Energy and GHG Emissions Savings Analysis of Fluoropolymer Foul Release Hull Coating

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Abstract

The purpose of this project was to review available data on fluoropolymer foul release (FFR) hull coating technology and prepare an analysis of the potential energy, greenhouse gas (GHG), and other emissions savings that may be achieved with this technology. In this report we examine fuel consumption data of three vessel types pre- and post-FFR application. The first vessel type is a tanker represented by a ship called Prem Divya; the second vessel type is a bulk cargo vessel represented by a ship called the Ikuna; the third vessel type is a container vessel where we compare the fuel oil consumption of three new build vessels coated with a tributyltin-free self-polishing copolymer (TBT-free SPC) to two new build vessels coated with FFR; all five container vessels are identical builds. Results indicate that the application of FFR reduced speed-adjusted fuel oil consumption by 10% for the Prem Divya, 22% for the Ikuna, and no change in consumption for container vessels when carrying approximately 10,000 metric tons of extra cargo. If similar fuel efficiency results were realized by all tanker and bulk cargo in the international fleet, annual fuel oil consumption could be reduced by roughly 16 million metric tons (MMT) per year, fuel expenditures could be reduced by \$4.4 to \$8.8 billion per year, and nearly 49 MMT of carbon dioxide (CO_2) emissions could be avoided annually. Furthermore, our analysis shows that reductions in CO_2 emissions are achieved at a negative cost—that is, avoided emissions are coupled with economic benefits to the shipowner. Additionally, we explore the potential fuel oil consumption reductions for other vessel types including ferries, Roll-on/Roll-off (Ro-Ro) vessels, very-large crude carriers (VLCCs), and liquid natural gas (LNG) vessels.

Introduction

The purpose of this project was to evaluate the potential energy, greenhouse gas (GHG), and other emissions savings that may be achieved from the application of FFR hull coating. The project included four tasks: (1) communication, data gathering, and literature review; (2) evaluation of marine vessel fleet characteristics and profile; (3) evaluation of FFR performance; and (4) report development. This report (task 4) presents the results obtained from the completion of tasks 1, 2, and 3.

Literature Review

Energy and Environmental Research Associates (EERA) conducted a literature review to better understand the history and use of antifouling hull coatings. In particular, we present a summary and description of biofouling, antifouling technologies, effectiveness of various antifouling coatings, environmental effects of antifouling coatings, and shipowner requirements for antifouling coatings.

Fluoropolymer foul release (FFR) hull coatings can be applied to vessels to mitigate biofouling. Biofouling is the presence of organisms attached to surfaces immersed in the ocean, in this case vessel hulls (Dennington, 2010; Yebra, Kiil, & Dam-Johansen, 2003). Biofouling increases drag and therefore also increases fuel use and emissions (Dennington, 2010; Hopkins, Forrest, & Coutts, 2010; Kane, 2010; Kattan, 2010; Yebra et al., 2003). Fuel costs can be as much as 50-60% of operating costs; therefore, loss of fuel-efficiency due to biofouling is a major concern for vessel owners and operators (Kattan, 2010). Shipowners apply various antifouling coatings to their vessels to help reduce biofouling. Antifouling coatings reduce average hull roughness, thereby increasing hydrodynamic efficiency, leading to reduced fuel consumption and greenhouse gas (GHG) emissions.

Fluoropolymer foul release coating is biocide-free and allows organisms to attach to vessels when stationary but these organisms are detached when the vessel is underway (and traveling at high enough speed) due to hydrodynamic forces (Dennington, 2010). Other antifouling coatings contain biocides and include organotin compounds like tributyltin (TBT); non-TBT self-polishing copolymers (SPC); and copper (Kattan, 2010; Yebra et al., 2003). These coatings react with seawater to release biocides and help reduce biofouling. Coatings containing TBT have been banned and no vessel is currently allowed to use TBT as a biocide (European Parliament, 2003; International Maritime Organization, 2001). Antifouling performance with TBT was excellent but there were serious environmental concerns; current SPC technology does not perform as well as TBT-based coatings (Kane, 2010; Kattan, 2010).

Hopkins and Forrest (2010) studied the effectiveness of a rosin-based (ablative) antifouling coating on slow-moving (between 5 and 7.5 knots) barges and tugs in New Zealand. Rosin-based antifoulings dissolve in seawater releasing biocides (Dennington, 2010). Hopkins and Forrest (2010) found that the effectiveness of the antifouling depended on a number of factors including paint condition, length of time the vessel was stationary, frequency of vessel usage, and the length of time since the antifouling was applied. Specifically, the researchers found that the lowest level of biofouling was found on main hull areas where antifouling paint was in good condition. Biofouling can have a significant impact even when only small areas of the hull are affected (Dennington, 2010; Kattan, 2010).

Shipowners have cited cost, performance, life, and durability as key characteristics for effective antifouling coatings (Drew, King, McKenna, & Waddams, 2010; Kattan, 2010). Most ships (90-95%) are still coated with traditional (biocide) antifouling coatings but approximately 10% of new ship builds will use foul release coatings (FRCs) (Kattan, 2010). An advantage of FRCs, including FFR, is the absence of biocides. Biocides can face barriers from regulations due to environmental quality concerns (European Parliament, 1998; International Maritime Organization, 2001). First-generation FRCs faced problems with an inability to prevent slime buildup on container vessels, but new technologies are addressing that problem (Kattan, 2010). A remaining concern for FRCs is the fouling of areas with low water flow

(Dennington, 2010), but traditional antifouling coatings experience similar problems in what Hopkins and Forrest (2010) and Hopkins et al. (2010) describe as “niche” areas including dry-docking support strips and gratings. If FRCs can outperform traditional antifouling coatings, then shipowners will be more likely to adopt this emerging technology.

Methodology

This section describes the methodology of the analysis. EERA received data from International Paint for three vessel types: a tanker vessel called the Prem Divya; a bulk cargo vessel called the Ikuna; and five container vessels. The data from International Paint was provided to them by Mercator Lines Ltd. for the Prem Divya, Inco Ships Pty. Ltd. for the Ikuna, and a confidential source for the container vessels (International Paint, 2010). The attributes for the vessels are found in Table 1.

Table 1: Attributes of the vessels examined in this report: Prem Divya and Ikuna, and container vessels.

