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CCGS Cygnus – Hull and Propeller Cleaning

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16. Abstract
This report complements the report "M/V Cygnus Underwater Radiated Noise Level Measurements in Conception Bay, NL" and summarizes the propulsion efficiency analysis of the CCGS Cygnus operational data prior to and subsequent to cleaning the hull and propeller. This data is used to quantify any changes in vessel performance, specifically the power versus speed relationship. In addition, the vessel fuel consumption at a given power level will be quantified prior to and post cleaning events.

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16. Résumé

Le présent rapport vient compléter le rapport « Mesures du niveau de bruit rayonné sous l'eau du NM Cygnus dans la baie Conception, T. N. L. » [traduction] et résume l'analyse de l'efficacité de la propulsion réalisée à partir des données opérationnelles du NGCC Cygnus avant et après le nettoyage de la coque et de l'hélice. Ces données sont utilisées pour quantifier tout changement dans le comportement du navire, en particulier le rapport entre la puissance et la vitesse. De plus, la consommation de carburant du navire à un niveau de puissance donné sera quantifiée avant et après les opérations de nettoyage.

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Executive Summary

The Canadian Coast Guard Ship (CCGS) Cygnus is an offshore patrol ship that operates out of St. John's, NL. It is the first CCG vessel to be instrumented with a vessel performance monitoring system, developed by OpDAQ. The system measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. The National Research Council (NRC) of Canada has a separate Data Acquisition System (DAS) onboard the CCGS Cygnus since Fall 2015. The NRC DAS stores data from a number of vessel systems such as the navigation system and propulsion system. The NRC has also been obtaining OpDAQ data from the CCGS Cygnus since 2016. The data from the NRC DAS and OpDAQ system is used for the current project to quantify changes in vessel performance as a result of hull and propeller cleaning.

This report summarizes the propulsion efficiency analysis of the CCGS Cygnus operational data prior to and subsequent to cleaning the hull and propeller. This data is used to quantify any changes in vessel performance, specifically the power versus speed relationship. In addition, the vessel fuel consumption at a given power level will be quantified prior to and post cleaning events.

Three dedicated sea trials were conducted to support this project. Each set of trials is a dedicated Speed and Power trial and was planned and conducted in accordance with International Towing Tank Conference (ITTC) guidelines. The first set of trials is a baseline trial to quantify the performance before the hull or propeller are cleaned. The second set of trials is a post hull cleaning trial to quantify the performance subsequent to cleaning the vessel hull only. The third trial is conducted post propeller cleaning and is used to quantify any changes in speed and power performance as a result of cleaning the propeller.

The results of the study demonstrate an improvement in efficiency of 5% on average at the cruising speed range of 13.5-16 knots when analyzed using the prescribed method in the referenced guidelines. An improvement of similar magnitude was observed across a wider band of ship speeds when simply taking the mean of the data during the double runs. However, some variability was observed in the results due to the changing conditions between each set of trials. For example, the results were not corrected for variation in displacement across trials or the re-occurrence of slight fouling during the post cleaning trials, which was unknown at the time. The results compare reasonably to estimations of power increase for a mid-sized Naval frigate for similar baseline and fouled conditions.

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1 Introduction

The Canadian Coast Guard Ship (CCGS) Cygnus is an offshore patrol ship that operates out of St. John's, NL. It is the first CCG vessel to be instrumented with a vessel performance monitoring system, developed by OpDAQ. The system measures shaft torque, shaft speed, shaft power, and vessel fuel consumption. The National Research Council (NRC) of Canada has a separate Data Acquisition System (DAS) onboard the CCGS Cygnus since Fall 2015. The NRC DAS stores data from a number of vessel systems such as the navigation system and propulsion system. The NRC has also been obtaining OpDAQ data from the CCGS Cygnus since 2016. The data from the NRC DAS and OpDAQ system is used for the current project to quantify changes in vessel performance as a result of hull and propeller cleaning.

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The result of this project suggests how the power and speed relationship for the CCGS Cygnus changes after cleaning events within the scope of the trials. It also quantifies how the power and fuel consumption relationship changes as per the observed data. These changes are quantified using measured data from dedicated sea trials. This information could be used to support planning and optimization of vessel cleaning schedules.

2 CCGS Cygnus – Vessel Details

The CCGS Cygnus is an offshore fisheries patrol vessel that operates out of St. John's, NL. It operates on a two week rotational schedule. This generally involves the vessel departing St. John's, transiting to the Grand Banks area which it patrols and then returning to St. John's for crew change. The day after crew change the vessel departs again for Grand Banks to continue patrolling. The vessel has two main medium speed, diesel engines. The general particulars of the CCGS Cygnus are outlined in Table 1.

Table 1. CCGS Cygnus Main Particulars

Particular	**Value**
Length (m)	62.4
Breadth (m)	12.2
Draft (m)	4.0
Freeboard (m)	0.9
Cruising Speed (kts)	13.0
Maximum Speed (kts)	16.0
Number of engines	2
100% MCR (kW)	~3000
Number of propellers	1

3 Hull and Propeller Fouled Condition

Prior to cleaning the hull and propeller, a subsea survey was conducted to characterize the level of fouling present. A guideline from the Royal Navy (2011) was followed for this procedure. The hull fouling was characterized as a specific type and rated from 0 to 100 to indicate the level of severity. A description of the hull fouling types and rating values is provided in Appendix A. The hull cleaning was completed by divers when the vessel was docked in Conception Bay, NL. The diving company prepared a report to document the level of fouling on the hull. This report is provided as part of Appendix A for ease of reference. When assessing the level of fouling on the hull, the divers divided the vessel into 27 regions. At each of these regions photos were taken to document the fouling condition. The location of each region is shown in Figure 1, as taken from the divers report. Note that this image is not to scale, nor is it a representation of the CCGS Cygnus. It is used only to indicate general location and quantity of underwater areas that were surveyed.

