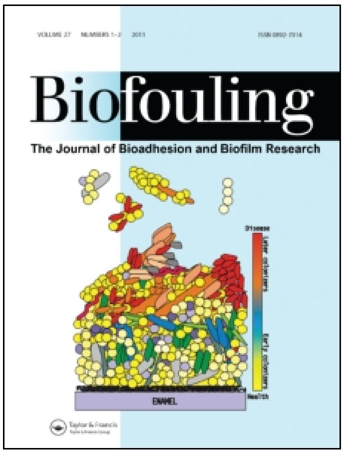

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Economic impact of biofouling on a naval surface ship

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In the present study, the overall economic impact of hull fouling on a mid-sized naval surface ship (Arleigh Burke-class destroyer DDG-51) has been analyzed. A range of costs associated with hull fouling was examined, including expenditures for fuel, hull coatings, hull coating application and removal, and hull cleaning. The results indicate that the primary cost associated with fouling is due to increased fuel consumption attributable to increased frictional drag. The costs related to hull cleaning and painting are much lower than the fuel costs. The overall cost associated with hull fouling for the Navy's present coating, cleaning, and fouling level is estimated to be $56M per year for the entire DDG-51 class or $1B over 15 years. The results of this study provide guidance as to the amount of money that can be reasonably spent for research, development, acquisition, and implementation of new technologies or management strategies to combat hull fouling.

Keywords: drag; powering; resistance; biofouling; roughness; antifouling coatings; economics

Introduction

It is well established that biofouling on ships increases the surface roughness of the hull which, in turn, causes increased frictional resistance and fuel consumption and decreased top speed and range (eg Kempf 1937; Benson et al. 1938; Denny 1951; Watanabe et al. 1969; Lewthwaite et al. 1985; Leer-Andersen and Larsson 2003; Schultz 2007). In order to control the problem of fouling, antifouling (AF) coatings are used. Most of these coatings incorporate biocides which are toxic to marine organisms and may impact non-target species. The impact of biocides on the environment has led to legislation regulating their use (Champ 2003). For example, the environmental impact of tributyl tin (TBT) biocides in AF coatings first led to their ban on vessels <25 m in length in most industrialized countries (Swain 1998) and has subsequently spurred a worldwide ban on these coatings by the International Maritime Organization (IMO) for all vessels in 2008 (Champ 2003). Alternative AF coatings employing copper and/or co-biocides (eg Irgarol 1051, zinc pyrithione and Sea Nine 211), are the principal replacement for TBT coatings. The present understanding of the environmental fate and effects of these biocides is addressed in the recent review by Thomas and Brooks (2010). Because of the increased environmental scrutiny to which copper and co-biocides have been subjected, there is a renewed interest regarding the economic impacts of fouling on ships and an increased effort to develop effective non-toxic coatings (eg Swain and Schultz 1996; Genzer and Efimenko 2006; Beigbeder et al. 2008; Aldred et al. 2010; Ista et al. 2010; Long et al. 2010; Magin et al. 2010). An excellent review of historical and present-day AF coating technologies as well as non-toxic alternatives is given by Finnie and Williams (2010).

The surface condition of the hull is of primary importance in the performance of marine vehicles. Frictional drag on some hull types can account for as much as 90% of the total drag even when the hull is free of fouling (Kempf 1937). For this reason, understanding and predicting frictional drag has been an active area of research for many years. Several studies have investigated the effect of surface roughness on the frictional drag of unfouled AF coatings, including the work of Musker (1980–1981), Townsin et al. (1981), Granville (1987), Medhurst (1989), and Grigson (1992). This research focused mainly on characterizing the change in roughness and drag of self-polishing copolymer (SPC) TBT systems and no effort to address the effect of fouling was made. This was due to the fact that the TBT systems provided long-term fouling control with minimal fouling settlement.

A large body of research has also been devoted to the effects of hull fouling on drag and powering. Townsin (2003) reviewed much of the research in this

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area and pointed out possible avenues for better understanding and prediction of the ship hull fouling penalty. Townsin (2003) asserted that the penalty due to calcareous macrofouling (eg barnacles and oysters) is much better understood than for soft fouling (eg bacterial and diatomaceous slime and algae). For example, Kempf (1937) conducted a particularly thorough investigation of the frictional drag increase resulting from barnacle fouling. Through this research, he was able to develop simple predictions of the frictional drag penalty based on barnacle height and coverage. According to Kempf's work, a maximum drag penalty occurred when the barnacle coverage was 75%. However, when the coverage was reduced to 5%, the drag penalty was only reduced by one third from the maximum penalty. Schultz (2004) noted that the height of the largest barnacles has the dominant influence on drag. And, in accordance with the findings of Kempf (1937), Schultz (2004) observed that the effect of increased coverage of barnacles on frictional drag was largest for low values of coverage and smallest for high values of coverage.

Research into the effect of low-form plant fouling and biofilms, often referred to as slime, dates back to McEntee (1915). Further work to better quantify the effect that slime films have on drag was carried out by Benson et al. (1938), Denny (1951), Watanabe et al. (1969), Picologlou et al. (1980), and Andrewartha et al. (2010). Full-scale ship trials were also carried out to measure the effect of biofilm fouling on the drag of copper-based coatings by Hundley and Tate (1980), Lewthwaite et al. (1985), and Haslbeck and Bohlander (1992). Schultz and Swain (1999, 2000) and Schultz (2000) made velocity measurements *via* laser Doppler velocimetry to study the turbulent boundary layers developing over biofilms and filamentous algae, respectively. Schultz (2004) compared the frictional drag of fouling-release coatings with biocide-based AF coatings in the unfouled, fouled, and cleaned conditions. The results of this study, as well as the results of previous research, indicate that even low-form algal fouling leads to a significant increase in frictional drag, although the magnitude of the increase depends strongly on the fouling type and coverage.

An entire chapter in the book 'Marine Fouling and its Prevention' (Woods Hole Oceanographic Institution [WHOI] 1952) is devoted to a review of the effect of fouling on ship resistance. Based on the data available at the time, the British Navy made an allowance of a 0.25% per day increase in frictional drag for ships operating in temperate waters and 0.50% per day for ships operating in tropical waters (WHOI 1952). This led to a prediction of a 35–50% increase in fuel consumption for a naval ship after operating for 6 months in temperate waters (WHOI 1952). While it should be noted that AF paint technologies have advanced considerably since 1952, naval vessels still pose a unique challenge to paint formulators because of their tendency to remain pierside for long periods of time compared to commercial ships. For example, Schultz (2004) predicted a frictional drag penalty, similar to that predicted by the British Navy allowance, for modern copper-based AF paints exposed in the static condition. This was based on the results of towing tank tests of coatings statically exposed in temperate waters for 287 days (Schultz 2004). A more recent investigation by Swain et al. (2007), utilizing field measurements of frictional drag, noted that there is a significant difference in the performance of both AF and fouling-release coatings when they are exposed dynamically *vs* statically. In particular, the fouling release surfaces showed much lower frictional drag under dynamic exposure than when exposed statically, and, in some cases, these surfaces had lower frictional drag than copper-based AF coatings.

