peak to valley roughness height. Each reading reflects the average surface roughness (peak to valley height) over a 50-mm trace of the substrate and anomalies of the AF/AC paint system that may arise from overspray, runs, sags, etc. Townsin (1979) assesses that for a smooth hull average roughness of 130 microns, an additional 10 microns increases power and fuel consumption by one percent. Therefore, considerations for acceptable hull coating systems need to include initial roughness from paint composition and application, to eventual roughness from the additions of marine biofouling organisms attaching to the hull. As a note, the HRA measure paint roughness and does not measure roughness caused by biofouling. Biofouling is removed before measurements are taken.

2. Introduction of Anti-Fouling Paints

The advent of ablative anti-fouling paints has fundamentally changed the process of keeping ship hulls free from marine fouling. The first generation ablative paints are introduced commercially in the mid 70's. These materials are designed to wash off the hull as a function of velocity and water temperature. They prove to be very attractive to commercial ship owners whose vessels were at sea for a considerable period of time. The toxicants used in these paints are organotins, usually tributyltin oxide and copolymers of tributyltin. Copolymer materials generally have lower release rates, thus making a longer lasting product (Bohlander, 1984).

In 1989, the Office of Naval Research tasked Naval Surface Warfare Center Carderock Division (NSWCCD) to evaluate AF coating systems as a replacement on U.S. Navy Surface ships for Formula 121, the standard Navy AF coating in use at that time. The Navy was looking for a replacement for Formula 121 because it provided inadequate long-term protection (Radakovich, Smith, & Jacobsen, 1997). Hull roughness data was collected to further differentiate the hull coating systems being considered for replacement to Formula 121. But the majority of the data collected are DFT measurements for determining the wear characteristics of the ablative hull coating systems.

3. Modeling Hull Coating Thickness Wear

Wimmer (1997) quantifies the effect of operational cycle, hull cleaning and hydrowashing on hull coating systems for aircraft carriers using DFT measuring methods described in his thesis. This finding uses the distribution of the paint thickness and how it changes with wear due to operational cycle time, the number of hull cleanings, and the number of hydrowashes in order to more accurately determine survivability of a ship's hull paint system. Using data collected from aircraft carriers in drydock from 1985-1997, it describes a least squares regression that develops a wear model capable of predicting total coating system wear. The model is then tested on thickness measurements taken from CV-59, a validation data set separate from the development set. The model tests well, predicting a distribution of paint thickness that was close to the hull's actual distribution of paint thickness.

Ellis (1999) determines an estimate for the mean thickness of a single coat of AF paint using data collected from 1985-1998. Using this estimate and the mean of the distribution predicted for the interim drydock, she also derives estimates for the mean thickness of a hull's total coating system following two operational cycles. The method provides enough information to facilitate choosing the number of applied coats of AF paint during the interim drydocks. This will ensure hull integrity is maintained until the second drydocking evolution. Ellis (1999) also validates the Wimmer (1999) model using five recent sets of data collected from additional aircraft carriers. Wimmer's model is able to predict the median coating thickness within one layer of AF paint. This prediction is sufficient for the purpose of making decisions concerning how many coats of paint to add.

Wimmer (1997) and Ellis's (1999) models predict the thinning of ablative antifouling layers of paint using dry film thickness measurements. These predicted distributions provide information not previously known about the wear of coating systems during one to two operational cycles. However both models have limitations. Both ablation and the smoothing of a surface are components in the thinning process of an ablative AF coating system and cannot be measured by thickness alone. Moreover, the means of measuring paint thickness while the ship is in the water has resulted in inaccurate data possessing extremely high variability. This reduces the ability to monitor paint wear during the operational cycle.

Dry film thickness is a complicated notion. It currently encompasses the thickness of the entire coating system of both AC and AF layers and is susceptible to paint swelling. Roughness measurements are "peak to valley" values differing from DFT measurements in an order of magnitude (microns versus mils). For example, if the average roughness value is 300 microns, the valleys may extend 10 to 12 mils and extend into the AF well past the second topmost AF layer. In accordance with NSTM guidelines, each coating system for a ship's hull should be identical, with all DFT measurements falling between a total coating thickness of 24 to 25 mils. This implicitly assumes that paint is applied uniformly over the entire hull, and Wimmer's (1997) research clearly disproves this. Therefore when the DFT is low, the roughness valleys may very well extend into the AC layer. NSTM also provides guidelines for pierside underwater hull coating system evaluation detailed in Appendix A.

B. THESIS OUTLINE

This study includes both a qualitative and quantitative analysis of the distribution of paint roughness, thickness and wear rates of an underwater hull coating system primarily for surface combatants. In Chapter II, the method for collecting roughness data is discussed as well as an exploratory analysis of the roughness data taken at the initial application in order to provide a "baseline". The change in the coating system's paint roughness and thickness as a function of time is studied in Chapter III. In Chapter IV, the Wimmer (1997) and Ellis (1999) wear models are tested with data collected from two surface combatants. Chapter V discusses a relationship between hull coating thickness and roughness. Finally, Chapter VI concludes the analysis with recommendations and discussion.

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II. DATA DESCRIPTION AND COATING SYSTEM PROPERTIES

Ships are continually selected to serve as test platforms in order to evaluate anti-fouling coating systems as replacements on U.S. Navy surface ships for Formula 121. The hulls of the ships are blasted to near white metal and coated with anticorrosive primers followed by several copper ablative AF coats in the form of test strips. The test coating systems were assigned a coating code, indicated by a capital letter. An example of coding code identification for USS VINCENNES (CG 49) in March 1993 is shown in Table 1.

Coating Code	Coating System
A,C	BRA 640, Manufactured by International Paint Co. (IPC)
B	ABC-3, Manufactured by Devoe Marine Coatings
D	7660-511, Manufactured by Hempel
F	Neptune 2, Manufactured by Woolsey
G	Intersleek, Manufactured by IPC
H	IC 531, Manufactured by Inorganic Coatings

Table 1. Six Antifouling Test Coatings Applied in March 1993 to USS VINCENNES (CG 49)

After the test coatings are applied, stencils are coated on the ship's hull to identify the different test areas by coating code, side of ship, and approximate frame number. If the capital coating code letter(s) precede(s) the approximate frame number, the stencil is on the starboard side of the ship and vice-versa if on the port side of the ship. For example B1-6 is the Devoe ABC-3 coating system test strip located on the starboard side frame 60 whereas 2B-6 is the same coating system on the port side frame 60. These stencils permit the measurement of data in about the same location during each evaluation and are particularly useful during underwater inspections performed by divers. An example of the location of the port and starboard test areas for USS VINCENNES (CG 49) in March 1993 is shown in Figure 1.

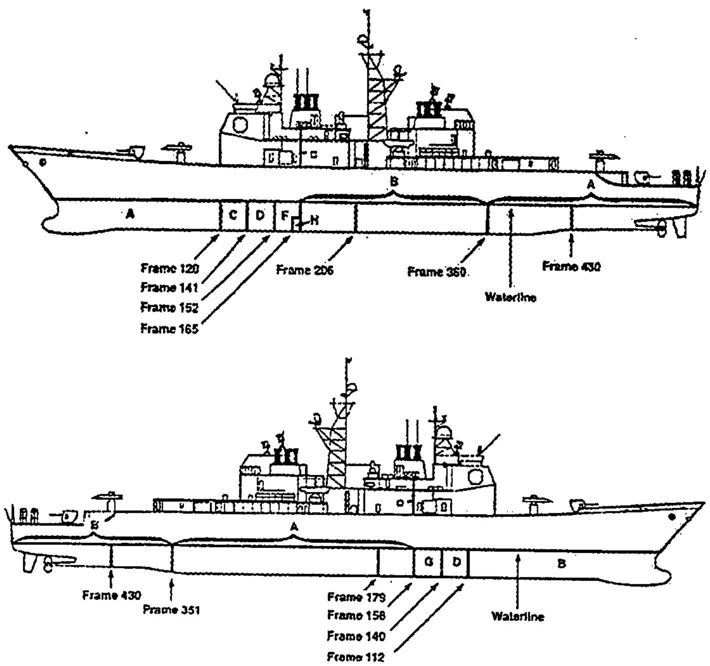

Figure 1. Port and Starboard Test Area Locations in March 1993 for USS VINCENNES (CG 49).