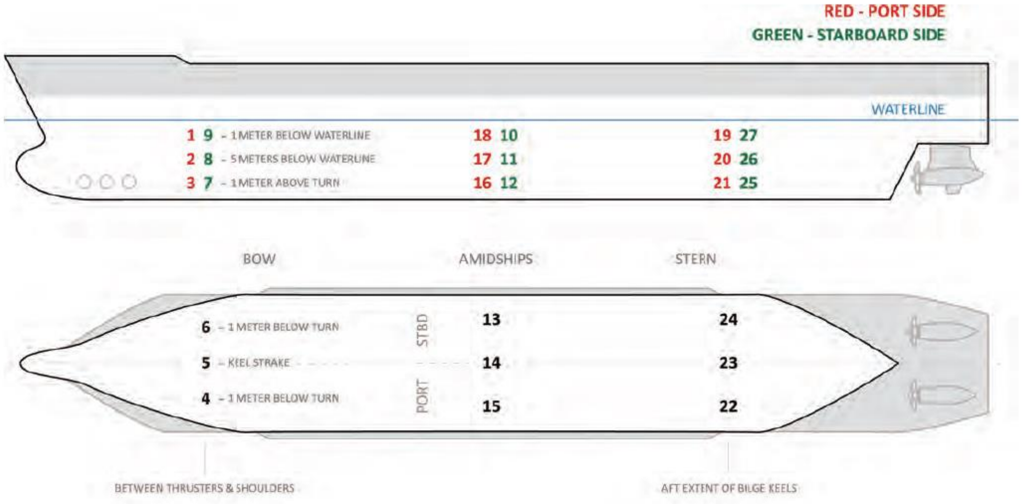


Figure 1. Hull fouling characterization locations (From diver's report)

An underwater video was also taken to support characterization of hull fouling. By evaluating the vessel in situ, through photographs and using the underwater videos, the divers characterized the level of fouling at each of the 27 locations across the hull. The diver's used the Royal Navy (2011) and US Naval Ships Technical Manual (2006) to define fouling type and rating values so that results would be consistent with Navy practices. A summary of the hull fouling characterization is provided in Table 2. All fouling on the CCGS Cygnus hull was noted to be soft. The dominant organisms in the soft fouling type are slime and grass. The fouling rating included FR 20 and FR 30. This type of fouling involves advanced slime and grass filaments up to 76 mm long. The percentage of fouling coverage in each area ranged from 40-100%. It was noted that fouling was located from waterline down to turn of the bilge with heavier growth present near the waterline.

Table 2. Hull fouling characterization – type, rating and percent coverage

Location	Fouling Type	Fouling Rating	Percentage Coverage (%)
1	Soft	30	80
2	Soft	20	50
3	Soft	20	75
4	Soft	20	100
5	Soft	20	80
6	Soft	20	90

7	Soft	20	100
8	Soft	20	50
9	Soft	30	50
9	Soft	20	50
10	Soft	30	70
11	Soft	20	50
12	Soft	20	40
13	Soft	20	80
14	Soft	20	80
15	Soft	20	90
16	Soft	20	90
17	Soft	30	65
18	Soft	30	80
19	Soft	20	90
20	Soft	20	60
21	Soft	20	90
22	Soft	20	100
23	Soft	20	90
24	Soft	20	100
25	Soft	20	95
26	Soft	20	50
27	Soft	20	80

The hull and propeller of the CCGS Cygnus had not been cleaned in two years prior to this project. The level of fouling present was a result of 2 years of operation. The CCGS Cygnus operates year round on a two week rotation with a two day layover. Vessels with an off-season or with long layover periods would likely have more fouling in similar operational and environmental conditions.

The propeller was also assessed by divers to quantify the level of fouling present. All propeller blade faces were covered in a light to moderate slime which was heavier at the root and tapered towards the tips. Under the slime the propeller blades were covered with a heavy calcium buildup. The level of propeller fouling was measured using a ship propeller roughness gage which characterizes the propeller roughness per the Rubert Comparator scale. The propeller fouling was rated as Rubert scale E. Once polished, the propeller was rated at a Rubert scale A/B. Post polishing trials were conducted at this polished state. Figure 2 illustrates the pre cleaning and post cleaning condition of a typical propeller pressure face of the CCGS Cygnus propeller. The diver’s report on propeller polishing is also included in Appendix A for ease of reference. This report includes a number of images of pre and post cleaned propeller surfaces.

Figure 2. Typical propeller pressure face pre (left) and post (right) cleaning

4 Sea Trials

Three separate sets of sea trials were completed. The first was conducted prior to cleaning the hull or propeller and provides data to use as a baseline. The second set of sea trials were completed after the hull was cleaned and the third set of sea trials were completed after the propeller was cleaned.

All trials followed the same procedure and occurred at the same location. The trials followed ITTC 2014 guidelines for the completion of speed and power trials. These guidelines outline boundary conditions as a cutoff point for the completion of such trials. These boundary conditions relate to location, water depth and environmental conditions and vary based on the vessel size. The specific trials boundary conditions for the CCGS Cygnus, are summarized in Table 3.