It should be noted, as has been shown by Svenson and Medhurst (1984) and Townsin et al. (1985), that the effects of propeller roughness on ship powering can also be very significant. However, the influence of propeller fouling on powering is not as well established as for generic roughness. For this reason, the effect of propeller fouling is not considered in the present work. However, it is clear that this is an area worthy of future study. For example, the study by Atlar (2003) indicates that coating the propeller may lead to significant performance increases as a result of a reduction in fouling and roughness.

The economics of hull roughness have also been the focus of previous research. For example, Townsin et al. (1981) conducted an economic analysis of ship bottom maintenance based on an extensive study of 47 in-service ships. This research focused on the effect of paint roughness changes rather than fouling because of the efficacy of the TBT SPC paints in controlling the fouling on the hulls that were investigated. Abbott et al. (2000) carried out a cost-benefit analysis with regards to TBT AF paints. They pointed out that any serious environmental study of these paints must take into account the increase in fossil fuel consumption, greenhouse gas emissions, and disposal costs and impacts when considering a shift from TBT to copper-based coatings (Abbott et al. 2000).

Despite the large volume of research into the drag penalties resulting from fouling, there are few, if any, rigorous studies of the resulting economic consequences of this added drag, particularly in the post-TBT era. Alberte et al. (1992) stated, for example, that increased drag resulting from hull fouling cost the US Navy $75–100 million in fuel penalties. However, no substantiation of this figure was offered. In the present paper an economic analysis of the hull fouling penalty for a naval ship is presented. The analysis focuses on the US Navy's conventionally-powered, mid-sized surface combatant; the Arleigh Burke-class destroyer (DDG-51), the largest class of conventionally-powered ships in the fleet. This study is unique not only in the fact that it is guided by actual hull fouling conditions gleaned from a vast database of ship hull inspections, but also because it utilizes data collected for ship operational tempo and in-water hull cleaning. Ship resistance and powering penalties are calculated based on the similarity-law scaling procedure presented in Schultz (2007), which is linked with the Navy's fouling rating (FR) system (Naval Ships' Technical Manual 2006). The resulting penalties are then used to assess the overall economic impact of hull fouling using the aforementioned ship operational and cleaning data. Finally, the economic model is employed to examine how changes in hull maintenance strategies affect operating costs.

Materials and methods

The present economic analysis focuses on costs associated with ship performance that are affected by fouling. The total cost for ship operations arises from various types of component costs, associated with manning, supply, and maintenance and modernization (Figure 1; Guimond et al. 2006). Only a subset of these costs is affected by the condition (in terms of fouling) of the hull and corresponding fuel usage. Costs associated with or resulting from hull fouling include expenditures for fuel, hull coatings, hull coating application and removal, and hull cleaning (Figure 2). These components are in turn affected by additional variables, including the region in which the ship is operating, the age or condition of the hull coating, and labor and production rates. Only costs and modifying factors associated with hull condition and fuel use are modeled in the present analysis.

Selection of ship class for analysis

Since the US Navy fleet is comprised of a range of vessels of various sizes, with different powering systems, operational profiles, and regions of operations, it is difficult to model the economics of particular hull coatings or maintenance strategies across the entire fleet. For example, the performance of nuclear-powered aircraft carriers (CVN) is not relevant to understanding the impact of alternative protection strategies or technologies on fuel usage. Further complicating this effort is the fact that the intensity of fouling varies spatially on a global scale (for an early review, see WHOI 1952). So models based on a single operational region, or on ship class(es) that are not broadly distributed across operational regions, may fail to account for the naturally occurring variance in fouling. In order to simplify the modeling task, a single ship class was identified whose distribution across operational areas matched that of the fleet as a whole (thus taking into account global variation in the intensity of fouling), and that made up a significant portion of the fleet in terms of hull count and wetted surface area. Data were obtained from US Navy fact sheets (downloaded from www.navy.mil on 24 March 2009) and from the Uniform National Discharge Standards program Nature of Discharge report on hull coating leachate (Uniform National Discharge Standards 1999). Based on these data, the Arleigh Burke-class destroyers (DDG-51) appeared to be representative of the wider fleet. For example, their distribution across operational areas closely mirrors

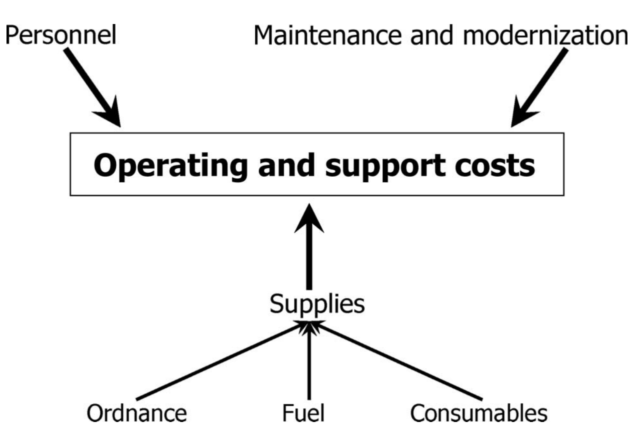

Figure 1. Categories of operating and support costs for a US Navy ship (modified from Guimond et al. 2006).

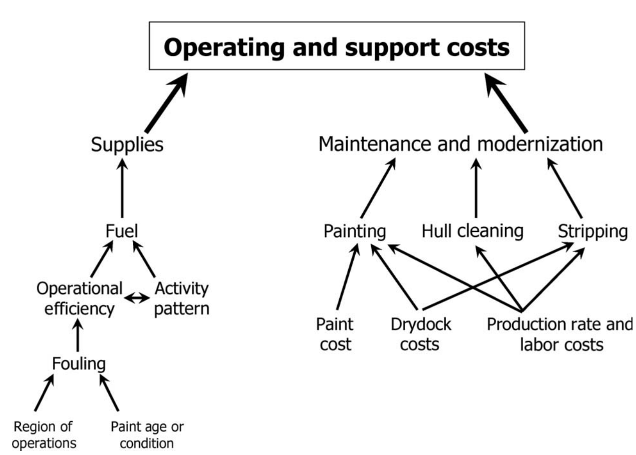

Figure 2. Components of operating and support costs that are directly related to condition of the hull.

that of the fleet as a whole. Also, the DDG-51 class represents a significant portion of the fleet in terms of both number of hulls and total wetted hull area. Excluding submarines, the DDG-51 class currently makes up 30% of the fleet by count and 22% by wetted hull area, and this makes it the largest surface ship class in terms of both number of hulls and total wetted hull area. Based on its aforementioned distribution across home ports in differing geographical regions and abundance in terms of both number of hulls and wetted hull area, the present modeling effort focused on the DDG-51 class as representative of the wider US Navy fleet. Further discussion of fleet distribution and hull demographic data is available in Bendick et al. (2010).