	Tanker	Bulker	Container Vessels				
Vessel Name	Prem Divya	Ikuna	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5
IMO Number	9138599	8512073	Confidential	Confidential	Confidential	Confidential	Confidential
Engine Builder	Dalian	Daihatsu	B&W	B&W	B&W	B&W	B&W
Engine Layout	In Line	In Line	In Line	In Line	In Line	In Line	In Line
Engine Make	Sulzer	Daihatsu	B&W	B&W	B&W	B&W	B&W
Engine Model	7RTA62U	6DLM-32	12K98MC	12K98MC	12K98MC	12K98MC	12K98MC
Number of Engines	1	2	1	1	1	1	1
Engine Stroke	2	4	2	2	2	2	2
Total Engine hp	21,128	3400	92,048	92,048	92,048	92,048	92,048
Total Engine kW	15,540	2500	68,640	68,640	68,640	68,640	68,640
Engine Type	Motor Diesel	Motor Diesel	Motor Diesel	Motor Diesel	Motor Diesel	Motor Diesel	Motor Diesel
Operating Speed (kts)	15.3	13.5	25	25	25	25	25

Prem Divya Fuel Oil Consumption Methodology

To evaluate the impact of paint treatment (applying the fluoropolymer foul release [FFR] coating) on fuel oil consumption for the Prem Divya, EERA applied a multiple regression model to an extensive dataset provided by International Paint on behalf of Mercator Lines Inc. (International Paint, 2010). EERA applied this analysis only to the data associated with the ship while at sea, and only in cases where there was non-zero fuel consumption in order to eliminate fuel consumption associated with port maneuvering. For the analysis, EERA accounted for other factors that could influence fuel consumption, including: “Wind Force,” “Sea State,” and “Loaded/Ballast” condition. For “Wind Force,” the empirical value in the dataset corresponds to the Beaufort Wind Force Scale (ranging from 1-8). For “Sea State,” a value of 1 to 5 was assigned based on the qualitative assessment in the dataset, as follows: calm = 1, slight = 2, moderate = 3, rough = 4, very rough = 5. Several samples had multiple inputs for the “Sea State” data field; in these cases, we used the lowest value. For example, if the data entry said “moderate/rough,” then we used “moderate.” This occurred in less than 1% of the cases.

Additionally, EERA took two steps regarding the dependent variable, which in this case is the fuel oil consumption by the main engines (FOC ME). The first step was to normalize fuel consumption based on vessel speed. This was achieved by applying the following formula to the FOC ME variable:

$$FOC\ ME_{norm} = FOC\ ME_i \cdot \left(\frac{Speed_{norm}}{Speed_i}\right)^3$$

This equation converts the main engine fuel oil consumption for data entry *i* ($FOC\ ME_i$) to a normalized value. For this analysis, we used a speed of 14.0 knots (kts) for the normalized speed ($Speed_{norm}$); that is, fuel oil consumption for each entry was adjusted to reflect the theoretical consumption that would have occurred at a speed of 14.0 kts.

The second step involved normalizing the main engine fuel oil consumption by distance. This was achieved by dividing the $FOC\ ME_{norm}$ value from above by the distance traveled for that entry. This provides a fuel consumption value in terms of kilograms per nautical mile (kg/nm). This value was defined as our dependent variable in the regression model. The multiple regression model is expressed as follows:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$$

where,

Y	is the dependent variable and is a measure of speed- and distance-adjusted main engine fuel oil consumption in kilograms per nautical mile;
X_1	is a dummy variable for the paint treatment and takes the value of "1" if the treatment is applied ("Post") and "0" if the treatment is not applied ("Pre");
X_2	is a value for "Wind Force" ranging from 1-8, discussed above;
X_3	is the "Sea State Rating" ranging from 1-5, discussed above; and
X_4	is a dummy variable for the loaded condition and takes the value of "1" for "Loaded" and "0" for "Ballast."

Results of the multiple regression analysis of fuel oil consumption for the Prem Divya are shown in Table 5 and Figure 1 in the results section. The coefficient of the X_1 term in the regression gives us the impact of the treatment on the dependent variable (Y). Here, this coefficient is interpreted as the reduced fuel oil consumption (in kg/nm) due to application of the hull coating. The fuel oil consumption value is converted to "percentage fuel savings" for later analysis by dividing the post-FFR fuel oil consumption by the pre-FFR fuel oil consumption, subtracting that value from "1," and multiplying by "100."

Ikuna Fuel Oil Consumption Methodology

The dataset for the Ikuna was not as complete as the Prem Divya and an alternative analytical method had to be used. To evaluate the impact of FFR coating on fuel oil consumption, EERA evaluated speed-adjusted fuel oil consumption (in kg/nm) for the vessel while at sea before and after the coating was applied. For this analysis we used a speed of 11.0 kts. A two-tailed Student's t-test[1] was used to evaluate the statistical significance of any differences found between these two conditions ("Pre" and "Post"). As above, differences were converted to a percentage of fuel consumption savings. Results of the t-test for the Ikuna are shown in Table 8, Figure 3, and Figure 4 found in the results section.

Container Vessel Fuel Oil Consumption Methodology

EERA used data provided by International Paint from a confidential source to compare the fuel oil consumption of five identical container vessels over one year of operation. Three of the vessels were coated with tributyltin-free self-polishing copolymer (TBT-free SPC) hull coating and two were coated

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[1] To be conservative, we assumed unequal variances between the two samples ("Pre" and "Post"). We also use a 95% confidence level for our significance test.

with FFR. We compared the fuel oil consumption of the vessels coated with FFR to that of the vessels coated with TBT-free SPC adjusting for speed. As with the Ikuna, we used a two-tailed Student's t-test to evaluate the statistical significance of any differences found between the fuel oil consumption of the TBT-free SPC coated vessels to the FFR coated vessels. Results of the analysis can be found in Table 12 and Figure 6 in the results section.

Fuel Oil Consumption Reductions for Other Vessel Types

International Paint provided EERA with some data for fuel oil consumption reductions based on vessel type. There was insufficient data for each vessel type to use comparative statistical analysis tools with confidence. Therefore, we present the average fuel oil consumption reductions after the application of FFR for bulk cargo vessels, ferries, product tankers, roll-on/roll-off (Ro-Ro) vessels, very-large crude carrier (VLCC) vessels, and liquid natural gas (LNG) vessels in Table 13.

Prem Divya, Ikuna, and Container Vessel Fuel Cost, Greenhouse Gas, and Cost-Effectiveness Methodology

Using the fuel oil consumption results from the Prem Divya, Ikuna, and container vessel analysis, EERA calculated annual fuel cost savings, greenhouse gas (GHG) emissions avoided, and cost-effectiveness for (a) individual vessels with characteristics similar to the Prem Divya and Ikuna and (b) the international fleet of similar vessels. EERA did not calculate annual fuel costs savings, GHG emissions avoided, and cost-effectiveness for the container vessels because we were unable to claim any difference in fuel oil consumption between those vessels coated with TBT-free SPC compared to those coated with FFR at the 95% confidence level. Please note that applying the historical regression to predict annual fuel consumption savings *assumes no change in operating behaviors*.

Fuel Cost Savings

Fleet-wide fuel cost savings were calculated by first obtaining the annual fuel consumption of the fleet by vessel type (i.e. tanker or bulk cargo) from the International Maritime Organization (IMO), shown in Table 7 and Table 10. Assuming similarity in performance among vessels, regression results can be used to estimate the percentage (%) of annual fleet-wide fuel consumption reductions by vessel type after the application of FFR. Fleet-wide annual fuel consumption reductions were multiplied by a range of heavy fuel oil (HFO) fuel prices, shown in Table 2, to estimate annual fleet-wide cost savings.

For individual vessels, fuel cost savings were estimated by multiplying the change in fuel consumption for each vessel by the average distance traveled by the vessel annually to estimate the total annual change in fuel consumption. The estimated change in fuel consumption was multiplied by a range of HFO fuel prices, shown in Table 2, to estimate annual savings in fuel cost per vessel.