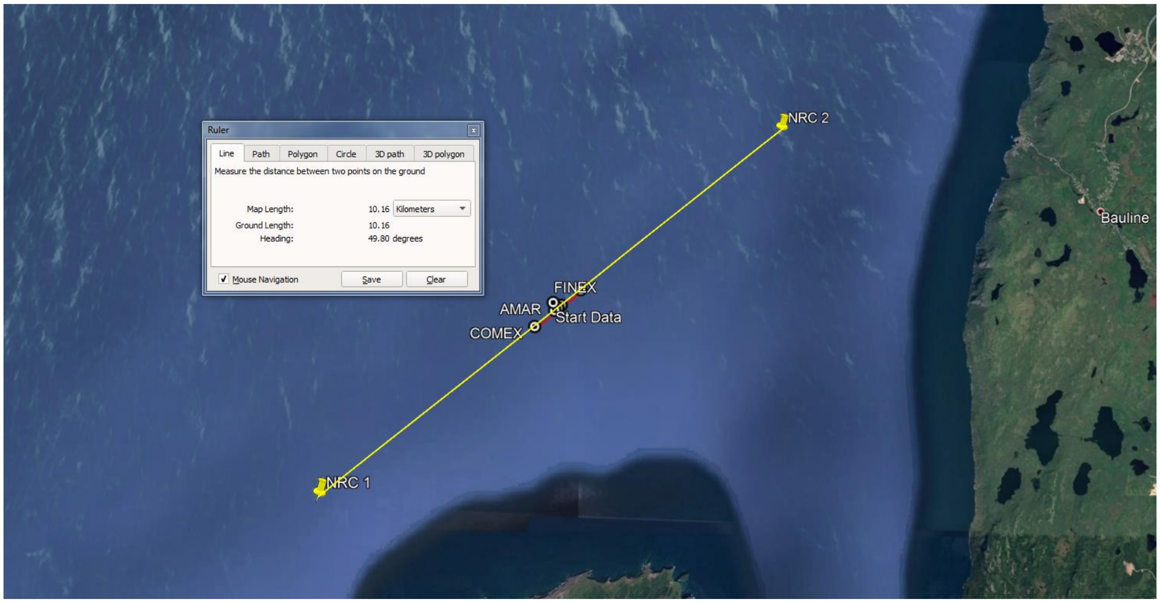
Table 3. Sea Trials Boundary Conditions

Parameter Description	**Parameter Detail or Value**
Location	Selected location should have minimal vessel traffic and should be sheltered to avoid wind / wave where possible.
Water Depth	Minimum water depth of 52.2 m. Data corrections required for water depths less than 71.8 m.
Wind	Wind shall not be higher than Beaufort 5. Beaufort 5 relates to mean wind velocity between 17-21 knots.
Sea State	The maximum wave height when derived from visual observation should be 1.2 m.
Current	Areas with known large current variations in time or space should be avoided. Small currents will be corrected for by completing tests in two directions, one upwind and the other downwind.

Prevalent weather conditions and vessel traffic intensity were considered when selecting a trials location. The location was selected to be within Conception Bay to reduce the likelihood of heavy sea states when compared to a location along the normal Cygnus operational route. The location was set to north of Bell Island since there was relatively little vessel traffic at this location than other areas of the Bay.

During each trial three or four different power settings were tested. The power settings tested included 50%, 65%, 80%, and 100% of the main engines Maximum Continuous Rating (MCR). All tests were completed in two directions: upwind and downwind. A double run at 65% MCR was conducted once during each set of trials. The double runs completed at 50%, 80% and 100% MCR were conducted twice, as per the ITTC 2014 guideline. The baseline trials included only three power settings (65%, 80%, and 100%) as the original plan did not specify runs at 50% power setting. After analysis of the baseline trial data, it was decided to include runs at 50% power in the subsequent trials to provide additional context for the higher power data points. It was attempted to perform all trials at a consistent displacement and as such there were no significant changes in cargo or machinery between trials.

The location of each set of sea trials is shown in Figure 3. The direction of all trials was along the yellow line, between the points NRC 1 and NRC 2. This track has a total length of approximately 10 km to provide space for the high speed runs. Each test required 10 minutes of constant rpm, pitch, and speed settings. As such, some tests were shorter in distance than others. All tests were centered near the subsea acoustic probe (Autonomous Multichannel Acoustic Recorder – AMAR) point in Figure 3. The AMAR point is located at 47°41.757' latitude and -52°56.509' longitude. The direction of the yellow line relates to in and out of the Bay, which corresponds with the prevailing wind direction. Once a test was completed in one direction (e.g. upwind) the vessel would turn around and complete the same test in the opposite direction.



Measure the distance between two points on the ground

Map Length: 10.16 Kilometers
Ground Length: 10.16
Heading: 49.80 degrees

Figure 3. Trials location and direction

Each trial run involved a period to get up to speed and attain constant settings, a 10 minute constant setting period, and then a Williamson turn to return vessel to opposite direction for subsequent testing. The trial trajectory was similar to that shown in Figure 4.

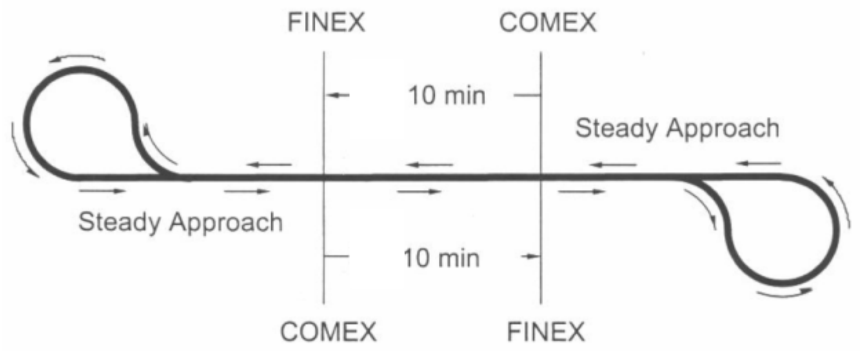


Figure 4. Trial trajectory

4.1 Baseline Trials

Baseline (pre-cleaning) trials were completed on May 23, 2018. The wind and sea conditions during the morning were higher than the boundary conditions for these tests and as such all tests were completed in the afternoon when conditions calmed. The conditions during baseline trials are summarized in Table 4. The trials log, in Appendix A, indicates the conditions during each specific test. There were 11 runs completed in total. Two of these were runs at a MCR setting of 65% (upwind and downwind), four at MCR of 80% (two upwind and two downwind) and four at a 100% MCR (two upwind and two downwind). There was a repeat test of the first run which was 65%

MCR in the upwind direction. The repeat was conducted because the wave and wind conditions were higher during the first test of the day than they were during the remainder of the tests.

Table 4. Baseline Trial Conditions

Condition	Value
Testing timeframe	13:30 – 16:15
Vessel forward draft (m)	3.35
Vessel aft draft (m)	4.83
Range in true wind speed (kts)	16 - 22
Range in wave heights (m)	0.5 – 1.0
Range in swell height (m)	0 – 0.5
Water temperature (^{o}C)	4.0

During the baseline trials the wave and swell heights were estimated by the vessel Captain. These values were not measured during baseline trials as the wave buoy was not deployed due to morning weather conditions. The water temperature was also estimated for the baseline trial, using historic water temperature values from the area. In addition, the estimated water temperature was compared to water temperature measurements taken from a wave buoy that was located in Holyrood Harbor, which is not too far from the trials site.

4.2 Post Hull Cleaning Trials

The post hull cleaning trials were completed on July 18, 2018. The weather conditions during post hull cleaning trials are summarized in Table 5. The trials log, in Appendix A, indicates the conditions during each specific test. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at a 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at a throttle setting of 100% MCR (two upwind and two downwind).

Table 5. Post Hull Cleaning Trial Conditions

Condition	Value
Testing timeframe	10:30 – 14:00
Vessel forward draft (m)	3.05
Vessel aft draft (m)	4.66
Range in true wind speed (kts)	14 - 25
Range in wave heights (m)	0.2 – 0.4
Range in swell height (m)	0 – 0.25
Water temperature (^{o}C)	10.2

During the post hull cleaning trials the wave and swell heights were estimated by the vessel Captain. These values were also measured by a wave buoy during these trials. Estimated values were compared with those measured. Values estimated were consistently higher than those measured, by approximately 50%. Measured values are summarized in the trials log as well as in Table 5.