Divers, using the Hull Roughness Analyzer (HRA) manufactured by British Maritime Technology, measure hull roughness. Typically measurements above 500 micrometers are not used for analysis. These high measurements are attributed to weld beads and other substrate roughness rather than the surface roughness of the AF coating. The reasoning is that 500 micrometers, about 20 mils (25.4 microns equals 1 mil) noticeably exceeds the total recommended DFT for the AF systems. In addition to limiting data sets to 500 microns, six percent of the reading is added to the data in order to account for signal loss due to the length of cable used in underwater measurements (three percent for every 30 feet of cable).

A. DATA SUMMARY

All usable data sets for hull coating roughness and thickness analysis are contained in Appendix A. However, not all the test paints are used. Currently there are only three paints widely used in surface combatant hull coating systems. Test strips for these three paints ABC-3, BRA 640 and Hempel 7660 are combined as one data set for each ship and analyzed as a single coating system. The paint characteristics and wear rates of these three types of AF paints are assumed to be identical by the US Navy and no distinction is made between the three types of paint throughout this study.

B. HULL COATING SYSTEM AT INITIAL APPLICATION

1. Initial Coating Application for Different Combatants

The initial underwater coating system for a surface combatant is the same for an aircraft carrier, consisting of multiple layers of anti-corrosive and anti-fouling paints applied to a hull that has been sand blasted to "white" metal. Each coat is applied manually using spray guns while the ship is in drydock. The three types of AF paints currently used by the Navy are International BRA 640 series, Devoe ABC-3 series and Hempel 7660 series. All three of these paints are designed to ablate slowly, continuously exposing a painted surface with high a concentration of cuprous oxide. The wear rates of these three types of anti-fouling paints are assumed to be identical by the Navy. Therefore, all data sets with these paints as well as the side of the ship they were applied to will be aggregated throughout this study. Due to factors such as the environment, painters experience level and obstructions, a coat of paint may not be applied uniformly at its prescribed thickness or uniformly at a particular roughness. Not only are there considerable variations in paint thickness but also in paint roughness. Moreover, their variability increases with each additional applied coat.

The best way to illustrate this variability is to display the DFT and roughness measurements collected from various selected locations on the hulls of three surface ships in terms of a frequency histogram. Each data set contains DFT and roughness measurements collected immediately before or after a ship's operational cycle or maintenance procedure, such as a hydro washing or hull cleaning. Table 2 and Table 3 give the summary statistics of paint thickness and roughness for the hull coating systems of the USS DEWERT (FFG 45), USS VINCENNES (CG 49), and USS MOOSBRUGGER (DD 980) immediately following hull coating application.

Ship	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Sample Size
USS MOOSBRUGGER (DD 980)	9.22	24.08	27	27.32	30.26	48.78	1200
USS VINCENNES (CG 49)	3.05	25.14	30	31.86	36.61	71.31	3804
USS DEWERT (FFG 45)	18.9	25.4	27.7	27.81	30.1	41.6	1200

Table 2. Summary Statistics of Thickness (mils) for Two Applied Coating Systems

Ship	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Sample Size
USS MOOSBRUGGER (DD 980)	11	57	83	190.02	133.25	500	2628
USS VINCENNES (CG 49)	28	107	140	156.87	188	496	3812
USS DEWERT (FFG 45)	70	135	167	179.57	207	500	2506

Table 3. Summary Statistics of Roughness (microns) for Two Applied Coating Systems

Note the large ranges of paint thickness, 37.56, 68.26, and 22.7 mils for DD 980, CG 49, and FFG 45 respectively. In accordance with NSTM standards, each of these coating systems should be identical, with all DFT measurements falling between a total thickness of 24 to 25 mils. Additional insight into these thicknesses can be seen in the variability of roughness. The larger the peak to valley roughness measurements may very well account for the low thickness measurements.

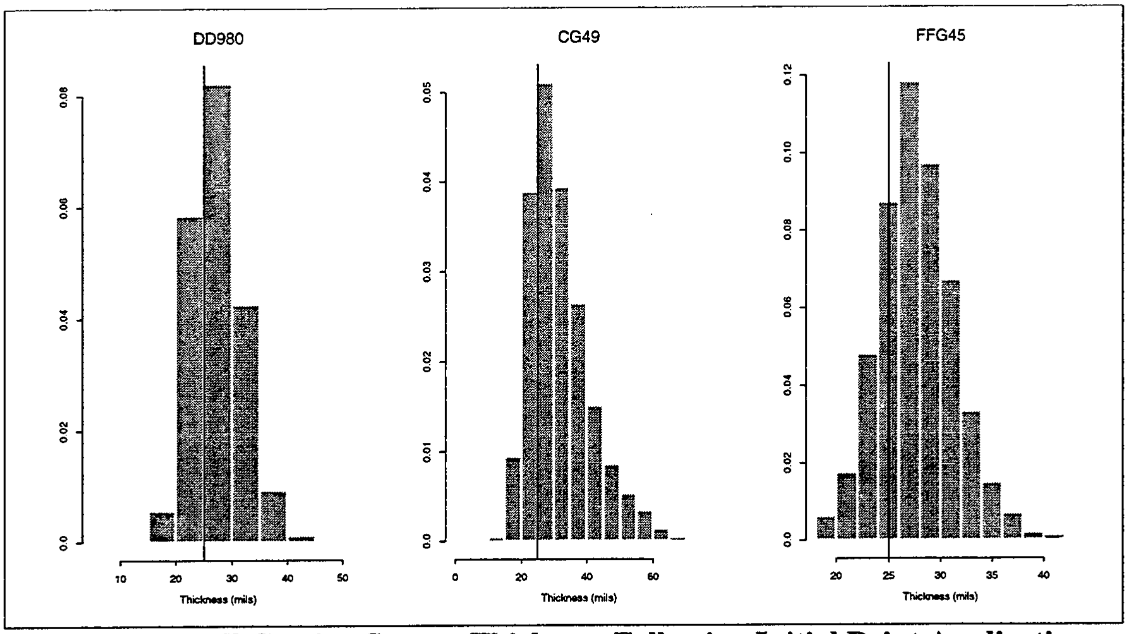

Figure 2. Hull Coating System Thickness Following Initial Paint Application.