Fouling of underwater hulls

Significant costs to ship operations are associated with the occurrence of fouling on the underwater hull, as a result of increases in hull roughness, drag, and corresponding fuel use. Clearly, any model of the potential costs and benefits of particular fouling control strategies must account for the occurrence and dynamics of hull fouling. The Naval Ships' Technical Manual (NSTM) (2006) provides instructions for the regular conduct of underwater hull inspections for fouling and coating damage. Divers note the Fouling Rating (FR, Table 1) and coverage of fouling on multiple sections of the hull, propellers, struts and rudders, and seachests. The results of these inspections are recorded in a database. In order to develop model parameters for the fouling level on the ships' hulls, this database was examined in detail. In the present work, the occurrence of fouling on DDG-51 class hulls was investigated by means of 320 individual inspection reports spanning a 3-year period from 1 January 2004 to 31 December 2006.

Initial analyses of these data (not shown) indicated that the distribution of FR values, and level of coverage, was skewed with most ships being relatively lightly fouled. Median tests suggested fouling intensity varied across home ports; however, the temporal components of variation associated with, for example, paint age or time since last hull cleaning, were small. Given that important temporal variation in fouling was absent, and that DDG-51 class vessels were distributed broadly across geographical regions (thus spanning geographical variation in fouling intensity), it was decided to represent hull fouling in the model as a single value characteristic of the hull class as a whole.

Detailed analyses of the inspection reports (Bendick et al. 2010) suggest that the majority of DDG-51 hulls support some macrofouling capable of generating significant roughness and thus increasing drag and fuel use. Maximum values of the fouling rating ranged from 10 to 100 with distributions (by section of the hull) typically featuring a broad peak from FR-30 to FR-70. The most frequent value of the second highest fouling rating was FR-30 in all cases. The spatial extent of the maximum fouling rating was low (usually 10% or less of the hull) and did not differ greatly among sections of the hull. The relationship between drag and the spatial distribution of roughness elements for these low coverage levels is highly nonlinear and extremely complex (Kempf 1937; Schultz, personal observation). Consequently, the fouling condition of the typical DDG-51 hull was characterized as FR-30, with an upper bound of FR-60.

Table 1. A range of representative coating and fouling conditions as given by Schultz (2007). The NSTM rating is a fouling index used by the US Navy based on Naval Ships' Technical Manual Chapter 081 (NSTM 2006).

Description of condition	NSTM (FR rating[a])
Hydraulically smooth surface	0
Typical as applied AF coating	0
Deteriorated coating or light slime	10–20
Heavy slime	30
Small calcareous fouling or weed	40–60
Medium calcareous fouling	70–80
Heavy calcareous fouling	90–100

[a]NSTM (2006).

Waterborne underwater hull cleaning

Waterborne underwater hull cleaning allows for the removal of fouling accumulations on hulls and propellers without drydocking. Appropriate use of these cleanings increases the availability of the ship to the fleet and extends the life of the hull coating system while minimizing maintenance costs associated with drydocking. Waterborne hull cleaning also recovers performance or operating efficiency (in terms of fuel expenditures) lost due to fouling accumulation, to a condition similar to that of a clean hull.

Since the effects of fouling on performance vary among ship classes, and the intensity of fouling differs with type of hull coating, operational profile and area of operations of the vessel, the Navy does not specify intervals for the conduct of hull cleanings (Naval Ships' Technical Manual 2006). Instead, the decision on whether to clean is based on the results of regular inspections. A full hull cleaning is called for when fouling occurs at a rating of FR-40 $>$ 20% of the hull (for ablative AF paints) or FR-50 $>$ 10% of the hull (for fouling-release coatings) (Naval Ships' Technical Manual 2006). Performance criteria can also be used to indicate the need for a hull cleaning, including a 1 knot reduction in speed at constant shaft revolutions, an increase in fuel use of 5% to maintain a specified rate of revolution of the shaft, and an increase in shaft revolution rate of 5% to maintain a particular speed (Naval Ships' Technical Manual 2006).

Several types of waterborne cleaning are available to restore performance (Naval Ships' Technical Manual 2006). In a Full Cleaning, fouling is removed from the entire underwater hull, propellers, shafts, struts and rudders, and all openings. Interim Cleaning refers to removal of fouling from propellers, shafts, struts and rudders. Partial Cleaning covers removal of fouling from particular sections of the ship hull, and can be performed in combination with an Interim Cleaning.

In order to estimate costs associated with waterborne hull cleaning, the frequency of full, partial, and interim cleanings carried out on the Arleigh Burke-class destroyers was quantified over a 3-year period from 1 January 2004 to 31 December 2006. Data were obtained from the database of ships' hull inspections. Due to their very low frequency, partial cleanings were pooled with full hull cleanings before analysis. Over the reporting period, 46 DDG-51 class vessels underwent 28 full/partial hull cleanings and 282 interim cleanings. The average frequency of full hull cleanings over the study period was 0.21 $year^{-1}$, while the average frequency of interim cleanings was 2.4 $year^{-1}$.

Costs for full/partial and interim hull cleanings vary across ports. Costs used in the model were unweighted averages across the ports based on a NAVSEA contract awarded in 2001 to Seaward Marine Services, Inc. for providing waterborne hull cleaning services. The model estimated current costs by correcting the 2001 contract cost for 8 years of inflation at a rate of 3%. The estimated 2009 cost for a full hull cleaning was $26,808, and for an interim cleaning $18,735. Due to variation in actual annual prices, the actual costs in 2009 and moving into the future may be slightly different. For example, under the current (2010) contract, costs range from $26,200 to $34,200 for a full cleaning and $15,000 to $21,500 for an interim cleaning. It should be noted that a significant portion of these costs is associated with efforts to inspect and document condition of the hull, hull openings, appendages, and running gear.

Prediction of the hydrodynamic impact of hull fouling

In order to predict the impact of hull fouling on the total resistance and powering of the DDG-51, the procedure detailed in Schultz (2007) was employed. In the present work, towing tank test results for a 1:36 scale model of a mid-sized naval surface combatant taken at the US Naval Academy Hydromechanics Laboratory were used to obtain the baseline resistance and powering requirements for the hydrodynamically smooth condition (White, unpublished). The model tested was similar to the DDG-51, the dimensions of which are shown in Table 2.

Estimates of the change in total resistance (ΔR_{Ts}) for an Arleigh Burke class destroyer (DDG-51) as result of hull condition at speeds of 7.7 m s^{-1} and 15.4 m s^{-1} (15 knots and 30 knots) are shown in Tables 3 and 4, respectively. The resulting change in required shaft power (ΔSP) as result of hull condition at speeds

Table 2. Dimensions of the Arleigh Burke-class destroyer (DDG-51).

Waterline length, L_s	142.0 m
Beam, B_s	18.0 m
Draft, T_s	6.4 m
Wetted hull area, S_s	3001 m^2
Displacement, Δ_s	8768 metric tons

Table 3. Predictions of the change in total resistance (ΔR_{Ts}) and required shaft power (ΔSP) for an Arleigh Burke-class destroyer (DDG-51) with a range of coating and fouling conditions at a speed of 7.7 m s^{-1} (15 knots).