4.3 Post Propeller Cleaning Trials

The post propeller cleaning trials were completed on August 1, 2018. The weather conditions during post propeller cleaning trials are summarized in Table 6. The trials log, in Appendix A, indicates the conditions during each specific test. There were 14 runs completed in total. Four of these were runs at 50% MCR (two upwind and two downwind), two at 65% MCR (one upwind and one downwind), four at 80% MCR (two upwind and two downwind) and four at 100% MCR (two upwind and two downwind).

Table 6. Post Propeller Cleaning Trial Conditions

Condition	**Value**
Testing timeframe	11:45 – 15:05
Vessel forward draft (m)	3.02
Vessel aft draft (m)	4.72
Range in true wind speed (kts)	4.5 – 10.2
Range in wave heights (m)	0.3 – 0.6
Range in swell height (m)	0
Water temperature (°C)	14.9

During the post propeller cleaning trials the wave and swell heights were measured by a wave buoy. These values were not estimated by Captain during this particular trial.

5 Measured Speed and Power Data

The measured shaft power versus speed through water for each test during each trial were plotted on the same plot for ease of comparison (see Figure 5). All data points align to the same general curve relatively well. There appears to be less variability in the post propeller trials data when compared to the other trials results for a given engine setting. This was expected since the wind and sea conditions during the post propeller polishing trials were lower than those for the other two trials.

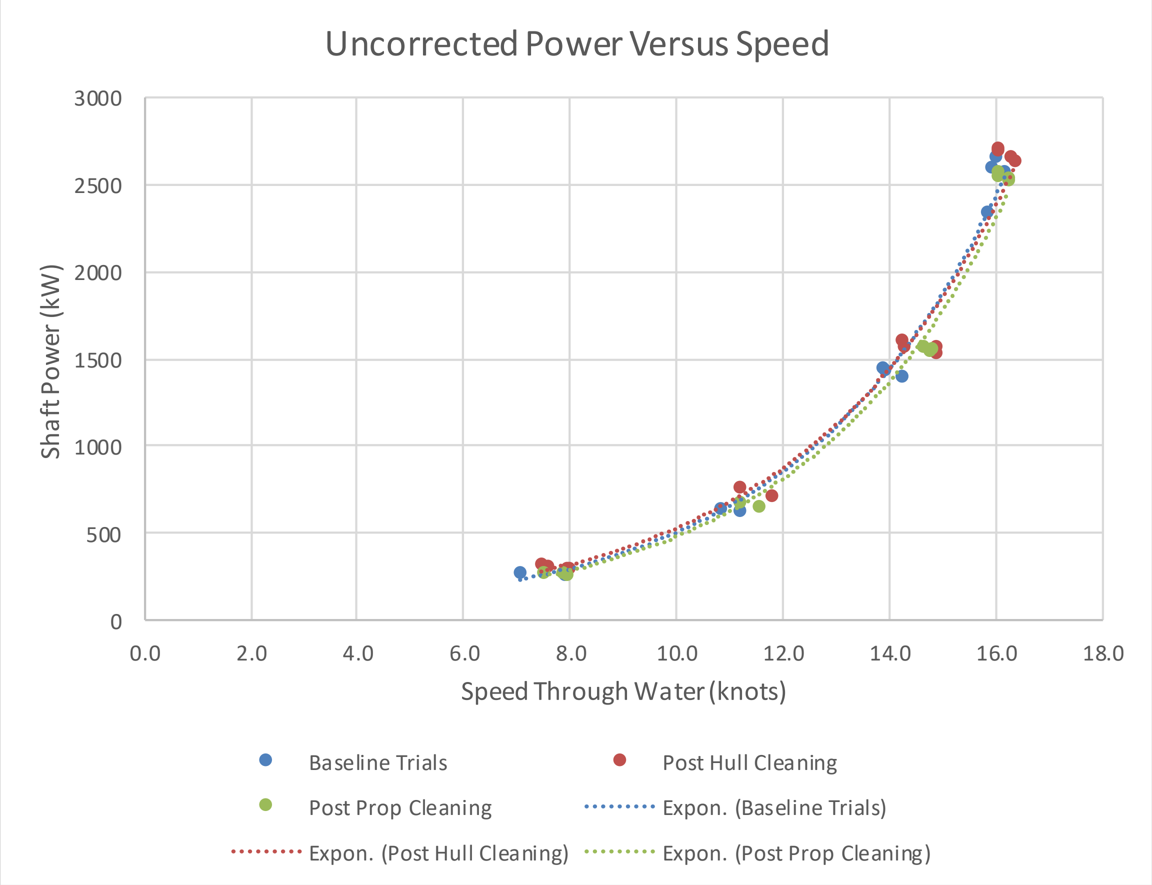


Figure 5. Uncorrected power versus speed

The measured data was analyzed first using the mean of means method to provide further insight towards data trends between trials. The mean of means method involves taking the mean of consecutive double runs at a given engine setting and then taking the mean of those means to represent the speed and power values at that engine setting. The intent of this method is to eliminate the unidirectional effects of wind and current under the assumption that these effects will average to zero. The mean of means for all trials completed at a given engine setting, within each sea trial, were calculated. The results of shaft power and vessel speed through water for each sea trial were plotted (Figure 6). Trend lines were fitted through the data for each sea trial.