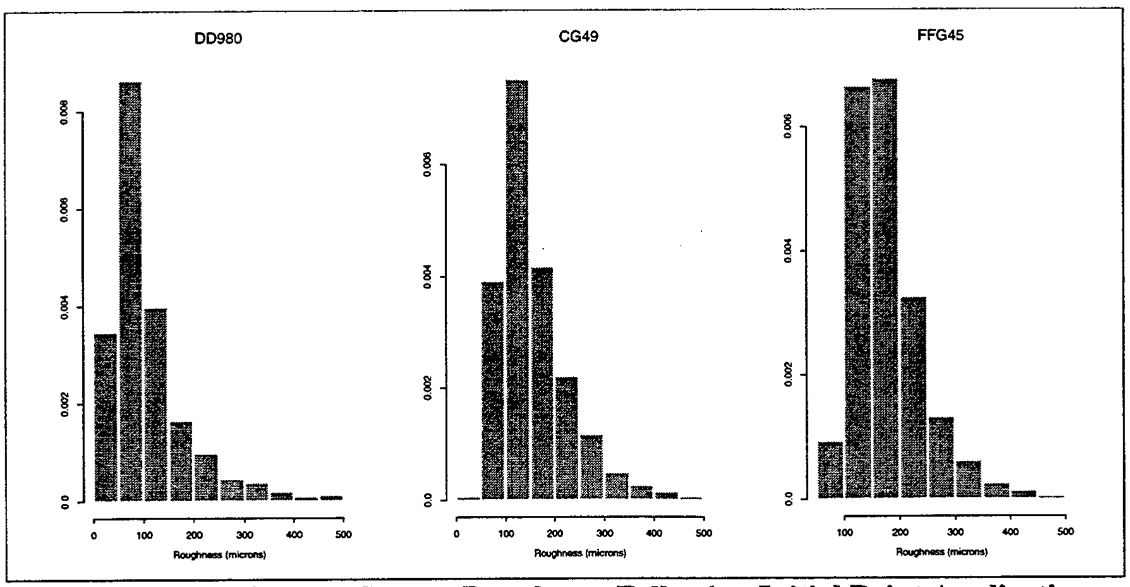

Figure 3. Hull Coating System Roughness Following Initial Paint Application.

The relative frequency histograms in Figure 2 and Figure 3 provide further insight. Just as Wimmer (1997) concluded, only a small percentage of each ship's DFT measurements actually fall within the NSTM guidelines and the thin DFT measurements ultimately play a critical role in determine the expected service life of a coating system. Figure 3 shows the variation in roughness, which too may clarify non-uniform wear further determining the expected life of a coating system.

2. Fitting Distributions to Initial Hull Paint Roughness

As with the thickness distributions, the paint roughness distributions are asymmetric and possess large variances. Comparing the roughness measurements of a coating system with a Normal distribution will illustrate this more clearly. In Figure 3, a "heavy" right tail is clearly visible for all three coating systems. The positive skew shows up more clearly in the Normal Probability Plots in Figure 4.

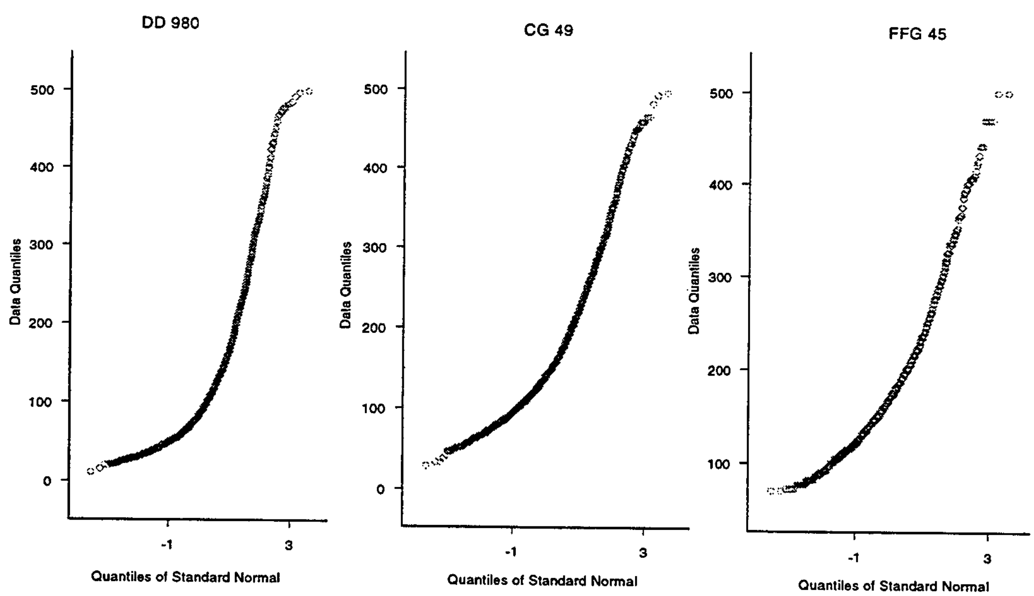

Figure 4. Normal Probability Plots for the Roughness Measurements of Three Freshly Applied Coating Systems on DD 980, CG 49, and FFG 45

As is found for DFT measurements, Wimmer (1997) and Ellis (1999), a single parametric family of distributions is not adequate for describing the roughness distributions. The asymmetry of the data shown in Figures 3 and 4 clearly shows the non-normality of the data. Other families of distributions, such as Log-Normal, Gamma and Weibull distributions are fit to the three data sets to determine if all three freshly applied coating systems may be consistently and adequately characterized by a single family of distributions. The Komorogov-Smirnov Goodness-of-Fit test rejects the other families of distributions with p-values less than 0.0001 and with large sample sizes. A feasible alternative is to use a simple nonparametric estimator such as the empirical cumulative distribution function (cdf).

3. Initial Coating Application for Different Periods

It is well understood that coatings are not applied uniformly over the entire hull of the ship. As stated previously, application is affected by various factors such as environment, equipment and operator. Previous analysis has already determined that rougher paint or areas of thicker paint as explained by Wimmer (1997) tend to wear faster than other areas. Though an acceptable variance in paint roughness may be tolerated, a certain level of quality assurance can be performed in order to feel comfortable with the expected smoothing rate of the coating system. Figure 5 illustrates the empirical cdf's of initial coating systems applied to USS VINCENNES (CG 49) during three different time periods 1989, 1993 and 1998.

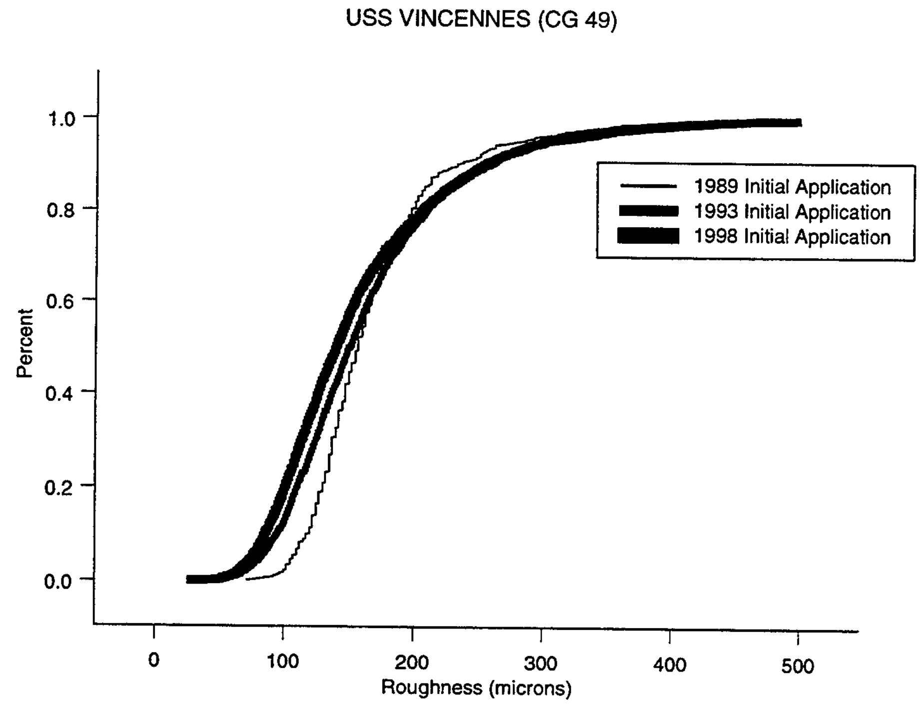

Figure 5. Empirical cdf's of Coating System Roughness at Initial Applications.