Table 2: Assumed HFO prices in dollars per metric ton ($/MT)

Year	$/MT
Ten-year Average (2000-2009)	$ 282
2009	$ 387
2008	$ 559

Greenhouse Gas Emissions Avoided

As with the fuel cost savings calculations, the annual GHG emissions avoided due to the use of FFR were calculated using estimated reductions in annual fuel consumption (see Fuel Cost Savings section above). Emissions factors in kilograms per metric ton (kg/MT) for several key GHG and climate-forcing emissions were obtained from the IMO and other sources (see Table 3). To estimate changes in carbon dioxide (CO_2) emissions, annual estimated changes in fuel consumption were multiplied by the CO_2 emissions factor (3130 kg/MT HFO).

Carbon dioxide emissions are not the only GHG or climate-forcing emissions associated with the combustion of HFO. Several other GHGs and climate-forcing emissions are associated with a warming impact (e.g., black carbon [BC], nitrous oxide [N_2O], and methane [CH_4]). Reducing these emissions would be akin to reducing CO_2 emissions even further, in terms of a net impact on the climate. Other emissions are associated with a cooling effect (e.g., sulfur dioxide [SO_2] and organic carbon [OC]). Reducing these emissions could offset GHG reductions. Each of these pollutants have a different relative strength in climate impact per unit of weight, called the global warming potential (GWP) (Lashof & Ahuja, 1990; Shine, Fuglestvedt, Hailemariam, & Stuber, 2005). The GWPs of key emissions are shown in Table 3. As the table shows, N_2O has a much higher GWP than CO_2; however, the N_2O emissions factors (0.08 kg/MT HFO) are much lower than CO_2 emissions factors (3130 kg/MT HFO). We calculate the net climate impact of reducing fuel consumption using the emissions factors combined with the GWP of the GHGs shown in Table 3. These estimates use 100-year equivalents for GWP ratios. Other time horizons can be estimated using shorter time horizons which produce higher CO_2 equivalent GWP ratios, but a shorter time horizon results in greater uncertainty in the ratio. The estimated net global warming impact of combusting one MT of HFO is the emissions of 1221 kg of CO_2 equivalent (CO_2e). We multiply the net GWP impact by the estimated fuel reductions to calculate the annual net change in GHG emissions due to FFR use. Results are shown in Table 7 and Table 10.

Table 3: Emissions factors for HFO fuel consumption (kg/MT) and Global Warming Potential (GWP) of individual GHGs.

GHG/Climate-forcing particle	kg/MT fuel	Global warming potential (100-yr GWP)
CO_2	3130	1
SO_2	54	-40
BC	0.37	680
OC	0.43	-75
PM	6.7	0
N_20	0.08	298
CH_4	0.3	25
Net GWP Impact, 100-yr	1221 kg CO_2e/MT fuel	

Sources: IMO (2009); (Agrawal, Malloy, Welch, Miller, & Cocker, 2008); Lack et al (2009); and Petzold et al (2009, 2010)

Cost-effectiveness Analysis

To calculate the cost-effectiveness of FFR in reducing GHG emissions (\$/MT CO_2 avoided), we calculate the incremental costs of FFR over a ten-year time period. We use data provided by International Paint (Table 4), which includes FFR application and repair costs, as well as application and repair costs of an alternative biocidal antifouling treatment. We subtract the alternative biocidal antifouling costs from FFR costs to obtain incremental costs. We subtract the fuel savings for the ten-year period from the incremental costs for the same time period to obtain net costs or benefits. Fuel savings and repair costs are discounted at 7% per year. We calculate avoided CO_2 emissions for the same time period and divide net costs or benefits by MT CO_2 avoided to estimate \$/MT CO_2 avoided. This calculation could also be done for \$/MT CO_2e, but here we calculate \$/MT CO_2 only. Note that if the fuel cost savings exceed the costs of FFR application and repair, the \$/MT CO_2 could be negative (indicating an overall cost-savings from applying FFR). Results are shown in Table 6 and Table 9. Note that the FFR costs we use are *incremental* application and repair costs compared to alternative biocidal anti-fouling treatment, rather than total costs. Therefore, savings and cost-effectiveness estimates presented in the results may be overstated if compared to a no-treatment scenario.

Table 4: Comparison of FFR and alternative biocide antifouling application costs and repair costs over a ten-year period for the Prem Divya and Ikuna.

	Prem Divya			Ikuna		
Year	**FFR**	**Biocide Alternative**	**Incremental Cost****	**FFR**	**Biocide Alternative**	**Incremental Cost**
0*	$1,160,000	$575,000	$585,000	$215,000	$95,000	$120,000
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	$140,000	$240,000	-$100,000	--	--	--
4	--	--	--	--	--	--
5	--	--	--	$145,000	$85,000	$60,000
6	$500,000	$240,000	$260,000	--	--	--
7	--	--	--	--	--	--
8	--	--	--	--	--	--
9	$140,000	$240,000	-$100,000	--	--	--

*The costs in Year 0 represent the initial application costs for the application of both FFR and the biocide alternative, all other costs relate to repair costs.

**The incremental cost is measured by taking the difference of the FFR cost and the biocide alternative cost. Also, all costs include off-hire costs when the dry-dock period is extended.

Results

Prem Divya Tanker Vessel Results

The results of the multiple regression analysis are shown in Table 5. The results demonstrate a statistically significant decrease in fuel oil consumption due to paint treatment (X_1) (i.e., when the vessel hull is painted with fluoropolymer foul release [FFR] coating) at the 95% confidence level. The model predicts a decrease of 15.58 kilograms of fuel per nautical mile (kg/nm), with a 95% confidence interval of 7.12 to 24.04 kg/nm.[2] Overall, the average fuel oil consumption for the Prem Divya decreased by approximately 10% after the application of FFR as shown in Figure 1.

Table 5: Results of the regression analysis for the Prem Divya.

	Coefficients	p-value	Lower 95%	Upper 95%
Intercept	98.79	2.37e-35	84.21	113.37
Paint Treatment (X_1)	-15.58*	0.0003	-24.04	-7.12
Wind Force (X_2)	5.35	0.1049	-1.12	11.82
Sea State Rating (X_3)	15.59*	0.0041	4.97	26.21
Load (X_4)	0.08	0.9840	-7.85	7.69

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[2] In addition, the results show a statistically significant increase in fuel oil consumption due to sea roughness (sea state rating, X_3) at the 95% confidence level. The predicted value of this increase is 15.59 kg/nm, with a confidence interval of 4.97 to 26.21 kg/nm. Wind force condition (X_2) and loaded condition (X_4) were not found to affect fuel oil consumption in a statistically significant way.

*Significant at the 95% confidence level.