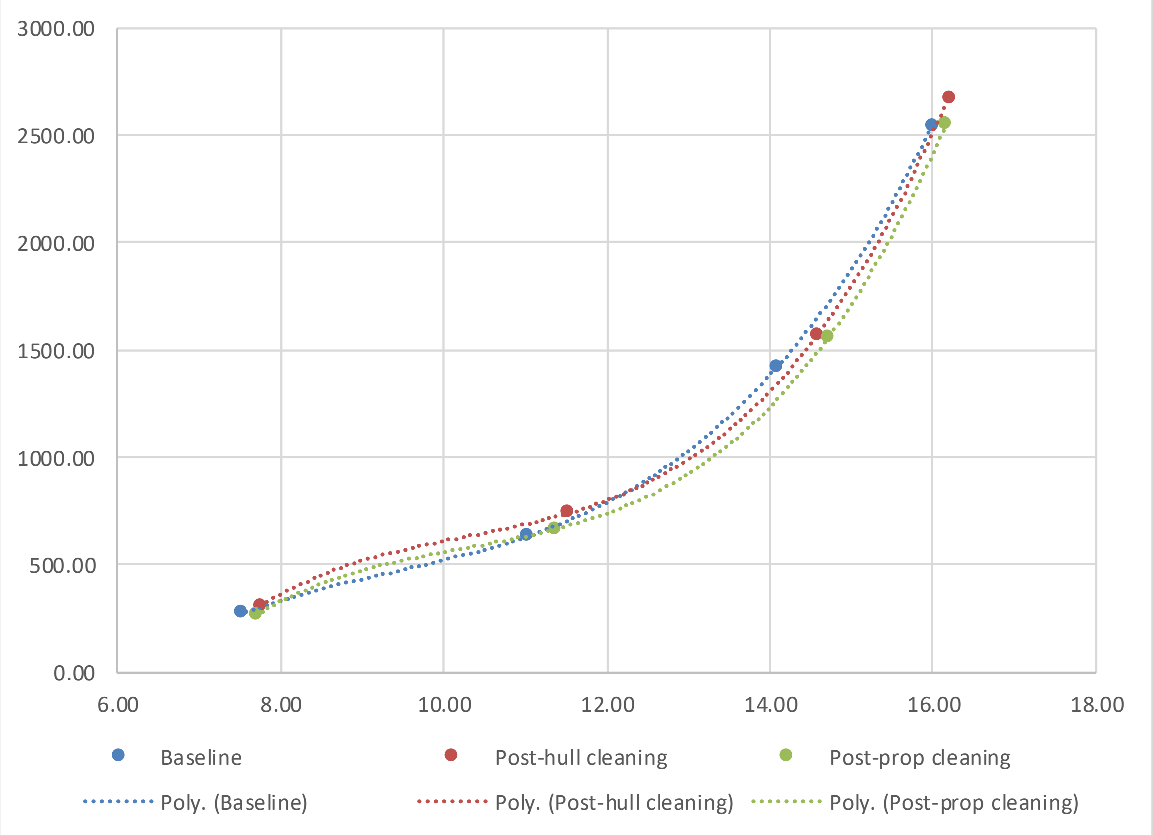


Figure 6. Means of Measured Data - Shaft Power versus Speed through Water

The differences in the relationships between power and speed for the three sea trials is clearer here. The trend line relationships between trials change across the speed range. The post-hull cleaning trials trend line requires on average ***4.1%*** less power to attain speeds between 12.5 and 16 knots. In this same speed range, the post-propeller cleaning trials trend line indicates that on average ***5.0%*** less power is required to attain a given speed when compared to the post hull cleaning trials. These results indicate that a total of approximately ***9%*** less power is required to attain a given speed (in speed range between 12.5-16 knots) as a result of cleaning both the hull and propeller. For speeds less than approximately 12 knots, more power is required to attain a given speed for the post hull cleaning trials when compared to the baseline trials. This result is unexpected and may be influenced by the higher level of uncertainty involved in the lower engine setting trials.

It is also noteworthy to discuss the fact that these results are presented in terms of power versus speed rather than overall resistance versus speed. Overall resistance is more difficult to characterize since it takes into account the propulsion as well as associated efficiencies (hull efficiency, propulsive efficiency, and relative rotative efficiency). The power can be roughly calculated by dividing the resistance multiplied by the vessel speed, by the overall system efficiency. The overall propulsion system efficiency is a combination of multiple complex factors. For example, the propulsive efficiency would increase as a result of cleaning the propeller. Another example is that the hull efficiency, which describes how the water flows around the hull and into the propeller, can affect the propeller efficiency as a result of cleaning the hull. It is therefore possible that the resistance versus speed relationship for each set of trials would not exhibit the same performance gains across the speed range compared to simply comparing power versus speed.

6 Speed and Power Analysis and Results

The speed and power data measured during field trials was analyzed to remove variations due to environmental differences between trials. This was completed following ITTC guidelines for the analysis of full scale speed and power trials (ITTC, 2005). This analysis method was complimented using insight from ISO 15016 when additional guidance was needed. The ITTC guideline requires the conversion of measured power data to vessel resistance in order to apply certain correction factors to account for environmental effects and correct data to a common, calm state. The ITTC guideline describes a method to determine the resistance of each trial run by using the measured torque along with information from associated propeller curves. A major element of uncertainty in this analysis is that the open water propeller curves for the Cygnus propeller are not available to support data analysis. As such, a standard B-Series propeller curve was assumed to be representative of the Cygnus propeller.

The ITTC guideline provides methods to calculate resistance corrections for: wind, waves, deviation in water temperature and density, water current, shallow water, and displacement variation. Resistance corrections were calculated for each trial run within each specific sea trial. For all cases, the resistance correction to account for water current was not calculated since the vessel speed through water was measured directly. Also, the shallow water correction was not calculated for any trials since the trials were conducted in deep water. The resistance correction to account for variations in vessel displacement were provided only for displacements that varied less than 2%. Based on the forward and aft draft measurements taken at the beginning of each trial, the displacement varied by approximately 8%, exceeding the range of the correction method. As such, there were no corrections added to account for displacement variation and the change in displacement is a source of variability within the results. Note that the forward and aft were estimated by the vessel crew based on draft marks prior to each trial and were not measured directly. Therefore, the variation in displacement could differ than the percentage value calculated using the estimated trim values.

The resistance corrections calculated for each trial were subtracted from the trial resistance that was calculated to reduce the resistance to a calm water baseline which could be used for direct comparison between trials. The corrected vessel resistance was used to calculate the corrected power. The ITTC analysis method required estimation of a number of coefficients specific to the vessel used in trials as well as the estimation of a number of environmental parameters that were not directly measured. Estimation of these parameters leads to a level of uncertainty in the results. A summary of the estimated parameters is provided below.

- Wake fraction, thrust deduction fraction and propeller relative rotative efficiency. These coefficients can be found from model test results for a particular vessel. Model test data for the CCGS Cygnus was not available for this data analysis. As such, the commercial software NavCad was used to model each trial and output the associated coefficients. The measured and predicted shaft power values compared well (within 10%) and thus the coefficients output from NavCad were deemed as reasonable.
- Thrust coefficient and advance coefficient. The ITTC analysis guideline states that the propeller open water thrust and advance coefficients, both required to calculate resistance, are to be retrieved from propeller open water curves. The CCGS Cygnus propeller open water curves were not available for this analysis. As such, standard B-Series open water propeller curves were used to represent the Cygnus propeller. The standard B-Series open water propeller curves were updated to match the pitch (as approximated by NavCad) of each trial run. Each unique set of curves was then used to retrieve the required data associated with the corresponding run. Unfortunately, the actual pitch relating to each test

was not known and had to be approximated based on the pitch percentage which was noted from a gage on the bridge of the vessel and using NavCad. This added to the uncertainty involved in using the standard B-Series curve. In addition, the Cygnus propeller is controllable pitch and the standard B-Series propeller is not. The ratio of hub diameter to propeller blade length is larger for a controllable pitch propeller than for a fixed pitch propeller.