An initial look at these three coating systems supports a hypothesis that the three coatings are not of the same shape and are not from the same distribution. To determine if the three coating systems are of the same distribution, the two sample Komorogov-Smirnoff (K-S) Test is performed on each pair of coating systems. The three K-S tests reject the hypothesis that the three unknown distributions are equal to each other with a p-value less than 0.01. To further illustrate the results of comparing the three distributions, Figure 6 graphically depicts the results of vertical differences amongst the three unknown distributions.

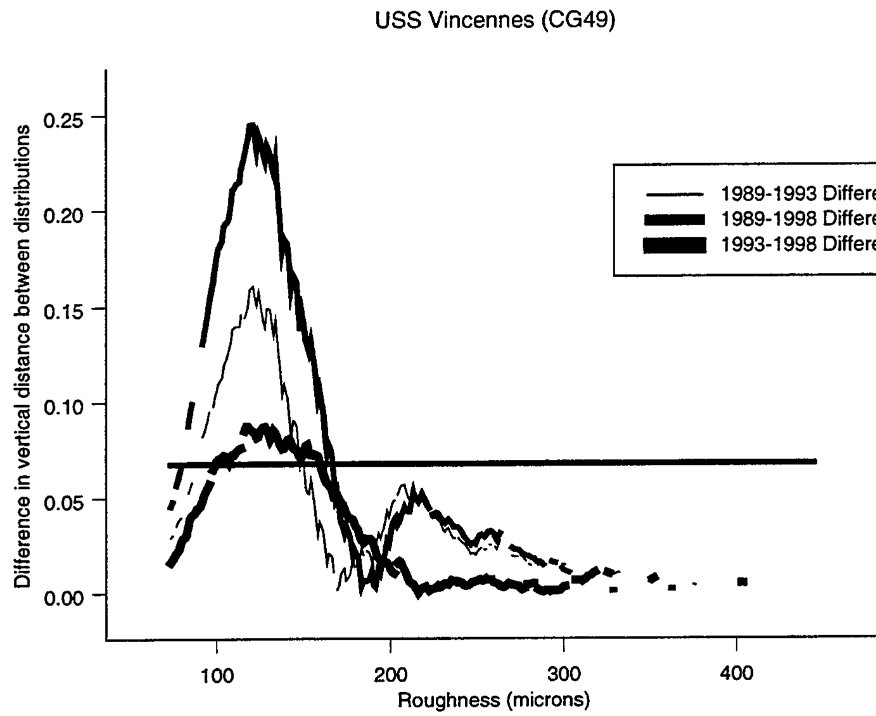

Figure 6. Vertical Distance Differences Among Applied Coating System's Distributions.

Because there are percentile differences for measurements of roughness greater than the K-S critical value (0.0677 shown as the dark horizontal line in Figure 6) for large sample approximations, the test rejects the hypothesis that the three distributions are equal. From this, it is evident that the three applied coating systems' are not from the same distribution.

The implication is that the conditions that cause variations in paint application are not the same during every drydock period. As stated by Ellis (1999), one possible explanation for variability involves temperature. Warmer months offer surrounding heat aiding in drying the paint whereas colder temperatures retard drying time allowing paint to shift. This shifting of paint may also effect the ability for the paint to consistently smooth itself during the curing process. Therefore, the assumption that different applications of paints are capable of drying to the same roughness is incorrect. Continued research in this area could possibly lead to a quality assurance process in paint application controlling the initial ablation rate of a hull coating system before and after maintenance procedures are performed.

III. MODELING CHANGES IN COATING SYSTEM ROUGHNESS

Any model to predict coating system wear must consider two key elements, capturing the change of the entire coating system as a function of various hull procedures and operational cycles, and predicting wear for any coating system regardless of the shape of its distribution (Wimmer, 1997). As explained in the previous chapter, coating systems possess very different roughness distributions following paint application. In order to meet the two described key elements, we will exploit the observation that the changes in quantiles of a coating system's roughness during an operation cycle are roughly linear, Wimmer (1997) exploits this in his thickness model. These changes in quantiles are used as the underlying premise of evaluation. It gives a fairly concise representation of the roughness distribution for any coating system and permits the use of a least squares regression to develop a quantitative model for coating system smoothing.

This chapter develops a mathematical model that quantifies the impact of the duration of operational cycle upon a coating system's roughness distribution using techniques originally developed by Wimmer (1997). Since existing data concerning coating system smoothing is restricted to a coating system's initial roughness distribution and length of operational cycle, the predictive model will contain only this variable. It will be considered from the perspective of its impact on a coating system's quantiles, specifically its median. Therefore the ultimate product of this model is the change in median roughness of an initial coating system's quantiles for a specific projected operational cycle.

A. PAINT SMOOTHING CHARACTERISTICS

A general overview of the paint smoothing is shown in Figure 7 depicting the change of paint roughness during USS VINCENNES (CG 49) and USS MOOSBRUGGER (DD980) operational cycle.

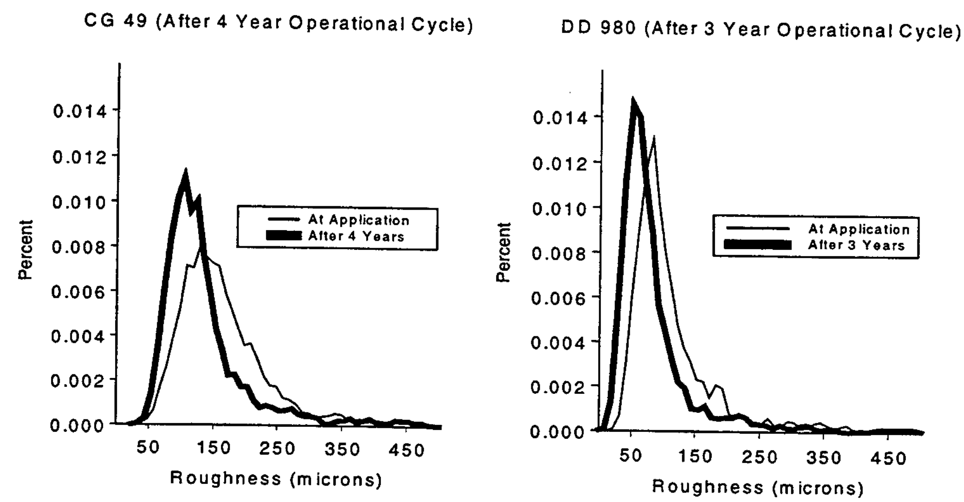

Figure 7. Distribution of a Coating System Roughness Before and After An Operational Cycle.

The shape of the paint thickness distribution indicates a decrease in variability with wear as well as shifts to the left. This suggests that the smoothing of the paint is predominately uniform with slight variations due to rougher areas smoothing faster in the beginning. To illustrate the change of ablative properties over time, the empirical cdf's are shown in Figure 8.