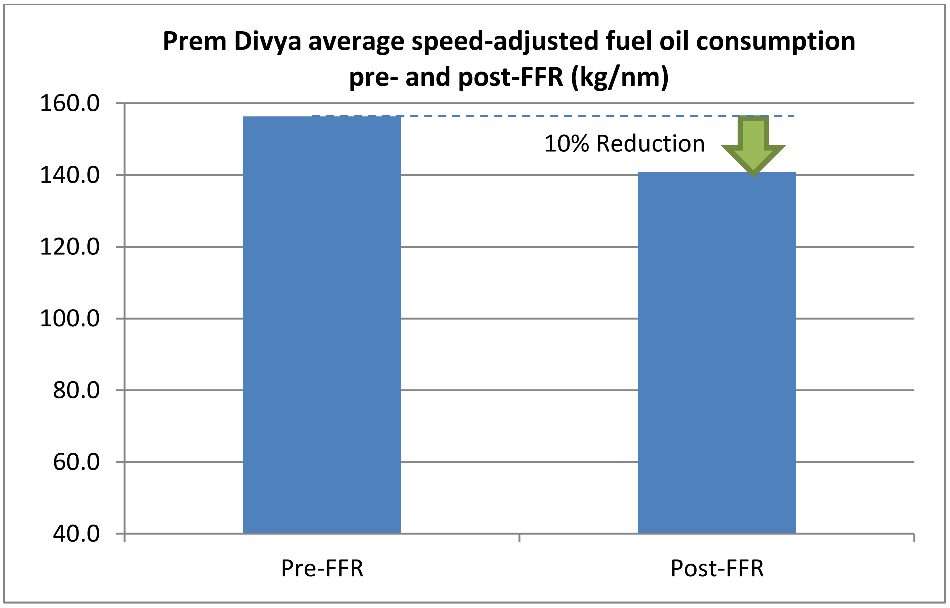

Figure 1: Prem Divya average speed-adjusted fuel oil consumption (kg/nm) pre- and post-FFR application.

The Prem Divya was previously coated with a tributyltin-free self-polishing copolymer (TBT-free SPC). Results indicate that fuel oil consumption was lower due to the FFR coating compared to the TBT-free SPC coating throughout the docking cycle as seen in
Figure 2.

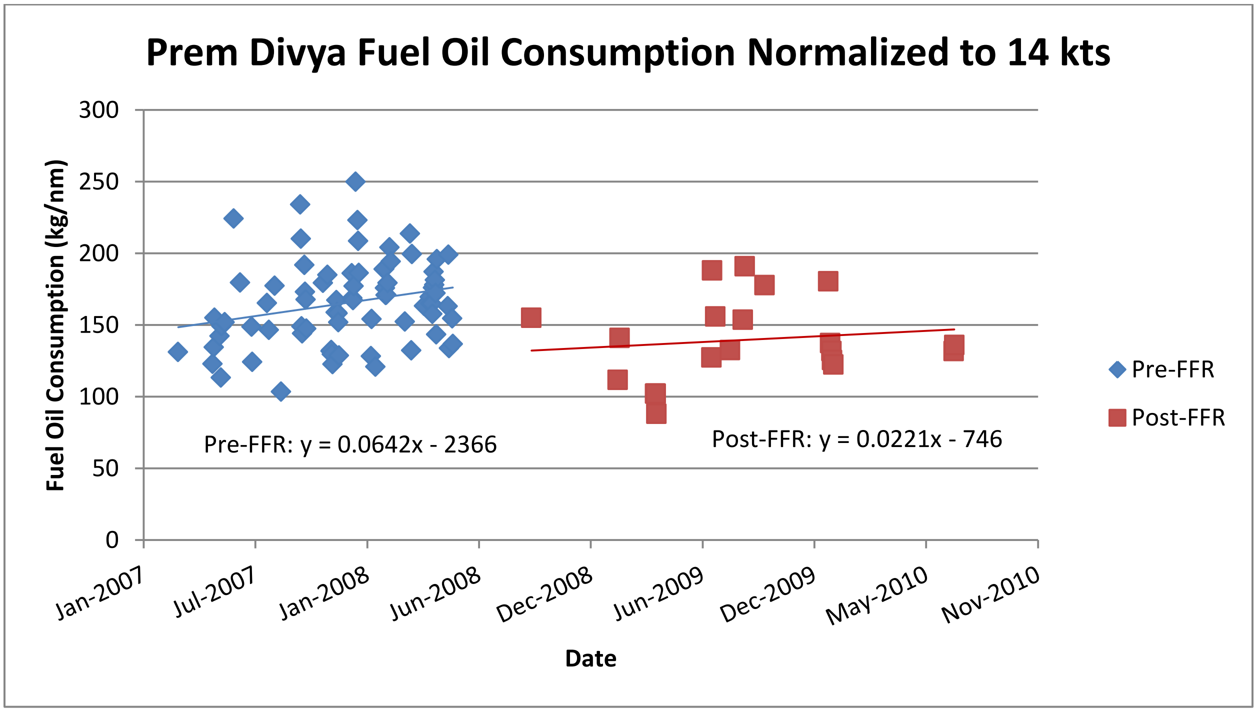

Figure 2: Prem Divya fuel oil consumption normalized to 14 knots (kg/nm) pre- and post-FFR application.

Estimated Impacts on Individual Tanker Vessels with Characteristics Similar to the Prem Divya

The potential impacts on individual tanker vessels with characteristics similar to the Prem Divya are presented in Table 6. Applying FFR could reduce fuel consumption by approximately 800 metric tons per year (MT/yr), reduce CO_2 emissions by approximately 2,400 MT/yr, and reduce greenhouse gas (GHG) emissions by approximately 900 $MTCO_2e$/yr. Total annual fuel savings could range between $183,000 and $363,000. The range of cost-effectiveness in $/MT of CO_2 reduced is between - $50 and -$125, depending on the reference fuel price (price point) in Table 6. A negative value indicates that the annualized cost of applying the FFR coating is more than offset by the annualized fuel cost savings, thus resulting in a negative marginal abatement cost.

Table 6: Annual fuel consumption, fuel savings, and greenhouse gas emissions avoided from applying FFR to individual tanker vessels with similar characteristics to the Prem Divya.

	Metric Tons/yr	Annual Fuel Savings, Ten Year Average Discounted ($/yr)	Cost-Effectiveness ($/MT CO_2 Reduced)*
Tanker Vessel Annual Fuel Oil Consumption (MT/yr)	7,700		
Fuel Oil Consumption Reduction (MT/yr)	800		
CO_2 Emissions Reduction (MT/yr)	2,400		
GHG Emissions Reduction ($MTCO_2e$/yr)	900		
Price point 1: Total Annual Fuel Savings Assuming 10-yr (2000-2009) Avg. Price ($282/MT)		$183,000	-$50
Price point 2: Total Annual Fuel Savings Assuming 2009 Avg. Price ($387/MT)		$251,000	-$79
Price point 3: Total Annual Fuel Savings Assuming 2008 Avg. Price ($559/MT)		$363,000	-$125

*A negative value indicates that the annualized cost of applying FFR to the hull is more than offset by the annualized fuel cost savings.

Estimated Fleet-wide Impacts for Tanker Vessels

Table 7 shows that applying FFR to the tanker vessel fleet could reduce fuel oil consumption by 7.5 million metric tons per year (MMT/yr). Fuel expenditures could be reduced between $2.1 billion and $4.2 billion per year. Lastly, emissions of CO_2 could be reduced by 23.3 MMT/yr and greenhouse gas (GHG) emissions could be reduced by 9.2 million metric tons of CO_2 equivalent per year ($MMTCO_2e$/yr).

Table 7: Annual fuel consumption, fuel savings, and greenhouse gas emissions avoided from applying FFR to the international tanker vessel fleet.