- Wetted surface area. The wetted surface area of the CCGS Cygnus was estimated with NavCad using input of the vessel main particulars and selection of representative vessel type.
- Transverse projected area above waterline. The transverse projected area above waterline of the CCGS Cygnus was estimated using measurements from the general arrangement drawing of the vessel and known draft.
- Wind resistance correction. The correction for wind resistance was estimated using recommended equations for the calculation of wind resistance.
- Wave height during baseline trials. The wave height was not measured during baseline trials. It was estimated using the measured wind speed and the fetch limited JONSWAP wave spectrum. The value of fetch used for the trials was 30 km. These estimates were compared to measured wave height data from a nearby (Holyrood) wave buoy and the results matched well (within 10%).
- Water temperature during baseline trials. The water temperature was not measured directly during baseline trials and was estimated based on historic water temperature data during the same time of year. The estimated value was compared to measured data from a nearby (Holyrood) wave buoy and the results were similar.
- Water density for all trials. It was assumed that 3.5% salinity was representative of the water density during trials.
- Kinematic viscosity for all trials. The water kinematic viscosity was not directly measured and was estimated using the water temperature and ITTC Salt Water Property tables.

Preliminary results of the analysis showed that the wind resistance correction the most significant factor in comparison to the other corrections, for all sea trials. In addition, for the baseline trials and the post hull cleaning trials, where wind speeds were towards the upper wind speed limits of the trials, the wind resistance correction was very large in comparison to the bare hull resistance, particularly at the lower speeds.

The measured speed and power data was analyzed three separate times to correct for environmental conditions, each using the ITTC 2005 method or a slight variation to the method. The first analysis approach was conducted strictly to the ITTC guideline. The second and third analysis approaches were conducted using the ITTC 2005 guideline with a different estimation of wind resistance correction. The second attempt involved a wind resistance correction estimation using the Fujiwara method. This method was one of the wind resistance predictors recommended in NavCad, a commercially available vessel performance evaluation software. The third attempt involved a wind resistance correction estimation of half the predicted value using the Fujiwara method. Three separate analysis were completed to illustrate the variation in result that occurs due to different estimations of wind resistance correction.

6.1 Results – Baseline Trials

The results of the three analysis methods for the baseline trials data is summarized in Figure 7. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

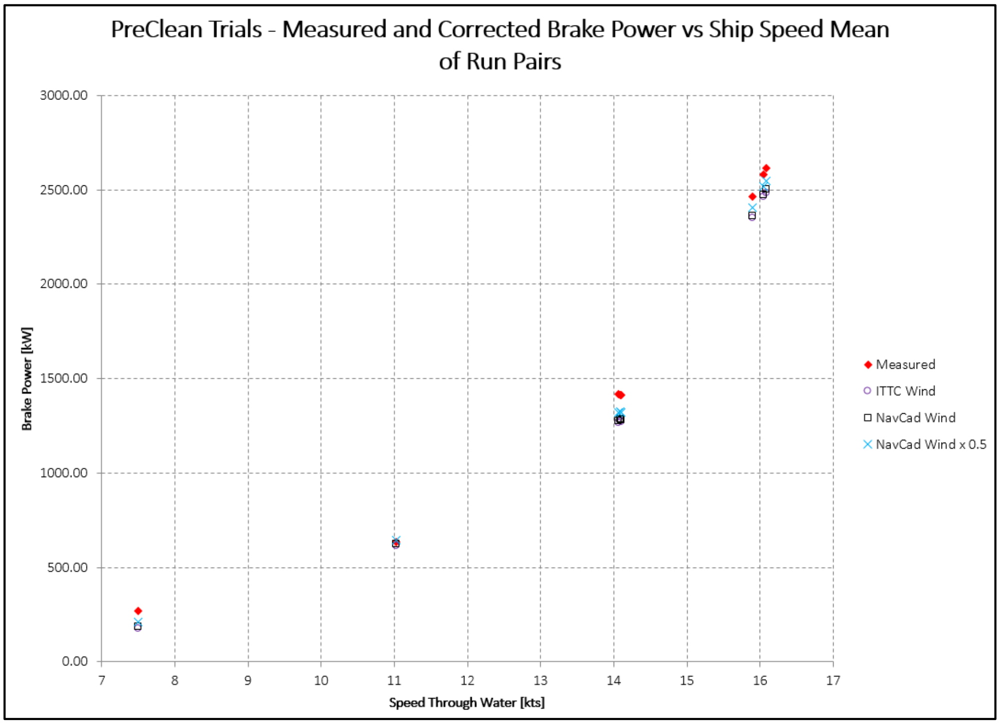


Figure 7. Corrected Speed and Power Results for Baseline Trials

The measured trials data have higher power per speed than the corrected data for all test cases except the 11 knot speed. It is expected that the measured power would be higher since the power is being corrected to a calm condition and less power would be required to attain a given speed in calm seas. The measured data is very close to the corrected values at 11 knots which suggests that the wind and wave conditions during these tests were relatively mild. There is not much difference between the corrected results using the ITTC wind correction and the NavCad (Fujiwara) wind correction, for all tests. The corrected data using half the Fujiwara wind correction, lies in between the measured data and the other corrected data. A summary of the measured power and corrected power values from each analysis method are provided in Table 7 for each test during the baseline trials.