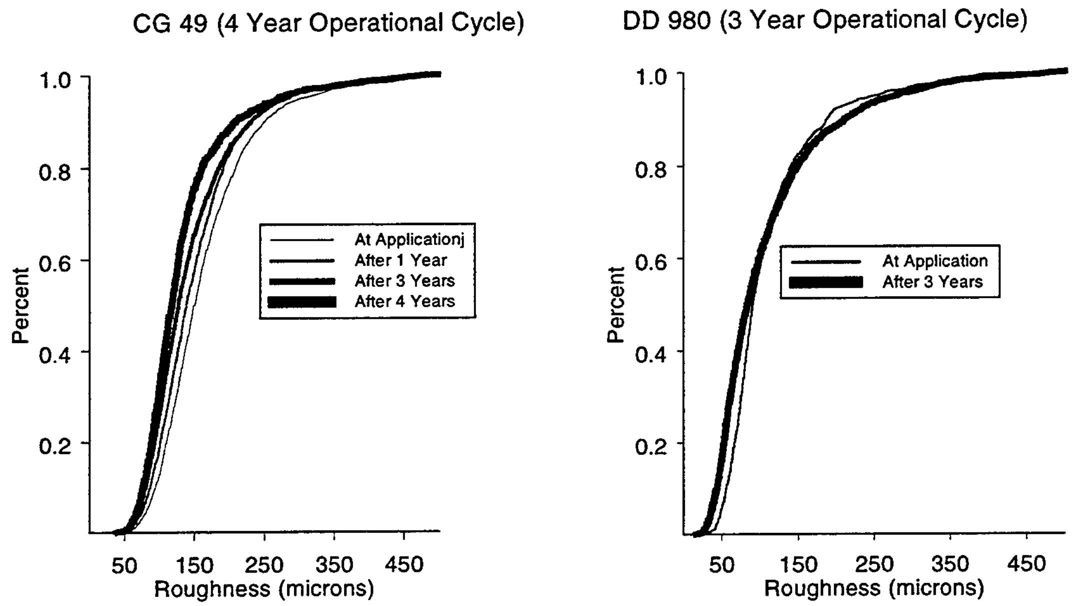

Figure 8. Empirical cdf's of Coating System Roughness During Operational Cycle.

These two diagrams illustrate a consistent shift in distributions. The shift in distributions for CG 49 is more pronounced for the higher percentiles of roughness or rougher areas and is expected to be the same for DD 980. The reason for the increase in roughness for DD 980 will be explored in the next section.

B. MODELING THE IMPACT OF OPERATIONAL CYCLE DURATION

The change in the quantiles of the roughness distribution for the coating systems of CG 49 following a four year operational cycle and DD 980 following a three year operational cycle are illustrated in Figure 9.

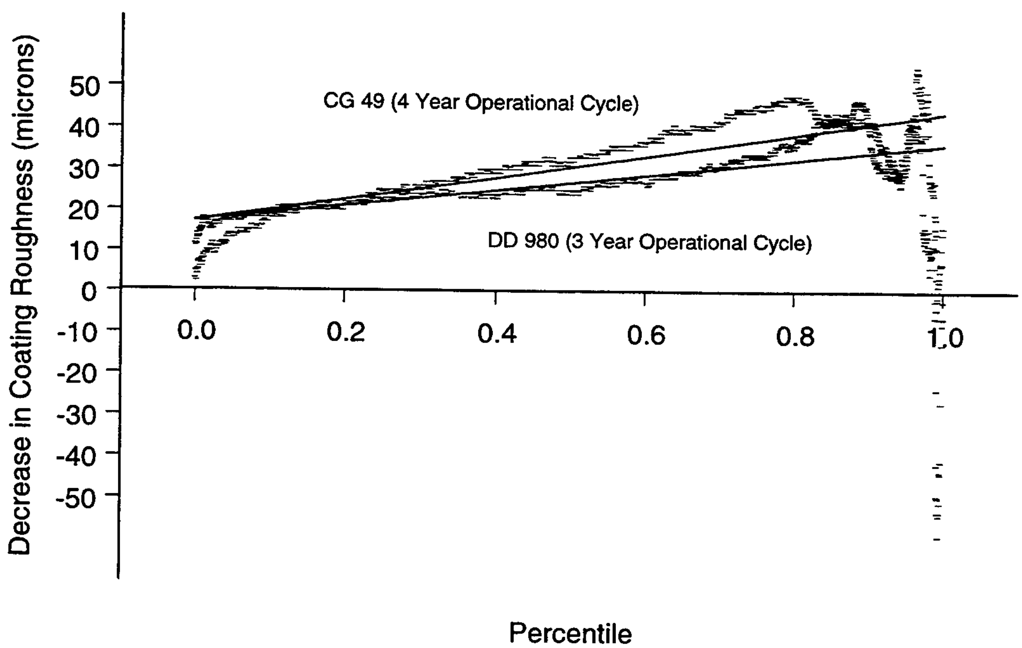

Figure 9. Change In Coating Quantiles for a Four and Three Year Operational Cycle.

Since no hydrowashes or hull cleanings are considered in the model, changes in coating roughness are exclusively a product of the length of time of each ship's respective operational cycle. Figure 9 shows an approximate linear relationship in the change in quantiles of roughness measurements across nearly the entire percentage scale for both coating systems. The linear increase in paint smoothing is quite pronounced for CG 49. Both curves confirm the findings presented earlier and by Wimmer (1997) that coating systems do not exhibit uniform paint ablation at all. For both ships, the negative change in quantile roughness at the right end of the scale indicates an increase in roughness. The reason for this behavior is not certain. Since the higher percentiles represent the peaks of the coating system, it is feasible that there is an increase in variability in the measurement of these areas. Variability could be contributed to things such as a diver's glove inadvertently roughing the paint in an attempt to clear the surface, the measuring device slipping, or the painted surface increasing roughness over time. This is seen with coating systems previously tested but no longer in use. (Radakovich, T., Giacomo, L., Smith N., 1997)

Due to the limited data available, only the change in a coating system's median will be modeled and is assumed to be a function of only the length of a ship's operational cycle. To approximate the median an operational cycle, a least squares fit is computed based on the empirical cdf's of the total coating system before and after the operational cycle of three data sets: CG 49 operational cycle from 1989 to 1991, from 1993 to 1997 and DD 980 operational cycle from 1994 to 1997. For purpose of continuity with previous modeling performed on ship's underwater coating systems, the response variable y_{50} is taken to be the 50^{th} percentile or median coating system roughness after an operational cycle. Consistent with the plots in Figures 8 and 9, y_{50} is modeled as linear in the length of the operational cycle of D. Additional binary variables G and F are added to the model to differentiate the type of ship being model. The variable G has a value of one if the ship being modeled is a Cruiser, zero otherwise, and the variable F has value one if the ship being modeled is a Frigate or Destroyer, zero otherwise. The intent is to model paint smoothing without any knowledge of how the duration of an operational cycle effects ablation or the time spent underway during the operational cycle. The relationship may be more complex than the one modeled here but with the minimal amount of data available, these effects cannot be adequately modeled. This model gives the following least squares estimates for y_{50},

$$\hat{y}_{50} = 157 - 15D + G(149.35 - 7.8D) + F(90 - 8D).$$

This model has a large adjusted squared multiple correlation coefficient, 0.9944 and the standard errors for the coefficients are listed in Table 4.

Coefficients	Standard Error
Intercept	2.2749
D (years)	1.6086
G (Cruiser)	2.9221
F (Frigate/Destroyer)	3.2171
GD	1.7621
FD	1.9333

Table 4. Standard Errors for Coefficients

The known data set to be used for prediction is the USS Dewert (FFG 45) for a four year operational cycle (D=4, G=0, F=1) shown in Table 5.

Data Set	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum	Std Dev.
Actual Initial	70.5	135	167	179.6	207	500	63.71
Actual Final	13.2	88	117	149.3	177.1	497	95.7

Table 5. Summary Statistics of Roughness (microns) for FFG 45

The resulting prediction is a median coating roughness of 155 microns. The absolute difference in median roughness is 38 microns and considering the variability of the roughness data used for modeling, the predicted value falls well within the standard deviation for the actual final roughness 95.7 microns.