	Ocean-going	Coastal	Total
Tanker Vessels Annual Fuel Consumption, (MMT/yr)*	63	12	75
Fuel Oil Consumption Reduced from the Application of FFR (%)	10%	10%	10%
Fuel Oil Consumption Reduced from the Application of FFR (MMT/yr)	6.3	1.2	7.5
Fuel Expenditure Savings		\$Billion/yr	
Price Point 1: Annual Fuel Expenditure Savings Assuming 10-yr (2000-2009) Avg. Price (\$282/MT)	\$1.8	\$0.4	\$2.1
Price Point 2: Annual Fuel Expenditure Savings Assuming 2009 Avg. Price (\$387/MT)	\$2.4	\$0.5	\$2.9
Price Point 3: Annual Fuel Expenditure Savings Assuming 2008 Avg. Price (\$559/MT)	\$3.5	\$0.7	\$4.2
Greenhouse Gas Emissions Avoided		MMTCO$_2$e/yr	
CO$_2$ Emissions Avoided (MMT/yr)	19.6	3.7	23.3
GHG Emissions Avoided (MMTCO$_2$e/yr)**	7.7	1.5	9.2

*Source: IMO (2009)

**GHG emissions (MMTCO$_2$e/yr) include all GHGs and climate forcing emissions presented in Table 3, and reflects global warming potential (GWP) over a 100 year time period.

Ikuna Bulk Cargo Vessel Results

The results of the *comparison of the means analysis* for the Ikuna are shown in Table 8. This comparison tests whether the average performance of two data sets is similar; the standard design is to assume the data are similar and require the comparison analysis be strong enough to reject this assumption, termed a "null hypothesis" or hypothesis of no difference. Statistically speaking, we can reject the null hypothesis that fuel oil consumption is equal pre- and post-application of FFR at the 95% confidence level due to a p-value of 0.003 (which is less than 0.05). Therefore, the results demonstrate a statistically significant decrease in average fuel oil consumption due to paint treatment (i.e., when the vessel hull is painted with FFR) at the 95% confidence level. On average, fuel oil consumption decreases by 11.74 kilograms per nautical mile (kg/nm) as shown in Figure 3, which equals a 22% reduction as shown in Figure 4.

Table 8: Results of the t-test analysis for the Ikuna bulk cargo vessel.

	Pre	*Post*	*Delta*
Mean (SFOC kg/nm)	53.25	41.51	11.74
Variance	241.04	395.31	
Observations	33	53	
Hypothesized Mean Difference	0.00		
df	84		
t Stat	3.05		
p-value two-tail	0.0030		
t Critical two-tail	±1.99		

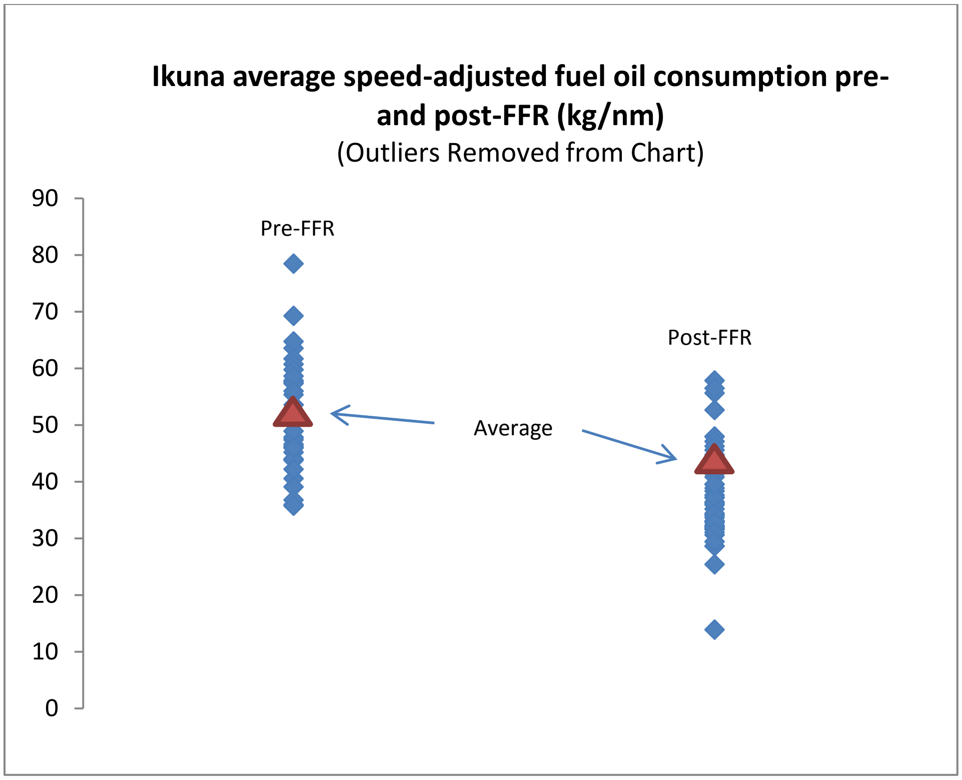

Figure 3: Ikuna average speed-adjusted fuel oil consumption (kg/nm) pre- and post-FFR application.

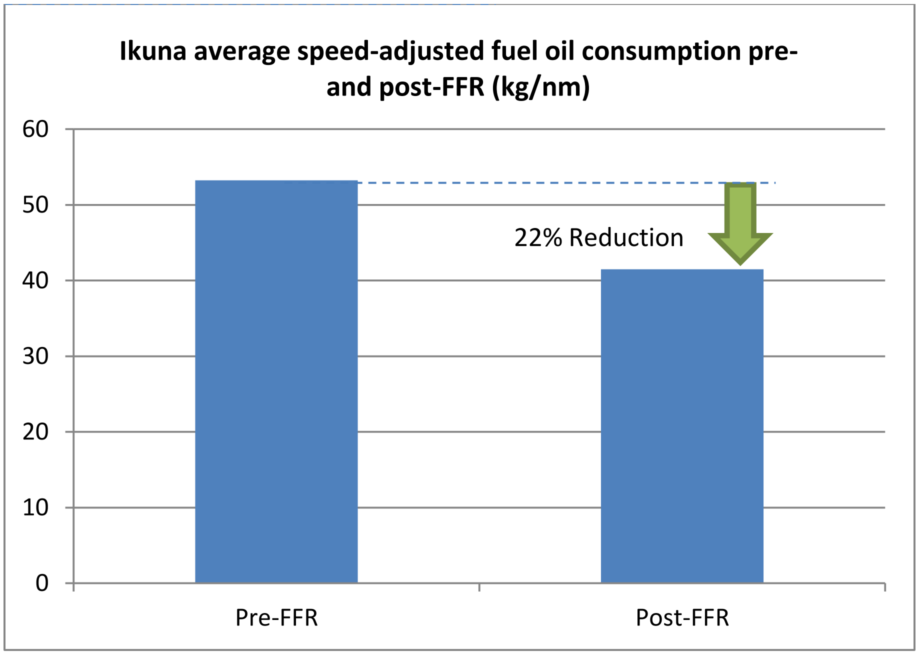

Figure 4: Ikuna average speed-adjusted fuel oil consumption (kg/nm) and % change pre- and post-FFR application.