Table 7. Corrected and Measured Power Data for Baseline Trials

Speed Through Water (knots)	**Power (kW)**			
	Measured (uncorrected)	**ITTC Wind**	**NavCad Wind**	**0.5 x NavCad Wind**
7.1	276	88	98	149
7.9	265	267	274	278
10.8	637	503	524	580
11.2	629	724	722	715
13.9	1446	1077	1111	1220
14.2	1395	1457	1445	1425
13.9	1433	1096	1128	1226
14.3	1393	1447	1435	1416
16.0	2653	2271	2328	2446
16.2	2574	2696	2677	2646

15.9	2592	2234	2272	2391
15.9	2338	2469	2451	2420

6.2 Results – Post Hull Cleaning Trials

The results of the three analysis methods for the post hull cleaning trials data is summarized in Figure 8. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

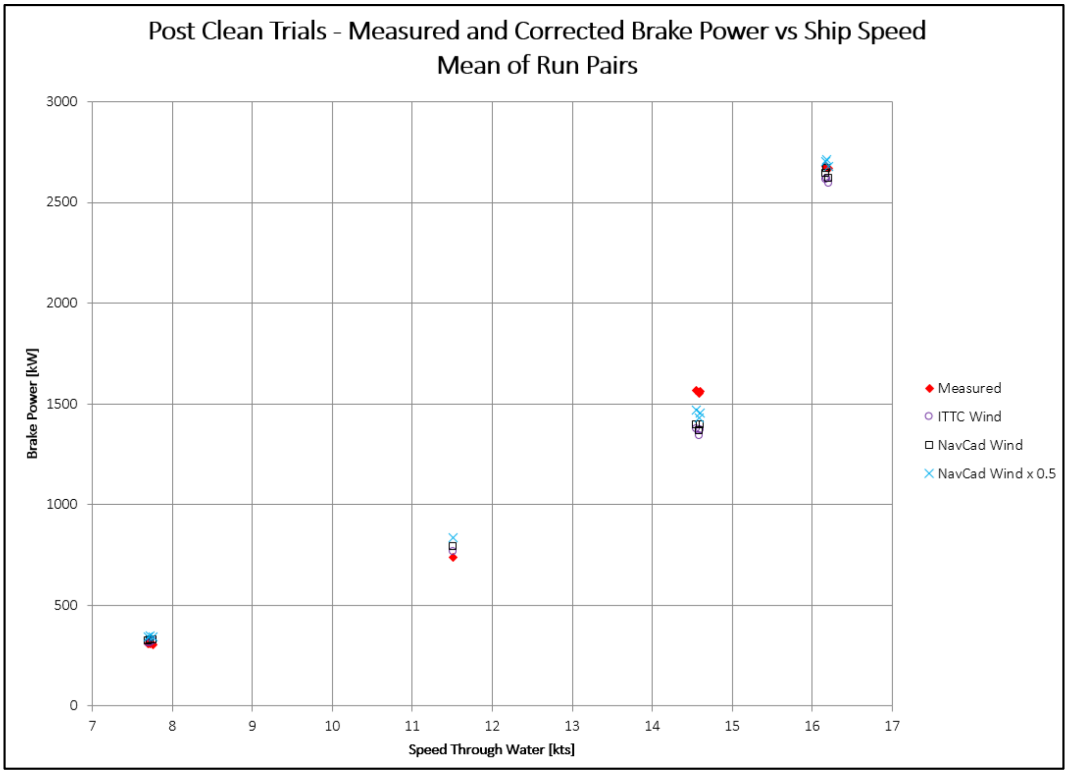


Figure 8. Corrected Speed and Power Results for Post Hull Clean Trials

The data corrected using the ITTC wind correction and the NavCad wind correction are very similar. The spread between the measured and corrected data increases with speed for the post hull cleaning trials. A summary of the measured power and corrected power values from each analysis method are provided in Table 8 for each test during the post hull cleaning trials.

Table 8. Corrected and Measured Power Data for Post Hull Cleaning Trials

Speed Through Water (knots)	**Power (kW)**			
	Measured (uncorrected)	**ITTC Wind**	**NavCad Wind**	**0.5 x NavCad Wind**
7.6	310	288	298	330
7.9	300	357	359	358
7.5	320	269	286	330
8.0	300	362	371	365
11.2	761	656	692	789

11.8	715	879	896	884
14.2	1601	1189	1231	1396
14.9	1537	1566	1561	1542
14.3	1563	1124	1176	1320
14.9	1563	1619	1616	1588
16.0	2702	2390	2462	2617
16.3	2654	2839	2823	2791
16.1	2694	2397	2518	2630
16.4	2639	2790	2721	2723

6.3 Results – Post Propeller Cleaning Trials

The results of the three analysis methods for the post propeller cleaning trials data is summarized in Figure 9. The measured (uncorrected) data is also included to reference the extent to which the measured data is modified as a result of the wind, wave and sea temperature corrections.