The predictive model is limited to analysis of the median roughness and presumes the smoothing characteristics of a Knox Class Frigate are similar to those of a Spruance Class Destroyer. Analysis of variance studies comparing the modeling of roughness using ship type and years of operation and the modeling of roughness using solely the year concluded that there are significant effects being contributed by the Destroyer and the Cruiser. Therefore aggregating the effects of a Frigate with that of a Destroyer may also contribute to some error. As more data are obtained with an increasing variety of surface combatant hulls, the analysis of hull roughness to include a more accurate model encompassing more quantiles and other ship classes is a logical "next step" for research.

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IV. ANALYSIS OF CARRIER THICKNESS MODEL ON SURFACE COMBATANTS

In deriving the model for the wear of a ship's hull paint system, both Wimmer (1997) and Ellis (1999) concluded that the variability amongst different aircraft carrier hull coating wear data was negligible for their models. On the other hand, the surface fleet's different hull configurations present a potential problem when trying to model wear amongst ships of different classes. At this point, the changes in quantiles of hull coating system's thickness and roughness before and after hull maintenance procedures and operational cycles are assumed linear. Without such an assumption, previous quantitative models that predict coating system wear could not be easily derived.

A. THE WIMMER (1997) AND ELLIS (1999) MODELS

Using two sets of from CV59, CVN 68, CVN 69, and CVN 72, the Wimmer (1997) model gives the following least squares approximation $\hat{y}_p$ for y_p, the difference in the p^{th} quantile thickness before and after an operational cycle, for p = 10,11, . . . 90,

$$\hat{y}_p = -1.8175 + .0465p + .4616D + 5.3411C + 4.460W - .0021pD - .042pC - .0527pW,$$

where D, C, and W represent duration of operational cycle, number of hull cleanings and number of hydro-washes respectively. Standard errors were not computed for this model since the assumptions needed for inference based on Normal linear model theory, specifically independence, were not met by the data. However, the model gave a squared multiple correlation coefficient of 0.983, indication a good fit (Wimmer, 1997).

Ellis (1999), after verifying Wimmer's model and deriving a mean AF coating thickness value, developed a model estimating μ_{2d}, the mean thickness of a hull's paint system at a second drydocking given the ship evolution information for the two operational cycles as,

$\hat{\mu}_{2d} = \hat{\mu}_k + 1.8175 - .4616D - 5.3411C - 4.640W - (.0465 + .0021D - .0425C - 0527W)(101/200)$,

where $\hat{\mu}_k = \hat{\mu}_d + k\hat{\mu}_c$, the estimate of the mean thickness of the hull paint system at the intermediate drydocking($\hat{\mu}_d$,) plus the product of number of AF coats of paint at the intermediate drydocking (k) and the mean thickness of one coat of AF paint ($\hat{\mu}_c = 6.629$ mils).

B. SURFACE COMBATANT MODELING

Data for surface ship hull coating thickness is extremely limited to just a few ships and during the past decade. The combination of the two as well as the fact that hull thickness readings are only taken when the ships is in drydock, limits analysis. The data to be used in the two models are from CD 49 during two operational cycles from (a) 1989 to 1993 (45 months) and (b) 1993 to 1998 (52 months). One hull cleaning was performed during each of these two periods but the thickness measurements for 1993 were taken after an additional coat of paint was applied.

Figures 10 and 11 compare the actual empirical cdf's and predicted using cdf's for the periods following the noted operational cycles and hull cleanings.

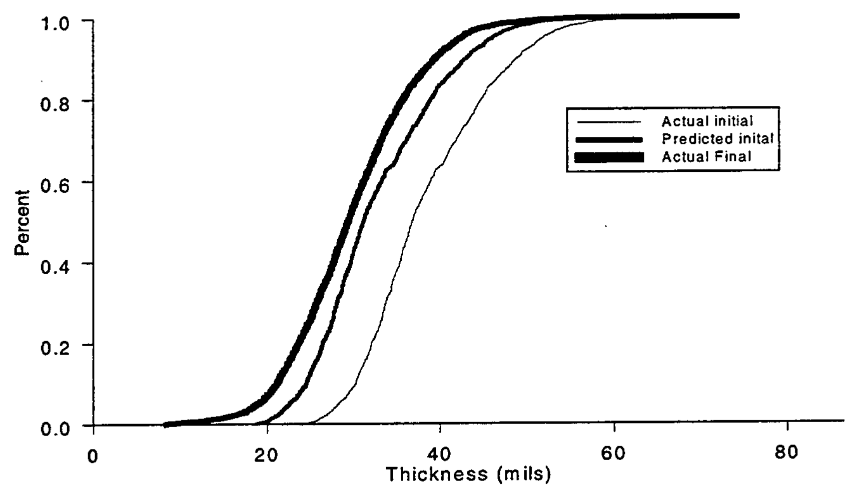

Figure 10. Predicting the Coating System Distribution for CG 49(a)

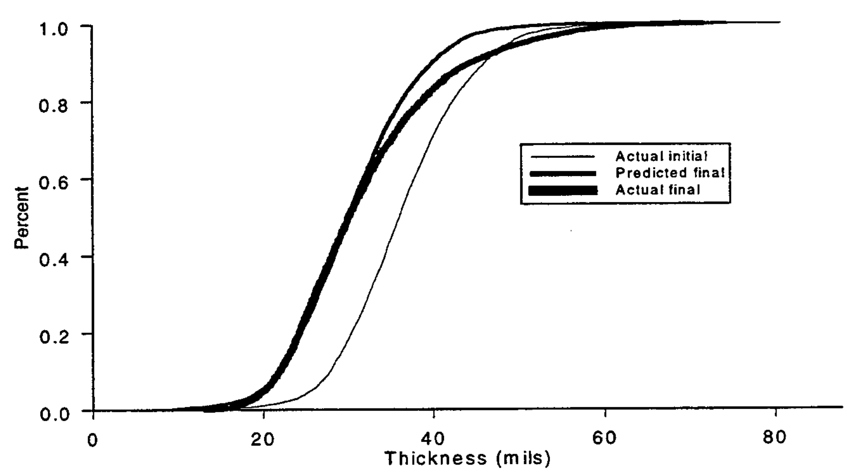

Figure 11. Predicting the Coating System Distribution of CG 49(b)

Both models are very close and the second produces a more conservative prediction. However, due to the lack of data sets to analyze, neither prediction can be substantiated as truly accurate for all surface ships in the fleet.

To further illustrate the predictability of the model, Figure 12 compares the differences between the predicted and actual total thickness measurements for percentiles 10 through 90 without the consideration of an additional coat of paint applied for CG 49(a).

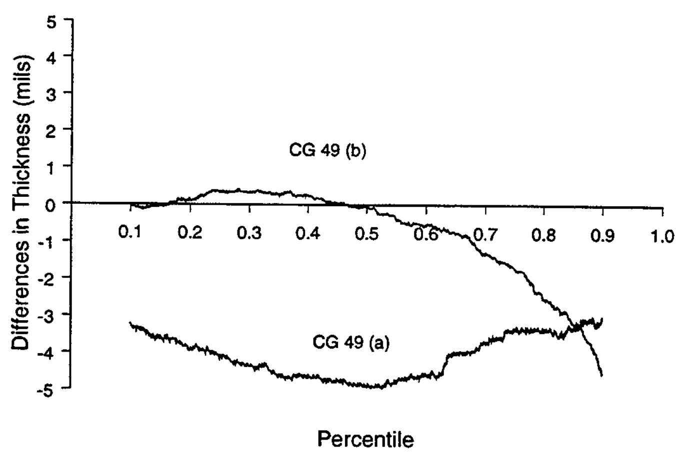

Figure 12. Difference Between Predicted and Actual Percentiles of the Total Thickness After An Operational Cycle.