The Ikuna was previously coated with a tributyltin self-polishing copolymer (TBT SPC) which has since been banned for use on all vessels due to environmental concerns. Results indicate that fuel oil consumption was lower due to the FFR coating compared to the TBT SPC coating throughout the docking cycle as seen in Figure 5.

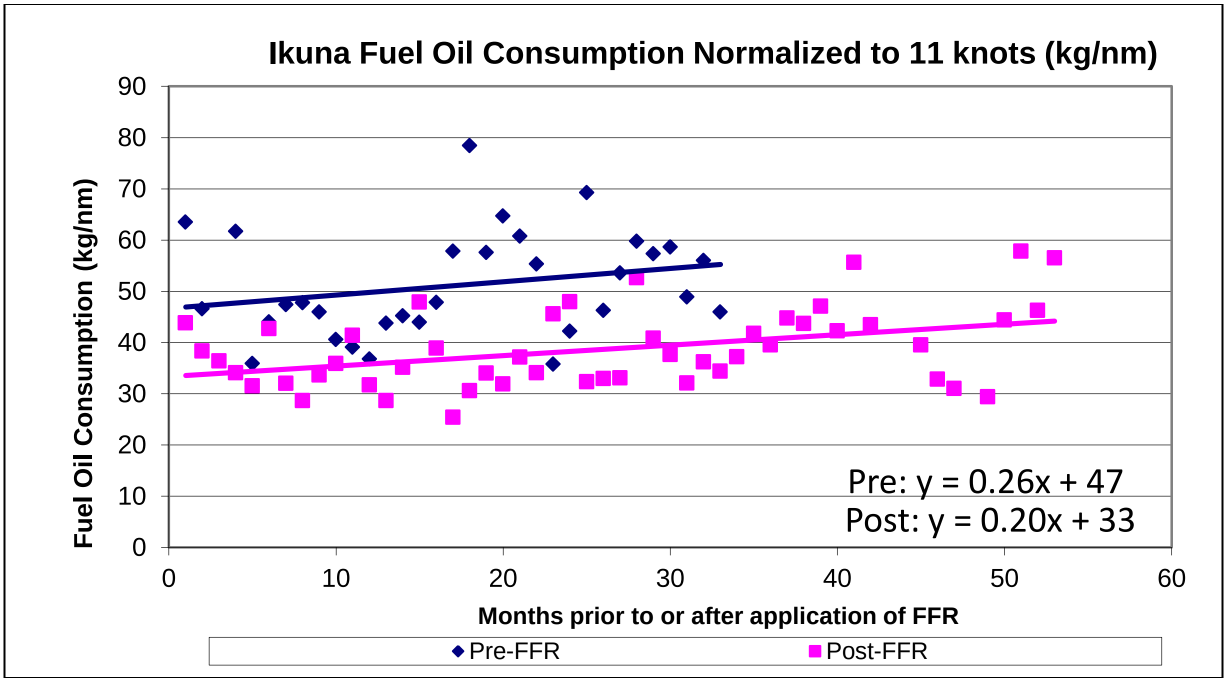

Figure 5: Ikuna fuel oil consumption normalized to 11 knots (kg/nm) pre- and post-FFR application.

Estimated Impacts on Individual Bulk Cargo Vessels with Characteristics Similar to the Ikuna

The potential impacts on individual bulk cargo vessels with characteristics similar to the Ikuna are shown in Table 9. Applying FFR could reduce fuel oil consumption by approximately 600 metric tons per year (MT/yr), reduce CO_2 emissions by approximately 2,000 MT/yr, and reduce GHG emissions by approximately 800 $MTCO_2e$/yr. Annual fuel savings could range between $152,000 and $302,000. The range of cost-effectiveness in $/MT of CO_2 reduced is between -$68 and -$143. As stated earlier, a negative value indicates that the annualized cost of applying the FFR coating is more than offset by the annualized fuel cost savings, thus resulting in a negative marginal abatement cost.

Table 9: Annual fuel consumption, fuel savings, and greenhouse gas emissions avoided from applying FFR to individual bulk cargo vessels with similar characteristics to the Ikuna.

	Metric Tons/yr	Annual Fuel Savings, Ten Year Average Discounted ($/yr)	Cost-Effectiveness ($/MT CO_2 Reduced)
Bulk Vessel Annual Fuel Oil Consumption (MT/yr)	2,800		
Fuel Oil Consumption Reduction (MT/yr)	600		
CO_2 Emissions Reduction (MT/yr)	2,000		
GHG Emissions Reduction ($MTCO_2e$/yr)	800		
Price Point 1: Total Annual Fuel Savings Assuming 10-yr (2000-2009) Avg. Price ($282/MT)		$152,000	-$68
Price Point 2: Total Annual Fuel Savings Assuming 2009 Avg. Price ($387/MT)		$209,000	-$96
Price Point 3: Total Annual Fuel Savings Assuming 2008 Avg. Price ($559/MT)		$302,000	-$143

*A negative value indicates that the annualized cost of applying FFR to the hull is more than offset by the annualized fuel cost savings.

Estimated Fleet-wide Impacts for Bulk Cargo Vessels

The potential fleet-wide impacts on applying FFR to bulk cargo vessels are shown in Table 10. Applying FFR to the bulk cargo vessel fleet could reduce fuel oil consumption by 8.2 million metric tons per year (MMT/yr). Fuel expenditures could be reduced between $2.3 billion and $4.5 billion per year. Lastly, emissions of CO_2 could be reduced by 25.5 MMT/yr and GHG emissions could be reduced by 10 million metric tons of CO_2 equivalent per year ($MMTCO_2e$/yr).

Table 10: Annual fuel consumption, fuel savings, and greenhouse gas emissions avoided from applying FFR to the international bulk cargo vessel fleet.

	Ocean-going	Coastal	Total
Bulk Cargo Vessels Annual Fuel Consumption, (MMT/yr)*	12	25	37
Fuel Oil Consumption Reduced from the Application of FFR (%)	22%	22%	22%
Fuel Oil Consumption Reduced from the Application of FFR (MMT/yr)	2.6	5.5	8.2
Fuel Expenditure Savings		$Billion/yr	
Annual Fuel Expenditure Savings Assuming 10-yr (2000-2009) Avg. Price ($282/MT)	$7.5	$1.6	$2.3
Annual Fuel Expenditure Savings Assuming 2009 Avg. Price ($387/MT)	$1.0	$2.1	$3.1
Annual Fuel Expenditure Savings Assuming 2008 Avg. Price ($559/MT)	$1.5	$3.1	$4.6
Greenhouse Gas Emissions Avoided		$MMTCO_2e$/yr	
CO_2 Emissions Avoided (MMT/yr)	8.3	17.3	25.5
GHG Emissions Avoided ($MMTCO_2e$/yr)**	3.2	6.7	10.0

*Source: IMO (2009)

**GHG emissions ($MMTCO_2e$/yr) include all GHGs and climate forcing emissions presented in Table 3, and reflects global warming potential (GWP) over a 100 year time period.

Container Vessel Results

EERA was provided with data comparing one year's fuel oil consumption of five identical 8,240 twenty-foot equivalent (TEU) capacity container vessel newbuildings. Three of the vessels used TBT-free SPC hull coatings and two of the vessels used FFR hull coatings. Table 11 provides a summary of the (unadjusted) fuel oil consumption, speed, and draft of each container vessel studied.