Description of condition	ΔR_{Ts} (kN)	ΔR_{Ts}	ΔSP (kW)	ΔSP
Hydraulically smooth surface	–	–	–	–
Typical as applied AF coating	5.2	1%	61	1%
Deteriorated coating or light slime	34	9%	405	9%
Heavy slime	64	17%	766	18%
Small calcareous fouling or weed	110	29%	1325	31%
Medium calcareous fouling	168	44%	2050	47%
Heavy calcareous fouling	261	69%	3274	76%

Table 4. Predictions of the change in total resistance (ΔR_{Ts}) and required shaft power (ΔSP) for an Arleigh Burke-class destroyer (DDG-51) with a range of coating and fouling conditions at a speed of 15.4 m s^{-1} (30 knots).

Description of condition	ΔR_{Ts} (kN)	ΔR_{Ts}	ΔSP (kW)	ΔSP
Hydraulically smooth surface	–	–	–	–
Typical as applied AF coating	66	3%	1533	3%
Deteriorated coating or light slime	182	7%	4300	7%
Heavy slime	303	12%	7202	12%
Small calcareous fouling or weed	485	19%	11699	20%
Medium calcareous fouling	715	28%	17519	30%
Heavy calcareous fouling	1088	43%	27315	47%

of 7.7 m s^{-1} and 15.4 m s^{-1} (15 knots and 30 knots) are also shown in Tables 3 and 4, respectively.

Calculation of fuel consumption and fuel costs

In order to relate the required shaft power predictions to ship fuel consumption, further discussion of the Arleigh Burke-class destroyer (DDG-51) and its operation is required. The DDG-51 is a twin-screw ship powered by four General Electric LM2500 gas-turbine engines. Together these engines produce in excess of 80,000 kW in shaft power. When the ship is underway, there are three common plant operation modes (Brown et al. 2007). The first is the trail-shaft mode in which only one of the gas turbines is operational. In this mode, a single engine powers a single shaft while the other shaft remains idle. This is the most fuel efficient operation mode at cruising speed. The second mode of operation is termed the split-plant mode. In this mode, two engines are online with each powering a separate shaft. The last operational mode is the full-power mode. In this case, all four engines are used with two powering each shaft. This mode is used for high speed operations. For the analysis presented here, it was assumed that the ship operated in trail-shaft mode while cruising at 7.7 m s^{-1} (15 knots) and in full-power mode while steaming at 15.4 m s^{-1} (30 knots). In the full-power mode, it was also assumed that the power supplied by the four engines was equal.

The relationship between the output shaft power of the engine and its fuel consumption can be obtained from the engine's specific fuel consumption (SFC) curve. Figure 3, adapted from Guimond et al. (2006), gives the SFC curve for the General Electric LM2500 gas-turbine engines. By entering Figure 3 with the required shaft power for an engine, the specific fuel consumption (SFC) can be obtained. The SFC is mass of fuel consumed per kW-h. This along with ship operational data can then be used to calculate the mass of fuel consumed.

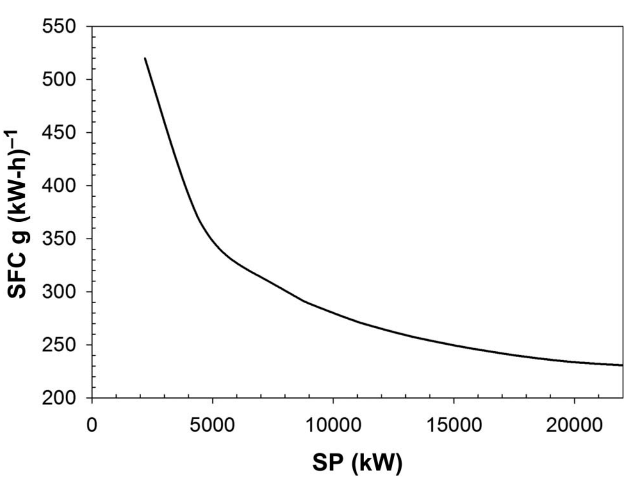

Figure 3. Specific fuel consumption (SFC) curve for the General Electric LM2500 gas-turbine engine adapted from Guimond et al. (2006).

In order to translate results into annual rates of fuel consumption and fuel costs, data on steaming time, proportion of steaming time spent in various powering modes, and fuel costs (per barrel) are required. Analysis of the Navy VAMOSC (Visibility and Management of Operating and Support Costs) database of steaming hours showed that the average steaming time for an Arleigh Burke class-destroyer (DDG-51) was 2835 h per year. Guimond et al. (2006) reported a typical operational tempo for DDG-51 class vessels as ~90% of steaming time at cruising speed (15 knots or 7.7 m s^{-1}) and approximately 10% of steaming time at high speed (30 knots or 15.4 m s^{-1}). For the purposes of the economic model, the direct cost of fuel (distillate fuel marine – DFM) was assumed to be \$104.16 per barrel based on guidance from the Naval Sea Systems Command (NAVSEA) released in December 2008. The indirect cost, or burden, for DFM was taken to be \$59.93 per barrel, based on similar NAVSEA guidance. Note that the direct cost of fuel can vary greatly over time. For example, the NAVSEA guidance for July 2008 was \$170.52 per barrel and for February 2009 was \$69.30 per barrel. Significant changes in fuel prices outside of those due to inflation will affect the performance of the model.

Hull coatings

The underwater hulls of Arleigh Burke class destroyers are painted according to specifications described in Naval Ships' Technical Manual Chapter 631. Ship hull anticorrosive and AF paints are qualified under performance specification MIL-PRF-24647D. The Type II, Class 1, Grade A, Application 3 designation of the performance specification corresponds to two coats (125 μm dry film thickness each) of anticorrosive paint and three coats (125 μm dry film thickness each) of copper ablative AF paint. Shipyard experience with these paints indicates that, depending on the type of paint, approximately 760-910 l is required for a single coat for DDG-51 class vessels. Assuming the wetted area of the DDG-51 class hull is 2951 m^2 (Uniform National Discharge Standards program Nature of Discharge report on hull coating leachate; Uniform National Discharge Standards 1999), this resulted in model entries for paint usage rate of 0.28 l m^{-2} for each coat of anticorrosive paint, and 0.31 l m^{-2} for each coat of AF paint. Characteristic roughness for this coating system as typically applied is $Rt_{50} = 150\ \mu m$ (Schultz 2004). Rt_{50} is the average hull roughness based on hull surveys using the BMT Hull Roughness Analyzer (Medhurst 1990). Repainting was assumed to occur every 7.5 years. Painting costs included only the price of the paint required and labor for surface preparation and application. Although the complete hull coating system is applied in drydock, the model assumed that other maintenance in addition to (re)painting was carried out during the drydock interval, and that all drydocking costs were absorbed by these other maintenance activities.