Figure 12 illustrates a significance difference between the predicted and actual percentiles for the operational period from 1989 through 1993. The median thickness value for that period is an absolute measurement of 4.91 mils which is more than the four mil thickness of a single coat of paint by NSTM standards. This difference for median thickness is deceiving though since as stated earlier, a coat of paint was added to the hull before a measurement was taken. If the added coat of paint is accounted at an additional 6.629 mils, the difference is now only an absolute measurement of 1.71 mils. The model predicted the median thickness value for the period from 1993 to 1998 to be an absolute measurement of .03 mils. Both models show a prediction well within the standard of one coat of paint.

In order to compare the predicted versus the actual value of the mean thickness of a hull's paint system at a second drydocking, the number of coats applied during the interim docking period is added to the initial paint application. The ship received one coat (approximately five mils) which increases the mean hull thickness to 36.39 mils. The mean thickness combined with two hull cleanings ($C = 2$) and 97 month operational cycle ($D = 8.08$) results in the Ellis model predicting a mean thickness of 23.8 mils. The actual mean thickness from the data examined is 31.9 mils which is 8.1 mils, almost two coats of paint, thicker than the prediction. This is a conservative but not an acceptable prediction (within one coat of paint).

Though there may not be acceptable evidence that all non-aircraft carrier ship hull coating systems wear the same as aircraft carrier hull coating systems, there is strong evidence for the need of future research in this area. As Wimmer (1997) stated, the data collected from aircraft carrier underwater hull coating system to "fit" the model should be consistent with the wear characteristics of all surface ships. Since the impact of hull maintenance procedures are completely independent of the shape or size of the hull that the maintenance is being performed, the impact of hull maintenance should be consistent for all Navy ships. The difference in paint ablation may not be as simple as the duration of a ship's operational cycle but rather the shape of the hull affecting the fluid dynamics along the hull.

V. CONSIDERATION FOR ROUGHNESS VERSUS THICKNESS

As stated previously, the ultimate goal for all this research is to more accurately predict hull coating system wear using a measurement taken every year and not just during drydocking periods every three to five years. Ellis (1999) in her analysis of measurement taken by underwater remotely operated vehicles (ROV) discussed two models currently being used to measure paint thickness while the ship is tied to the pier. Unfortunately, the probe of the gauge must be perpendicular to the surface of the ship on order to get an accurate measurement of paint thickness. Since the ROV is submerged and maneuvered remotely from a pier, it is very difficult to determine if the probe is perpendicular to the surface of the ship, especially when maneuvering around the curves of the hull. Thus, some of the measurements retrieved are not accurate representations of hull paint thickness and could potentially present an incorrect picture of the overall hull coating thickness.

Another problem with the measurement of hull coating thickness while the ship is still submerged is paint swelling. Hull coating systems are not impervious to water. Thus when a ship is submerged in water for an extended period of time, water permeates the coating, causing the surface of the coating to become bloated. Any measurement taken in this environment is expected to be inflated in comparison to the same measurements taken once the hull is dry.

Both the variations described above makes it very difficult to assess the hull coating system wear tracking with the prediction formulated by the model. A potential solution to this problem would be to have an ability to analyze the progress of hull wear every year using a relatively accurate form of measurement. An alternative to thickness measurement by an ROV would be the Hull Roughness Analyzer.

Ablative paints smooth themselves over operational cycle time and Wimmer (1997) surmises that the thicker areas tend to wear at a faster rate initially than do the thinner areas. This can be explained on a smaller level by roughness, where the rougher "peaks" would initially wear faster than the smoother "valleys". Taking a look at CG 49 over a four-year operational cycle, the hull coating shows a median wear in thickness of 5.99 mils and a smoothing of 33 microns. With an understanding that one mil is equal to approximately 25.4 microns, it is easy to see that approximately one mil of paint loss is attributed to the paint smoothing.

To further show the impact of smoothing rates, Wimmer (1997) attributed a loss of 0.4616 mils for every year in operation equating to approximately 2 mils over the four-year (52 month) operational cycle. The median reading of 5.99 mils was taken after the hull cleaning which Wimmer (1997) predicted the hull cleaning would account for approximately 5.3411 mil loss of paint thickness. Thus the difference between the final median reading and the predicted loss due to hull cleaning results in the amount loss due to the operational cycle which according to the smoothing rate is 1.3 mils versus the Wimmer (1997) prediction of 2 mils. The increase of 0.7 mils of paint thickness improves the accuracy of the model to 1.01 mils vice the 1.71 mils determined previously. Though this does not seem much for the Wimmer (1997) model, the difference would be more apparent for the longer operational cycles analyzed by the Ellis (1999) model and may result in the difference between adding or not adding an additional coat of paint. The topic of the effects of roughness measurements on the hull coating thickness prediction and a connection between roughness and the decision repaint is left as a topic for future research when more data is available.

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VI. SUMMARY AND CONCLUSION

Reduction in the number of ships and personnel has become inevitable as the Navy searches for ways to maintain the surface fleet with an ever-decreasing budget. One contributor to the total cost is attributed to the physical maintenance and preservation of ships to include hull coating systems. The need to maintain operational commitments as well as reduce the costs associated with drydocking surface ships, has prompted the Navy to attempt to extend the service life of hull coating systems thus extending time between drydocks. Both qualitative and quantitative analysis has been performed on the wear characteristics of an aircraft carrier's hull coating system in order to meet the challenges of extended operational cycles.

The Wimmer (1997) research provides insight to the wear characteristics of an aircraft carrier hull coating system resulting from operational duration and hull maintenance procedures. A model was then developed to predict the coating system wear. Ellis (1999) took a second step by providing a simple model which determined the number of coats of AF paint to add to a carrier's existing paint system at a future interim drydock in order to ensure the hull remains protected for a second operational cycle.

Though previous analysis has resulted in a tremendous improvement in extended survivability of aircraft carriers, the scope of research has been limited to hull coating thickness. This thesis takes a look at modifying the existing models to allow for the additional use of roughness data being collected during the operational cycle. The hull coating system roughness can potentially provide better insight to paint ablation rates independent of ship operation, resulting in a more encompassing and accurate model as the aircraft carrier 12 year hull coating system lifetime becomes more realistic. This thesis also supports the assumption that the Wimmer (1997) prediction model is capable of providing a "conservative" estimate of coating system wear for non-aircraft carrier ships.

A. RECOMMENDATIONS FOR FUTURE DATA COLLECTION

Current NSWCCD hull roughness analysis is limited to aircraft carriers. Though the initial purpose of conducting these measurements was to find another method of differentiating coatings systems, potential insights to the coating system wear are evident. The use of roughness data provides a means of determining wear more reliably than the current use of an underwater ROV and may further incorporate the changes in roughness due to underwater hull cleanings. Advantages of roughness measurements over thickness measurements includes a reliable measurement not affected by paint swelling and a simple method of underwater measurement that reduces the variability discovered in the thickness measurement gauge in use.

More and consistent data gathering is necessary to further develop the model presented. Hull roughness analysis should be extended to aircraft carriers to include before and after underwater hull cleanings and hydrowashes and whenever hull thickness readings are taken. Aircraft carriers present a better data gathering source at this time due to hull measurements on combatant ships is limited to test panels whereas roughness measurements on an aircraft carrier will encompass the entire ship from bow to stern and water line to keel.