Table 11: TBT-free SPC coated versus FFR coated container vessel fuel oil consumption, average speed, and average draft.

	Vessel 1 (SPC)	Vessel 2 (SPC)	Vessel 3 (SPC)	Vessel 4 (FFR)	Vessel 5 (FFR)	Average
Average Fuel Oil Consumption (kg/nm)	324	323	342	343	342	329 (SPC) 343 (FFR)
Average Voyage Speed (kts)	20.5	20.0	21.0	21.0	20.8	20.5 (SPC) 20.9 (FFR)
Average Draft (m)	10.1	10.5	10.9	11.2	11.9	10.5 (SPC) 11.5 (FFR)

Source: International Paint

Notice that the average speed of the vessels coated with TBT-free SPC is 0.40 kts slower than the vessels coated with FFR (Table 11). Therefore, we apply a speed-adjusted normalization to the fuel oil consumption for the TBT-free SPC vessels and the FFR vessels in order to compare the fuel oil consumption between the two sets of vessels. Normalizing fuel oil consumption is done by the following equation defined in the methodology:

$$FOC\ ME_{norm} = FOC\ ME_i \cdot \left(\frac{Speed_{norm}}{Speed_i}\right)^3$$

In this case,

$FOC\ ME_{norm}$	is the normalized fuel oil consumption for the TBT-free SPC vessels;
$FOC\ ME_i$	is the average fuel oil consumption for the TBT-free SPC vessels;
$Speed_{norm}$	is the theoretical speed of the TBT-free SPC vessels (which we will set to 21 kts); and
$Speed_i$	is the average speed of the TBT-free SPC vessels.

After applying the normalization equation, we determine that the speed-adjusted average fuel oil consumption of the TBT-free SPC coated vessels equals 355.2 kg/nm. The speed-adjusted fuel oil consumption of the FFR coated vessels equals 353.7 kg/nm. Comparing the normalized fuel oil consumption of the TBT-free SPC vessels and the FFR vessels, we find an average decrease in fuel oil consumption of approximately 0.56% (Figure 6).[3] Other variables can affect fuel oil consumption for each vessel and are not captured in the data set including the roughness of the seas, wind resistance, and so on. A data set including such variables could lead to a multiple regression analysis similar to that performed on the Prem Divya data which may result in stronger confidence in our statistical results.

It is important to note that the fuel oil consumption for the FFR coated vessels will be affected by increased cargo loads compared to the TBT-free SPC coated vessels, as indicated by the increased average draft of the FFR coated vessels found in Table 11. The two FFR coated vessels have a draft of 11.5 meters (approximately 102,000 metric tons of cargo) and the three TBT-free SPC vessels have an average draft of 10.5 meters (approximately 91,000 metric tons of cargo). The precise additional power required for the extra 11,000 metric tons of cargo will depend on a number of variables (speed, trim, weather, etc.) but will be in excess of 5% (Willsher, 2010). Therefore, if the FFR coated vessels were loaded similarly to the TBT-free SPC vessels, their fuel oil consumption could decrease by 5% or more compared to the TBT-free SPC coated vessels. The ability of a vessel to carry extra cargo without increased fuel consumption would have a positive impact on the Energy Efficiency Design Index (EEDI) of the vessel.

Statistical Test for Difference in Means of TBT-free SPC and FFR coatings

In order to test whether the 0.56% reduction in fuel oil consumption for FFR coated vessels compared to TBT-free coated vessels is statistically significant, we compare the mean speed-adjusted fuel oil consumption of the TBT-free SPC coated vessels to the FFR coated vessels using Student's t-test. Prior to performing the t-test, we removed outliers from the data set by omitting fuel oil consumption values that were greater than two standard deviations from the mean in absolute value. This resulted in the omission of 6 out of 248 data entries for the TBT-free SPC coated vessels and 2 out of 168 data entries for the FFR coated vessels.

The results of the t-test are found in Table 12. We find that we cannot reject the null hypothesis that the mean fuel oil consumption for the TBT-free SPC coated vessels is the same as the mean fuel oil

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[3] 1 – 353.7 kg/nm ÷ 355.2 kg/nm = 0.0056; or, 0.56%.

consumption for the FFR coated vessels at the 95% confidence level since the p-vale of 0.90 is much greater than 0.05. Therefore, we cannot claim that the fuel oil consumption is less for the FFR coated vessels compared to the TBT-free SPC coated vessels. However, our results indicate that vessels coated with FFR may perform statistically similarly to those coated with TBT-free SPC while avoiding the release of biocides into the environment and other environmental benefits shown in Table 14.

Table 12: Results of the t-test comparing the mean fuel oil consumption of TBT-free SPC coated vessels to FFR coated vessels.

	TBT-free SPC	*FFR*	*Delta*
Mean (SFOC kg/nm)	355.2	353.7	1.5
Variance	19,180	8,537	
Observations	242	166	
Hypothesized Mean Difference	0.00		
df	406		
t Stat	0.13		
p-value two-tail	0.90		
t Critical two-tail	±1.97		