Other variables

The economic model projected costs over 15 years. This time period was selected so that the costs associated with repainting (assumed to occur every 7.5 years) could be factored into the analysis while not projecting unduly far into the future in which costs become more uncertain. Calculations assumed an annual inflation rate of 3%. Costs associated with environmental compliance and regulatory issues, mission readiness, acoustic signature, mechanical wear, and other technical risks were not incorporated into the economic model. The economic model allowed projection of costs over the whole DDG-51 class (currently 56 ships). All costs are in the fiscal year 2009 US dollars.

Results

Economic impact of hull roughness and fouling

Hull roughness due either to the presence of a coating or to hull fouling incurs an operational cost to the vessel due to increases in shaft power to reach a given speed and associated increases in fuel consumption. The cumulative costs per ship over 15 years for four hull roughness conditions were calculated (Table 5). These include an ideal hydraulically-smooth paint (Case 1), a newly applied Navy-qualified ablative AF coating with no fouling (Case 2), a typical hull roughness given the Navy's present practices including qualified ablative AF coatings and regular interim and full hull cleanings (Case 3), and a scenario featuring an upper bound for hull fouling (Case 4). See the section 'Fouling of underwater hulls' above for details of how the 'typical' and 'upper bound' fouling scenarios were determined.

The hydraulically-smooth hull scenario (Case 1, Table 5) served as the baseline for all other cases and the scenarios described in the Results section. In this scenario, the baseline cost for propulsive fuel is approximately \$11.1M per ship per year, but there is no additional fuel cost resulting from hull paint roughness or fouling. The cumulative costs over 15 years (Figure 4), over and above the baseline cost, are entirely due to surface preparation and painting and amount to approximately \$0.45M per ship. The Navy's qualified ablative AF hull coatings generate additional hull roughness ($Rt_{50} = 150\ \mu m$) even when unfouled (Case 2, Table 5). In this case, the 15 year cumulative cost (over the baseline cost) is approximately \$3.33M per ship (Figure 4). Despite the vessel remaining free of fouling, the typical paint roughness of as-applied AF coatings leads to an increase in fuel consumption of 1.4% per year, or about \$0.15M per ship per year.

Cases 3 and 4 (Table 5) demonstrate the enormous effect of fouling on fuel consumption and subsequent operating costs. The 15 year cumulative cost (over baseline) for operations under current Navy hull maintenance practices is approximately \$22.7M per ship (Figure 4). The largest source of this cost is increased fuel consumption due to hull fouling (see below for analysis of painting and hull cleaning costs). The NSTM fouling rating for this case, FR-30, is indicative of heavy slime and no hard fouling. Based on the present analysis, this level of fouling generates an increase of 10.3% in fuel consumption relative to the hydraulically-smooth condition of Case 1. This increase equates to a present-day cost of approximately \$1.2M per ship per year. For the worst-case scenario (Case 4), representing a ship operating with a mixed community of relatively small hard fouling organisms (FR-60), the cumulative cost over 15 years from coating roughness and fouling is approximately \$43.8M per ship (Figure 4). As with the previous case, this cost is overwhelmingly due to increased fuel

Table 5. Four hull roughness and fouling scenarios for the Arleigh Burke class-destroyer (DDG-51).

Scenario	Coating description	Fouling level	Interim cleaning frequency (year^{-1})	Full cleaning frequency (year^{-1})
Case 1	Hypothetical hydraulically-smooth ablative copper AF	FR-0	0	0
Case 2	Ablative copper AF, as typically applied (Rt_{50}=150 μm)	FR-0	0	0
Case 3	Ablative copper AF, as typically applied (Rt_{50}=150 μm)	FR-30	2.4	0.21
Case 4	Ablative copper AF, as typically applied (Rt_{50}=150 μm)	FR-60	2.4	0.21

consumption resulting from hull fouling. Hull fouling of FR-60 causes an increase of 20.4% in fuel consumption compared to the hydraulically-smooth condition. This equates to a present-day cost of approximately $2.3M per ship per year.

Economic impact of changes in maintenance practices

The previous section focused on costs associated with coating roughness and varying levels of fouling on the underwater hull. While accumulation of fouling (and corresponding increases in hull roughness, drag, and fuel use) can be mitigated through proper maintenance (for example, application of AF or fouling-release hull coatings, hull cleaning), maintenance practices have their own associated costs. The sensitivity of the economic model to changes in two maintenance variables was examined. These variables are the price of the fouling-control coating and the frequency of waterborne underwater hull cleanings.

The present economic analysis models hull coatings as a two layer system; one layer of anticorrosive coating and one layer of a fouling-control topcoat. Both layers can consist of several coats, the number of which is allowed to vary in the model. The effect of price of the fouling-control coating on operating and support costs was examined by projecting cumulative costs over 15 years, for topcoats costing approximately 2, 4, and 8 times that of the current US Navy AF paint. No other variables were altered; the complete protective system consisted of the same number of coats, the cost of the anticorrosive coating was held constant, the alternative topcoats had the same inherent roughness as the current paints and had no differential effect on accumulation of fouling. Under these conditions, change in the cost of the fouling-control coating had only a small effect on cumulative operational costs (Figure 5). For example, increasing the topcoat price by a factor of approximately 8.5 increased the cumulative operational costs over 15 years by only 3.9%. If more expensive coatings result in a significant long-term reduction in hull fouling, then substantial cost savings may be realized despite increased coating cost.

The economic analysis also includes costs and frequencies for two types of waterborne underwater hull cleanings, full and interim, with average frequencies of 0.21 year^{-1} and 2.4 year^{-1}, respectively. The sensitivity of operating and support costs to variation in the frequency of full hull cleanings was explored. This was carried out both with the frequency of interim cleanings held constant, and with the frequency of interim cleanings adjusted on a 1:1 basis to account for changes in frequency of the full hull cleanings. Cumulative costs were again projected over 15 years, while multiplying the frequency of full hull cleanings by approximately 0.5, 1 (ie actual values), 2 and 4. No other variables, including fouling rating of the hull, were altered. As with paint cost, change in the frequency of underwater hull cleanings, with no change in the accumulation of fouling, had little effect on cumulative operational costs (Figure 6). Cutting the frequency of full hull cleanings in half resulted in a 0.24% savings when the frequency of interim cleanings

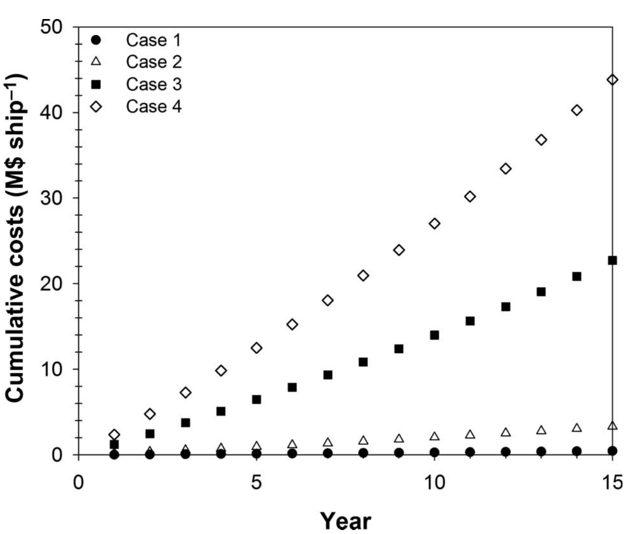

Figure 4. Cumulative costs (per ship) over 15 years resulting from coating roughness and fouling. See Table 5 for descriptions of the cases.