B. ADVANTAGE OF HULL ROUGHNESS MODELING

Although the data limits the scope of this thesis to serve as a pilot study, it provides important insight into ablation rates and can serve as a potentially useful model. Using an ROV with an attached thickness probe has already proven to be a fairly unreliable means of gathering data for hull coating system wear modeling (Ellis, 1999). By collecting roughness data, the amount of variability in the measuring device is drastically reduced and is capable of taking measurements against any slope. Furthermore, the roughness model immediately yields possibly a more precise coefficient of paint lost due to one operational cycle and will further increase the accuracy of the Wimmer (1997) and Ellis (1999) models. Incorporating this research with past advancements in wear modeling, future surface combatant hull maintenance procedures will be planned and performed on more quantitatively-based estimations.

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APPENDIX A. HULL COATING SYSTEM EVALUATION CREITERIA

Pierside underwater hull coating system evaluation is based on the following criteria:

- AF performance, i.e. how well the fouling was controlled;
- The physical condition of the coating system; and
- Hull roughness measurements.

A. ANTI-FOULING PERFORMANCE

AF performance is evaluated on a 100 point scaled using the fouling ratings (FR) presented in Table 081-1 and Figure 081-1 of the NSTM chapter 081. The FRs are comprised of 11 ratings from zero to 100. A surface that is clean and foul free would be rated as zero while the most severe fouling would receive a rating of 100. This evaluation method consists of a written description of each FR, and a series of photographs showing a fouled surface at each FR. Table 6 provides a description of the FRs as described in Table 081-1 of the NSTM, chapter 081.

FR	Description
0	A clean, foul-free surface; red AF paint (for a ship just out of drydock)
10	Continuos graduations of shades of red and green (incipient slime)
20	Slime as dark green patches with yellow or brown colored areas (advanced slime)
30	Grass as filaments up to 3 in. (76 mm) in length, projections up to ¼ in. (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in color.
40	Calcareous fouling on edges, welded seams, corners, or as discrete patches covering flat areas roughly 9 to 10 in. (229 to 254 mm) in diameter
50	Random and scattered tubeworms or barnacles (or both) on slightly curved or flat surfaces
60	Area distributed of tubeworms or barnacles, ¼ in. (6.4 mm) in diameter or less; fouling does not completely cover or blank out surface
70	Tubeworms and barnacles completely cover surface in patches exceeding 9 to 10 in. (229 to 254 mm) in diameter. Tubeworms lying flat with radiating fringes of growth or barnacles ¼ in. (6.4 mm) in diameter or less
80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another. Calcareous shells appear clean or white in color
90	Dense growth of tubeworms with barnacles ¼ in. (6.4 mm) in diameter or greater. Calcareous shells brown in color or with slime or grass overlay
100	All forms of fouling present, particularly soft sedentary animals without calcareous covering (tunicates)

Table 6. NSTM Fouling Rating Description

B. PHYSICAL CONDITION OF THE COATING SYSTEM

The physical condition of the coating system is evaluated using the paint deterioration ratings (PDR) presented in the NSTM, chapter 081 Table 081-5 and Figure 081-5. The PDR is comprised of ten ratings from 10 to 100. A PDR of ten is the best surface condition and a rating of 100 is the worst. This evaluation method consists of a written description of each PDR and a series of photographs showing the surface at each level of paint deterioration. Table 7 provides the written description of PDRs, as described in Table 081-5 of the NSTM, chapter 081.

PDR	Description
10	AF paint intact, red in color or with molted pattern of light green or red
20	AF paint missing from edges, corners, seams, welds, rivet or bolt heads to expose AC paint
30	AF paint missing slightly curved or flat areas to expose AC paint
40	AF paint missing from intact blisters to expose AC paint
50	AF blisters rupture to expose AC paint
60	AF/AC paint missing or peeling to expose steel substrate, no corrosion present
70	AF/AC paint removed from edges, corners, seams, welds, rivet or bolt heads to expose steel substrate with corrosion present
80	Ruptured AF/AC blisters on slightly curved or flat surfaces with corrosion and corrosion stains present
90	Area corrosion of steel substrate with no AF/AC paint cover because of peeling or abrasion damage
100	Area corrosion showing visible surface evidence of pitting, scaling, and roughening of steel substrate

Table 7. NSTM Paint Deterioration Rating Description

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APPENDIX B. DATA AVAILABLE FOR ANALYSIS

Hull Number	Month-year data collected
CG 49	Jul-89
CG 49	May-91
CG 49	Jul-92
CG 49	Mar-93
CG49	May-94
CG 49	Aug-96
CG 49	Jul-97
CG49	Jul-98
FFG45	Sep-89
FFG45	Unknown-93
FFG45	May-96
DD980	Jun-94
DD980	Sep-97

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LIST OF REFERENCES

Bohlander, G.S. (1984). Ablative antifouling paint: Effect on hull roughness and power. Annapoilis, MD: David Taylor Research Center.

Byrne, D. (1979, February) Hull roughness of ships in service. A paper at the meeting of the North East Coast Institute of Engineers and Shipbuilders.

Cologer, C.P., Smith, N.A., Bohlander, G.S. (1986). Baseline documentation of ablative copper anti-fouling hull coatings for service evaluation on USS MARVIN SHIELDS (FF 1066). USS VINCENNES (CG 49). and USS DEWERT (FFG 45) (SM[E Report DTRCSME-90-19). Bethesda, MD: David Taylor Research Center.

Conover, W. J. (1980). Practical nonparametric statistics (2nd ed.). New York, NY: John Wiley and Sons.

Devore, J. (1990). Probability and statistics for engineering and the sciences (3rd ed.). Pacific Grove, CA: Brooks/Cole Publishing Company.

Ellis, Mitzi A. (1999). Estimation of anti-fouling paint thickness and its use in extending the lifetime of a ship's underwater hull coating system. Unpublished master's thesis. Naval Postgraduate School, Monterey, California.

Giacomo, L., Smith, N. (1997). 1997 Evaluation, Antifouling coatings on the USS VINCENNES (CG 49) (SSMD Technical Report NSWCCD-TR-64-98/02). West Bethesda, MD: Naval Surface Warfare Center, Carderock Division.

Naval Sea Systems Command. (1997). Naval Ships Technical Manual NSTM01 1 [CDROM]. Washington, DC.

Naval Surface Warfare Center, Carderock Division Broad Agency Announcement, (1995). Ship Hull Cleaning and Maintenance System (SOL N61533-95-BAA-0066). Annapolis, MD.

Navy Office of Information. (1999). Status of the United Sates Navy as of May 17,1999. [On-line], Available: www.chinfo.navy.mil/navpalib/news/.www/status.html

Radakovich, T., Smith, N., Jacobsen M. (1997). Application and evaluation of experimental coating systems, Antifouling coatings on the USS VINCENNES (CG 49) (SSMD Technical Report NSWCCD-TR-64-97/01). West Bethesda, MD: Naval Surface Warfare Center, Carderock Division.

Radakovich, T., Giacomo, L., Smith N. (1997). Evaluation after 41 months of service, Antifouling coatings on the USS VINCENNES (CG 49), (SSMD Technical Report

NSWCCD-TR-64-97/04). West Bethesda, MD: Naval Surface Warfare Center, Carderock Division.

Townsin, R.L. (1979, April) The economic consequences of fouling and roughness. A paper at the Marine Fouling Seminar, London.

Wimmer, James R. (1997). Analyzing and predicting underwater hull coating system wear. Unpublished master's thesis. Naval Postgraduate School, Monterey, California.

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