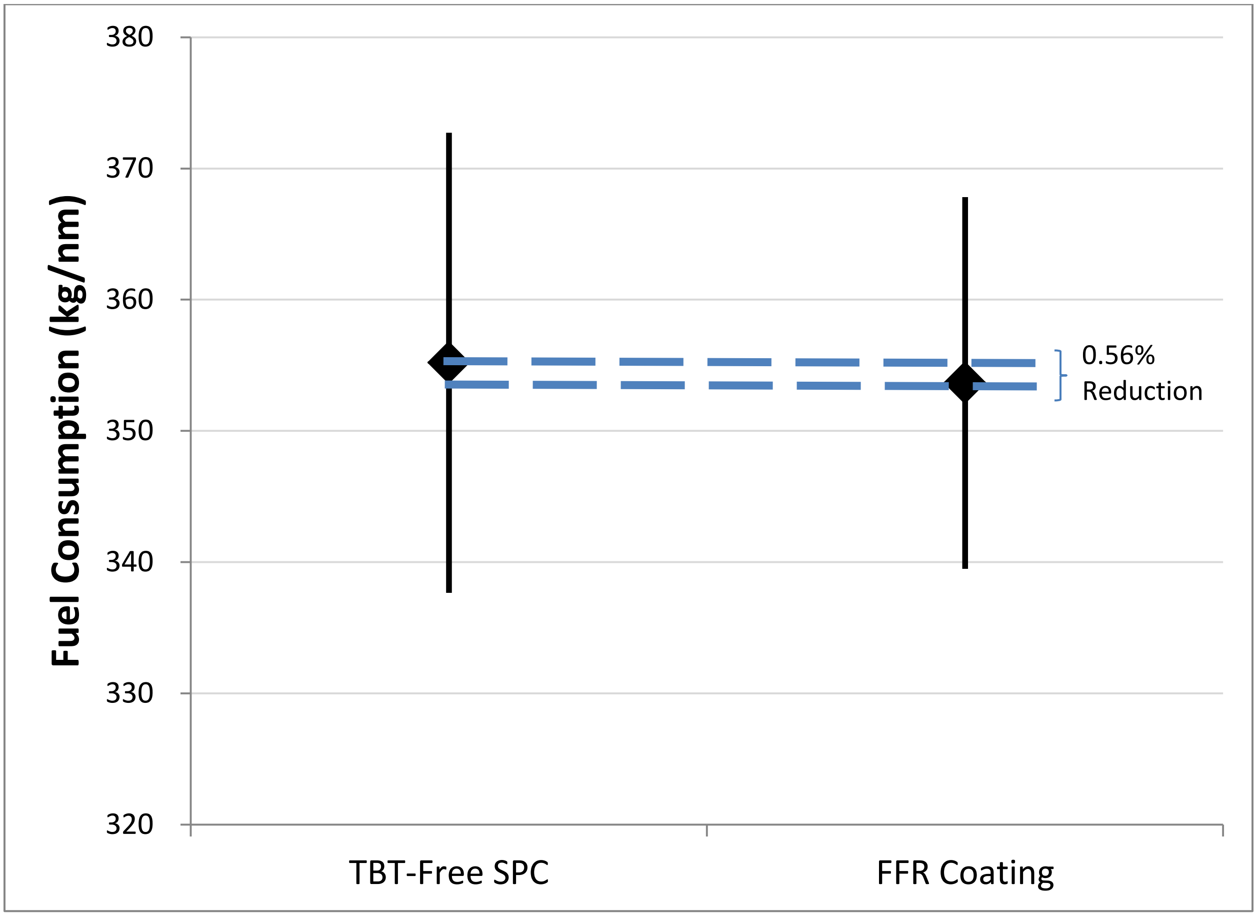

Figure 6: Average speed-adjusted fuel oil consumption for TBT-free SPC coated vs. FFR coated container vessels (kg/nm)

Fuel Oil Consumption Reductions for Other Vessel Types

The extensive data available on the tanker, bulk cargo, and container vessels allowed for confident statistical analysis to be conducted on the fuel oil consumption impacts of FFR hull coatings. In contrast, we had only a limited data set for other vessel types that have been coated with FFR which does not allow for the confident use of statistical analysis methods to compare performance pre- and post-FFR application. Therefore, Table 13 only presents the mean fuel oil consumption for various vessel types by dividing the sum of speed-adjusted fuel oil consumption values by the number of entries for each vessel type. Table 13 indicates that fuel oil consumption reductions may vary between 7.3% and 10.3% with a mean reduction of 9.4%; however, these reductions could change given a more thorough statistical analysis.

Table 13: Average speed-adjusted fuel oil consumption reduction after FFR application by vessel-type (%).

Vessel Type (number of vessels in data set)	Average Speed-Adjusted Fuel Oil Consumption Reduction after FFR Application (%)
Bulk Vessel (7)	9.9%
Ferry (4)	9.4%
Product Tanker (7)	10.4%
Roll-on/Roll-off (Ro-Ro) Vessel (4)	8.1%
Very-Large Crude Carrier (VLCC) Vessel (4)	10.3%
Liquid Natural Gas (LNG) Vessel (5)	7.3%
Mean	**9.4%**

Source: International Paint

Environmental Benefits of Fluoropolymer Foul Release Coatings

Biocidal hull coatings have been linked with environmental concerns other than GHG emissions. Using biocide-free hull coatings like FFR has environmental benefits including reduced paint volume, reduced volatile organic compound (VOC) emissions, reduced exposure to hazardous materials for workers during manufacturing and application, and no release of biocides into the aquatic environment. The environmental benefits of using FFR coatings versus biocidal hull coatings are summarized in Table 14 for three different vessel types over a ten-year period, from data provided by International Paint.

Table 14: Typical environmental benefits from FFR application over a ten-year period by vessel type.

	Very-Large Crude Carrier (VLCC) Vessel	Panamax Container Vessel	150,000 m^3 Liquefied Natural Gas (LNG) Vessel
Paint Volume Savings (L)	10,900	18,600	19,800
VOC Emissions Avoided (kg)	6,700	10,200	11,200
Copper Oxide Release Avoided (kg)	8,700	14,900	15,740

Source: International Paint

Conclusions

Our results confirm the potential for reduced fuel consumption, fuel costs, GHG emissions, and other environmental benefits through the application of fluoropolymer foul release (FFR) coatings. Fuel consumption reductions were statistically significant for the tanker vessel (Prem Divya) and the bulk cargo vessel (Ikuna). The comparison of two sister containerships with FFR coatings compared with the three sister containerships with tributyltin-free self-polishing copolymer (TBT-free SPC) coating showed statistically similar performance with regard to fuel consumption over a one-year period. Applying the results from these cases to the international fleet of tanker and bulk cargo vessels showed that reductions in fuel use, fuel cost, and emissions could be realized.

Under the examined economic circumstances (e.g., FFR and alternative biocide application and repair costs, and fuel price points), the tanker vessel and bulk cargo vessel were found to have substantial fuel savings, resulting in a negative marginal cost of carbon dioxide emissions reductions (\$/MTCO$_2$). A negative cost-effectiveness ratio for CO$_2$ reduction indicates that there is an economic benefit of reducing CO$_2$ emissions due to the correlation between reduced fuel usage (and associated cost) and reduced CO$_2$ emissions.

Results indicate that FFR application may be somewhat more cost-effective for smaller bulk cargo vessels like the Ikuna, rather than larger tanker vessels like the Prem Divya. This appears to be primarily due to the significant difference in initial application costs (which are much higher for the Prem Divya) and also due to the higher relative fuel savings for Ikuna (22%) compared to the Prem Divya (10%). Whether the relative fuel savings for vessels like the Ikuna are conditioned by operating speed (e.g., range of speeds underway), region of service, or other factors may merit further investigation.

We found that the fuel oil consumption between sister container vessels coated with FFR was not statistically different from the fuel oil consumption of those coated with TBT-free SPC at the 95% confidence level. However, our results do not account for differences in cargo load between the TBT-free SPC coated vessels and the FFR coated vessels. We believe that the speed-adjusted fuel oil consumption could be at least 5% lower for FFR coated vessels compared to TBT-free coated vessels if all of the vessels were similarly loaded.

We also found that a number of different vessel types show evidence of fuel oil consumption reductions. Further study and analysis is necessary to develop statistical conclusions on the effect of FFR on fuel oil consumption compared to other hull coatings for container vessels, ferries, roll-on/roll-off (Ro-/Ro) vessels, very-large crude carriers (VLCCs), and liquid natural gas (LNG) vessels.

Regarding CO$_2$ emissions reductions, it is important to note that CO$_2$ reductions from this analysis assume no change in operating behavior, including operating speed, after the application of FFR. This is important because increased speed or other operating behavior changes can counteract, or even negate, any fuel-use savings (and related GHG avoidance and cost savings) due to FFR application. The Ikuna vessel demonstrated a statistically significant increase in speed post-FFR application and the container vessels with FFR demonstrated a statistically significant higher speed than the no FFR container vessels, so this may be a common effect or consequence of industry economic drivers. It is also important to note that a similarity assumption is applied to scale the estimated benefits to a fleet-wide level. Additional study could also evaluate whether coating performance is devoted to fuel and CO2 savings, to better service through increased average speeds, or a combination of these.

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