Figure 5. Effect of paint price on cumulative operating costs over 15 years. Variation in paint price is expressed as a multiple of the standard price of the fouling-control topcoat [Paint price$_{(O)}$]. Change in cumulative operating costs is expressed as a percentage of the cumulative costs assuming the standard topcoat price.

was unchanged and a 0.07% savings when frequency of interim cleanings was adjusted to account for the decrease in frequency of full hull cleanings. A four-fold increase in frequency of full hull cleanings resulted in a 1.4% increase in cumulative costs when interim cleaning frequency was held constant, and a 0.4% increase when frequency of interim cleanings was decreased on a 1:1 basis with increase in full hull cleanings (Figure 6). Given that full hull cleanings result in vessels initially operating with less fouled (and thus smoother) hulls, it seems likely that changes in the frequency of hull cleaning may yield significant increases in operational cost if cleaning frequency decreases, or decreases in operational cost if cleaning frequency increases. However, increases in cleaning frequency must be balanced against the effects of the cleaning tools on coating physical condition and service life.

Economic impact of a novel maintenance approach (proactive hull cleaning)

Waterborne hull cleaning is typically a response to increased hull fouling with hulls being cleaned once they reach a condition where efficient ship operation is compromised. Tribou and Swain (2010) proposed a proactive approach to waterborne hull cleaning wherein the hull is cleaned at high frequency (for example, once every few days) using less aggressive tools than those usually employed, with the goal of maintaining the hull at a very low fouling rating. Results of initial trials suggested that light cleaning of the Navy's qualified ablative AF coatings every 3 to 24 days allowed only a light biofilm (FR-10 to FR-20) to form on the painted surface (Tribou and Swain 2010). The method of proactive cleaning or 'grooming' of the hull by small autonomous underwater vehicles ('Hull BUG', hull bio-inspired underwater grooming vehicle, under development by SeaRobotics Corporation, Palm Beach Gardens, Florida, USA) may generate cost savings if ships can be maintained at lower than typical fouling ratings without greatly increasing cleaning expenses or decreasing the coating lifespan.

The costs associated with use of the Hull BUG strategy were calculated for a range of fouling ratings that could plausibly be achieved by the device. This analysis assumed that hull grooming required three units per ship, with an annual maintenance cost of \$5K per unit. The Hull BUG strategy was simulated as a single full hull cleaning per year with a cost equivalent to the annual maintenance costs of the vehicles required (ie $3 \times \$5K = \$15K$). No acquisition costs for the Hull BUG units were included. It was assumed that use of Hull BUG would not change the frequency of interim cleanings, which focus on parts of the ship not readily accessible to the vehicles. It was also assumed that Hull BUG had no effect on the physical condition of the hull coating or the frequency of repainting. The results of the economic analysis suggested that the Hull BUG approach could provide substantial cost savings over current Navy practices if hull fouling were reduced (Figure 7). Hull BUG is

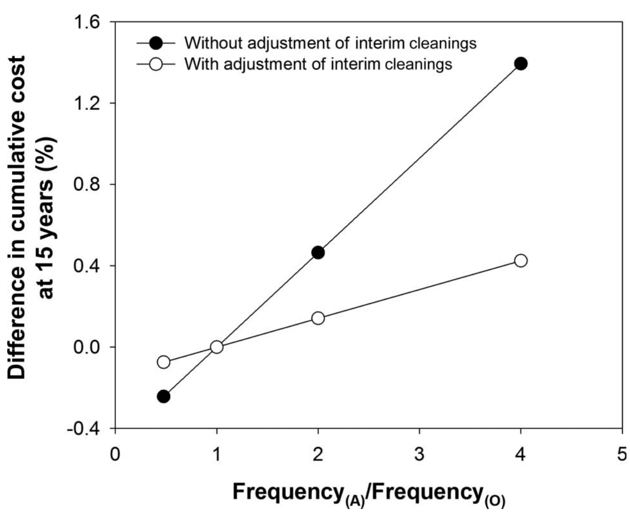

Figure 6. Effect of frequency of full hull cleanings on cumulative operating costs over 15 years. Variation in cleaning frequency is expressed as a multiple of the current mean frequency of full hull cleanings [$Frequency_{(O)}$]. Change in cumulative operating costs is expressed as a percentage of the cumulative costs assuming standard maintenance practices.

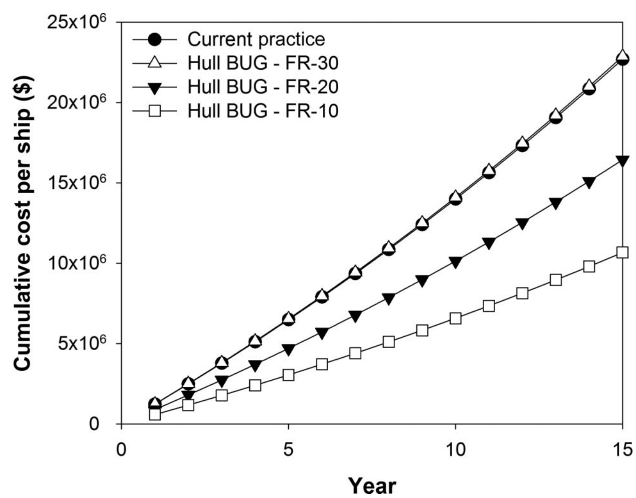

Figure 7. Cumulative costs (per ship) over 15 years for current hull coating and maintenance practices or maintenance using the Hull BUG strategy. Results for Hull BUG were calculated for three levels of efficacy (FR-10, FR-20, FR-30).

expected to maintain hulls at lower fouling ratings (FR-10 to FR-20) than appear achievable using the combination of ablative AF coatings and reactive hull cleaning (which maintains DDG hulls at FR-30). Savings ranged from approximately \$6.2M per ship over 15 years if Hull BUG achieved FR-20, to \$12M per ship over 15 years for FR-10 (Figure 7). If, however, use of the Hull BUG strategy resulted in no change in average fouling ratings (FR-30), cumulative costs (per ship) were comparable to those for current practices ($\sim$\$174K more expensive over 15 years, Figure 7). This is because the annual maintenance cost for three Hull BUG vehicles is greater than the fractional cost of a full hull cleaning.

Discussion

The analyses presented above indicate that the primary cost associated with hull fouling is due to increased fuel consumption attributable to increased frictional drag. The cost of propulsive fuel for the baseline, hydraulically-smooth DDG-51 class hull is \$11.1M per ship per year. Increasing fouling to FR-30, a level typical of the DDG-51 class as a whole, increases fuel consumption by 10.3% and fuel costs by approximately \$1.15M per ship per year. Costs associated with hull fouling increase in a nearly linear fashion for fouling ratings less than or equal to FR-70 (Figure 8). The effect of increasing fouling to the next highest FR (for example, from FR-20 to FR-30), with no corresponding change in expenses due to paint, hull cleaning, or other management practices, amounts to approximately \$300K–\$400K per ship per year. In contrast, increasing the cost of the AF paint by a factor of 8.5, without

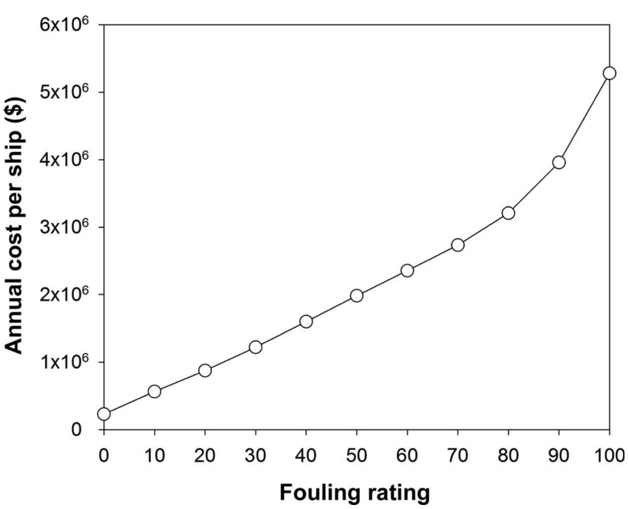

Figure 8. The annual costs (per ship) for a range of hull fouling levels (FR). The cleaning and coating costs are assumed to be the same as present practice (Case 3).

realizing any improvement in hull condition from FR-30, only increases annual costs by roughly \$47K per ship when painting costs are spread evenly across the 7.5 year repaint interval. Increasing the frequency of hull cleanings has an even smaller effect on cost (Figure 6). The present economic analysis predicts a cost associated with hull fouling for the Navy's present hull husbandry practices (Case 3, Table 5) of approximately \$56M per year or \$1.0B over 15 years for the entire DDG-51 class. If the entire DDG-51 class were to operate at the upper bound for fouling identified previously (Case 4, Table 5), these costs jump to \$119M per year or \$2.2B over 15 years.

The economic model and resulting cost estimates can also be used to project costs due to hull fouling for the fleet as a whole. Due to the fact that the US Navy fleet is composed of a diverse array of vessels representing a range of hull types, powering characteristics (conventional and nuclear), and operational tempos, all fleet-wide projections reported below are laden with a number of important assumptions the effect of which is not clearly understood. In particular, fleet-wide cost estimates from the economic analysis assume that operational patterns or tempos, and the relationship between operational tempo and power demand, is the same across all ship classes. This assumption fails for the Navy's nuclear aircraft carriers, at a minimum. A second important assumption relates to the contribution of fouling to total drag. Hull fouling primarily influences frictional drag, a component of the total drag. The proportion of total drag due to frictional drag will vary with ship class or hull form, but is assumed to be constant in the fleet-wide economic analysis. The fleet-wide economic analysis does, however, accurately account for differences among vessel classes in costs due to painting and cleaning. In addition, very crude estimates of cost can be derived by simply scaling the costs for the DDG-51 class to the fleet as a whole, on the basis of either number of ships, where the Arleigh Burke-class represents 30% of the fleet (see above), or wetted hull area, where the class represents 22% of the fleet (see above). A range of annual costs due to hull fouling for the entire US Navy surface fleet was calculated using these three methods. If the entire fleet operated with hulls in a condition typically seen for current Navy husbandry practices (Case 3, Table 5), the fleet-wide annual cost due to hull fouling would probably fall within the range of \$180M–\$260M. If the typical condition of all hulls is the upper band for fouling identified previously (Case 4, Table 5), the projected costs increase to between \$400M–\$540M annually. However, because of the aforementioned assumptions, the fleet-wide fouling penalty costs given here should be used with considerable caution. Similarly, it seems likely that the US Navy's ship hull fouling penalty would be dwarfed by that of the total world fleet, given that the US Naval fleet represents less than one-half of 1% of the world fleet in terms of number of ships (ie ships >400 metric tons), although some types of commercial vessels appear to operate with less fouling on their hulls than would be expected for a naval vessel (eg Davidson et al. 2009).

The present results imply that even modest improvements in the fouling condition of a hull, when considered across just the DDG-51 class, could save enough money to cover the costs of development, acquisition, and implementation of even relatively expensive technical or management solutions. As demonstrated above, a decrease in fouling from FR-30 to FR-20 results in an annual cost savings to the Navy of ~$340K per DDG-51, or approximately $19M over the entire DDG-51 class. Therefore, a $19M investment in research, development, and acquisition for a technology (eg novel hull treatment, cleaning device, or combination of approaches) or management practice (eg change in frequency or timing of hull cleanings) that reduced the typical fouling throughout the DDG-51 class from FR-30 to FR-20 would be paid back in 1 year. Costs savings if the technology or practice were implemented throughout the entire fleet would presumably offset even larger expenditures. The economic analysis presented here can thus be used to provide a guide to the amount of money that can reasonably be spent to combat hull fouling, and can aid in identifying areas of research in fouling control that would result in the greatest benefit, in terms of cost savings, to fuel use during ship operations.

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References

Abbott A, Abel PD, Arnold DW, Milne A. 2000. Cost-benefit analysis of the use of TBT: the case for a treatment approach. Sci Tot Environ 5–19.

Alberte RS, Snyder S, Zahuranec BJ, Whetston M. 1992. Biofouling research needs for the United States Navy: program history and goals. Biofouling 6:91–95.

Aldred N, Li G, Gao Y, Clare AS, Jiang S. 2010. Modulation of barnacle (*Balanus amphitrite* Darwin) cyprid settlement by sulfobetaine and carboxybetaine methacrylate polymer coatings. Biofouling 26:673–683.

Andrewartha J, Perkins K, Sargison J, Osborn J, Walker G, Henderson A, Hallegraeff G. 2010. Drag force and surface roughness measurements on freshwater biofouled surfaces. Biofouling 26:487–496.

Atlar M. 2003. More than anti fouling. Mar Eng Rev. March:31–33.

Beigbeder A, Degee P, Conlan SL, Mutton RJ, Clare AS, Pettitt ME, Callow ME, Callow JA, Dubois P. 2008. Preparation and characterisation of silicone-based coatings filled with carbon nanotubes and natural sepiolite and their application as marine fouling-release coatings. Biofouling 24:291–302.

Bendick JA, Schultz MP, Holm ER, Hertel WM. 2010. Economic analysis of underwater hull coatings and maintenance. NSWCCD-63-TR-2010/17. Bethesda (MD): Naval Surface Warfare Center Carderock Division. p. 49.

Benson JM, Ebert JW, Beery TD. 1938. Investigation in the NACA tank of the effect of immersion in salt water on the resistance of plates coated with different shipbottom paints. NACA Memorandum Report C&R C-S19-1(3). Washington (DC): National Advisory Committee on Aeronautics.

Brown GG, Kline JE, Rosenthal RE, Washburn AR. 2007. Steaming on convex hulls. Interfaces 37:342–352.

Champ MA. 2003. Economic and environmental impacts on port and harbors from the convention to ban harmful marine anti-fouling systems. Mar Pollut Bull 46:935–940.

Davidson IC, Brown CW, Sytsma MD, Ruiz GM. 2009. The role of containerships as transfer mechanisms of marine biofouling species. Biofouling 25:645–655.

Denny ME. 1951. B.S.R.A. resistance experiments on the Lucy Ashton: part I – full-scale measurements. Trans INA 93:40–57.

Finnie AA, Williams DN. 2010. Paint and coatings technology for the control of marine fouling. In: Durr S, Thomason JC, editors. Biofouling. Oxford, UK: Wiley-Blackwell. p. 185–206.

Genzer J, Efimenko K. 2006. Recent developments in superhydrophobic surfaces and their relevance to marine fouling: a review. Biofouling 22:339–360.

Granville PS. 1987. Three indirect methods for the drag characterization of arbitrarily rough surfaces on flat plates. J Ship Res 31:70–77.

Grigson CWB. 1992. Drag losses of new ships caused by hull finish. J Ship Res 36:182–196.

Guimond D, Marra J, Pavkov M, Wallace J. 2006. Fuel conservation concepts to achieve life cycle cost reductions for surface ships. Publication NSWCCD-INCEN-TR-2006/01. West Bethesda (MD): Naval Sea Systems Command. p. 74.

Haslbeck EG, Bohlander G. 1992. Microbial biofilm effects on drag – lab and field. Proceedings SNAME Ship Production Symposium. Paper No. 3A-1. p. 7. Jersey City (NJ): Society of Naval Architects and Marine Engineers.

Hundley LL, Tate CW. 1980. Hull-fouling studies and ship powering trial results on seven FF 1052 class ships. Report # DTNSRDC-80/027. West Bethesda (MD): DW Taylor Naval Ship Research and Development Center.

Ista LK, Mendez S, Lopez GP. 2010. Attachment and detachment of bacteria on surfaces with tunable and switchable wettability. Biofouling 26:111–118.

Kempf G. 1937. On the effect of roughness on the resistance of ships. Trans INA 79:109–119.

Leer-Andersen M, Larsson L. 2003. An experimental/numerical approach for evaluating skin friction on full-scale ships with surface roughness. J Mar Sci Technol 8:26–36.

Lewthwaite JC, Molland AF, Thomas KW. 1985. An investigation into the variation of ship skin frictional resistance with fouling. Trans RINA 127:269–284.

Long CJ, Schumacher JF, Robinson PAC, Finlay JA, Callow ME, Callow JA, Brennan AB. 2010. A model that predicts the attachment behavior of *Ulva linza* zoospores on surface topography. Biofouling 26:411–419.

Magin CM, Long CJ, Cooper SP, Ista LK, Lopez GP, Brennan AB. 2010. Engineered antifouling microtopographies: the role of Reynolds number in a model that predicts attachment of zoospores of *Ulva* and cells of *Cobetia marina*. Biofouling 26:719–727.

McEntee W. 1915. Variation of frictional resistance of ships with condition of wetted surface. Trans SNAME 24: 37–42.

Medhurst JS. 1989. The systematic measurement and correlation of the frictional resistance and topography of ship hull coatings, with particular reference to ablative antifoulings [PhD thesis]. UK: University of Newcastle-upon-Tyne.

Medhurst JS. 1990. Outline of a draft international standard for the measurement and characterisation of roughness topography in fluid flow. London: Royal Institute of Naval Architects. March 1990. p. 9.

Musker AJ. 1980–1981. Universal roughness functions for naturally-occurring surfaces. Trans Can Soc Mech Eng 1:1–6.

Naval Ships' Technical Manual. 2006. Chapter 081 – waterborne underwater hull cleaning of Navy ships. Publication # S9086-CQ-STM-010/CH-081 Revision 5. Washington (DC): Naval Sea Systems Command.

Picologlou BF, Zelver N, Characklis WG. 1980. Biofilm growth and hydraulic performance. ASCE J Hydraulics Div 106:733–746.

Schultz MP. 2000. Turbulent boundary layers on surfaces covered with filamentous algae. ASME J Fluids Eng 122:357–363.

Schultz MP. 2004. Frictional resistance of antifouling coating systems. ASME J Fluids Eng 126:1039–1047.

Schultz MP. 2007. Effects of coating roughness and biofouling on ship resistance and powering. Biofouling 23:331–341.

Schultz MP, Swain GW. 1999. The effect of biofilms on turbulent boundary layers. ASME J Fluids Eng 121:733–746.

Schultz MP, Swain GW. 2000. The influence of biofilms on skin friction drag. Biofouling 15:129–139.

Swain G. 1998. Biofouling control: a critical component of drag reduction. Proceedings of the International Symposium on Seawater Drag Reduction. Newport (RI). p. 155–161.

Swain GW, Schultz MP. 1996. The testing and evaluation of non-toxic antifouling coatings. Biofouling 10: 187–197.

Swain GW, Kovach B, Touzot A, Casse F, Kavanagh CJ. 2007. Measuring the performance of today's antifouling coatings. J Ship Prod 23:164–170.

Svenson TE, Medhurst JS. 1984. A simplified method for the assessment of propeller roughness penalties. Mar Technol 21:41–48.

Thomas KV, Brooks S. 2010. The environmental fate and effects of antifouling paint biocides. Biofouling 26:73–88.

Townsin RL. 2003. The ship hull fouling penalty. Biofouling 19(Suppl):9–16.

Townsin RL, Byrne D, Svensen TE, Milne A. 1981. Estimating the technical and economic penalties of hull and propeller roughness. Trans SNAME 89:295–318.

Townsin RL, Spencer DS, Mosaad M, Patience G. 1985. Rough propeller penalties. Trans SNAME 93:165–187.

Tribou M, Swain G. 2010. The use of proactive in-water grooming to improve the performance of ship hull antifouling coatings. Biofouling 26:47–56.

Uniform National Discharge Standards. 1999. Nature of discharge report: hull coating leachate; [cited 2009 Mar 25]. Available from: http://unds.bah.com/Nod/Hullcoat.pdf.

Watanabe S, Nagamatsu N, Yokoo K, Kawakami Y. 1969. The augmentation in frictional resistance due to slime. J Kansai Soc Naval Architects 131:45–51.

Woods Hole Oceanographic Institution [WHOI]. 1952. Marine fouling and its prevention. Annapolis, MD: United States Naval Institute.