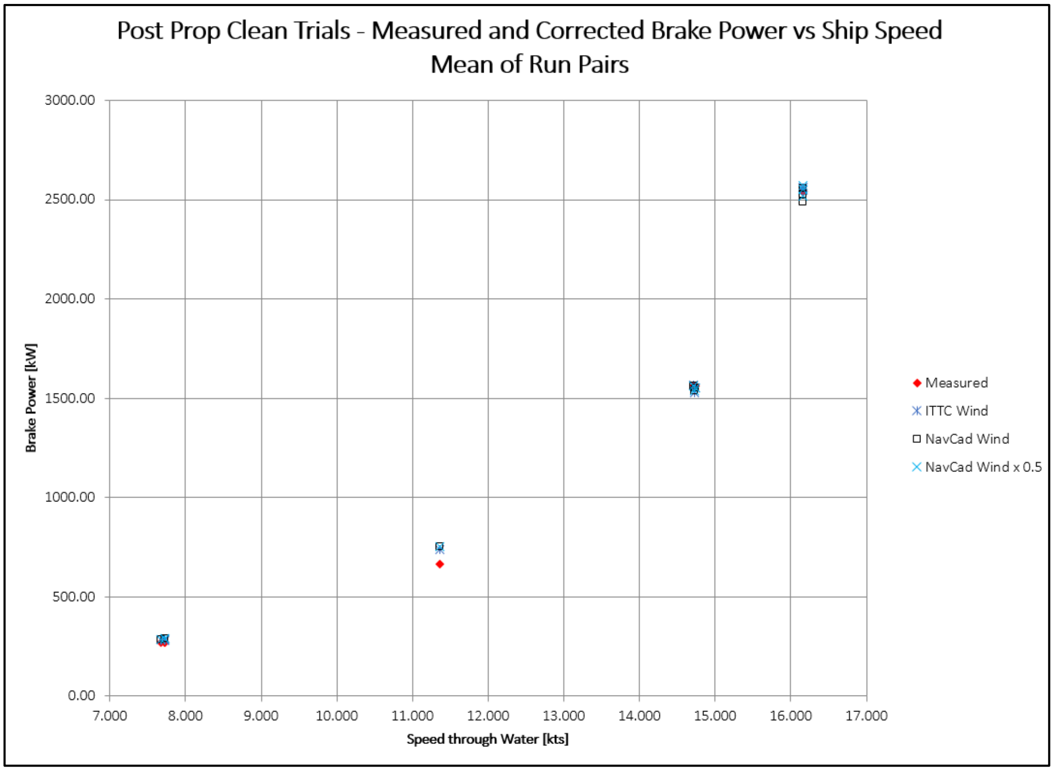


Figure 9. Corrected Speed and Power Results for Post Prop Clean Trials

The measured data is very close to the corrected data for the post propeller cleaning trials due to the mild environmental conditions during the trials. There does appear to be one outlier for the tests at speed between 11 and 12 knots for which the measured power is below the corrected power values. A summary of the measured power and corrected power values from each analysis method are provided in Table 9 for each test during the post propeller cleaning trials.

Table 9. Corrected and Measured Power Data for Post Prop Cleaning Trials

	Power (kW)

Speed Through Water (knots)	Measured (uncorrected)	ITTC Wind	NavCad Wind	0.5 x NavCad Wind
7.9	266	299	298	295
7.5	274	268	269	279
7.9	264	300	307	299
7.5	272	262	272	277
11.5	656	759	769	753
11.2	672	722	739	753
14.8	1549	1585	1576	1566
14.6	1572	1548	1547	1563
14.8	1553	1557	1556	1543
14.6	1566	1502	1516	1533
16.3	2540	2615	2599	2580
16.1	2567	2505	2517	2564
16.3	2527	2617	2536	2542
16.1	2553	2478	2438	2495

6.4 Results – Comparison of Trials

The corrected power results for each sea trial were plotted against speed on the same plot to illustrate differences in performance. This was completed for each of the three wind correction approaches considered. For each analysis method, the results of each trial are relatively similar in terms of the power required at a given speed. Given this, it is difficult to quantify the gain in power associated with cleaning the hull and propeller, from this data. The regression lines for each trial are very similar for all analysis methods used. For each approach, the baseline trial regression line is higher than the post hull and post propeller cleaning regression lines, at speeds higher than approximately 13 knots. This indicates that there is a benefit of cleaning the hull and propeller in these speed ranges in terms of power required to attain a given speed. Below, approximately 13 knots, the regression line for baseline trials falls below the regression line for the other two trials. This change in regression line relationship between trials is consistent to the measured data results and may be due to higher uncertainty levels at the low speed tests.

The power savings above 13 knots were quantified using the regression line equations from the NavCad wind correction approach. Between 13.5 and 16 knots an average of ***5%*** less power is required to attain a given speed after cleaning the hull, when compared to the baseline power requirements. There is no additional power reduction identified within this speed range as a result of cleaning the propeller which was unexpected. In fact, the performance after cleaning the propeller, in terms of power versus speed, is worse in this speed range.

Note that there is variability within the tests conducted at a given throttle setting for a given trial in terms of speed through water and corrected power. The corrected power for a throttle setting for one trial often falls within the range of corrected power for the same throttle setting in a different trial. For example, at a throttle setting of 10 the speed through water varies between 15.9-16.2 knots for the baseline trials, 16.0-16.4 knots for the post hull clean trials and 16.1-16.3 knots for the post propeller cleaning trials. For this same throttle setting the corrected power (NavCad wind) ranges from 2272-2677 kW for the baseline trials, 2462-2823 kW for the post hull clean trials and 2438-2599 kW for the post propeller cleaning trials. The speed and power values from one trial, fall within the speed and power range for a different trial for this throttle setting. This is consistent for the other throttle settings considered and is true for the measured data as well as the corrected. This may be due to variability between trials (e.g. displacement variation, fouling present) and leads to less reliability in the power savings quantified using this data.

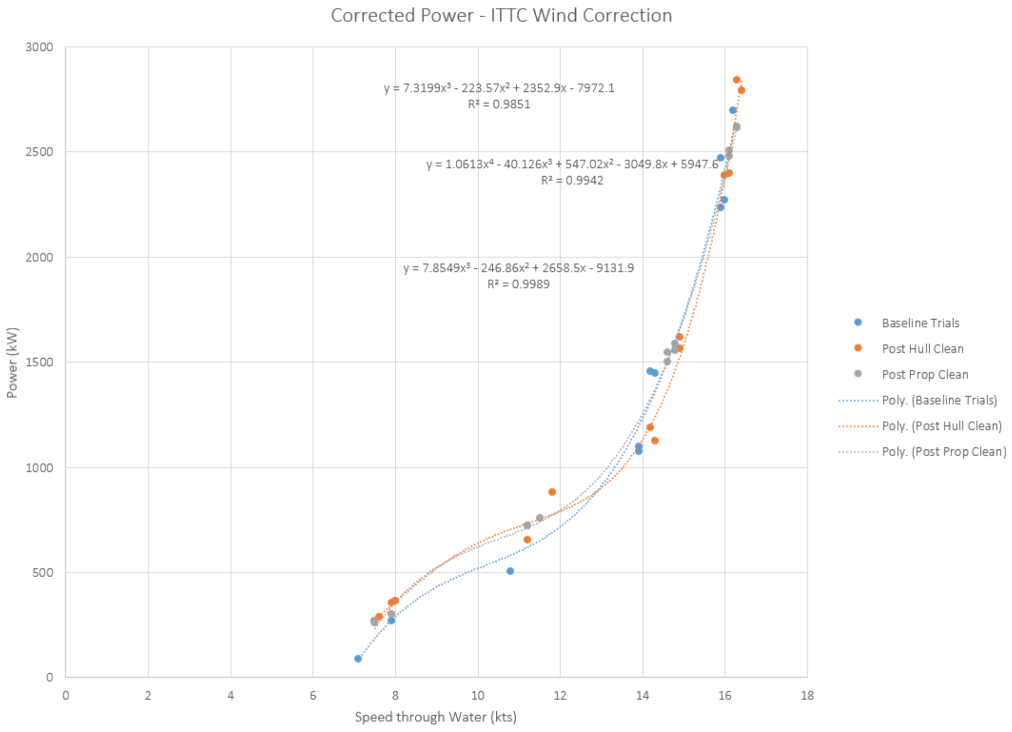


Figure 10. Corrected Power Results for All Trials – ITTC Wind Correction

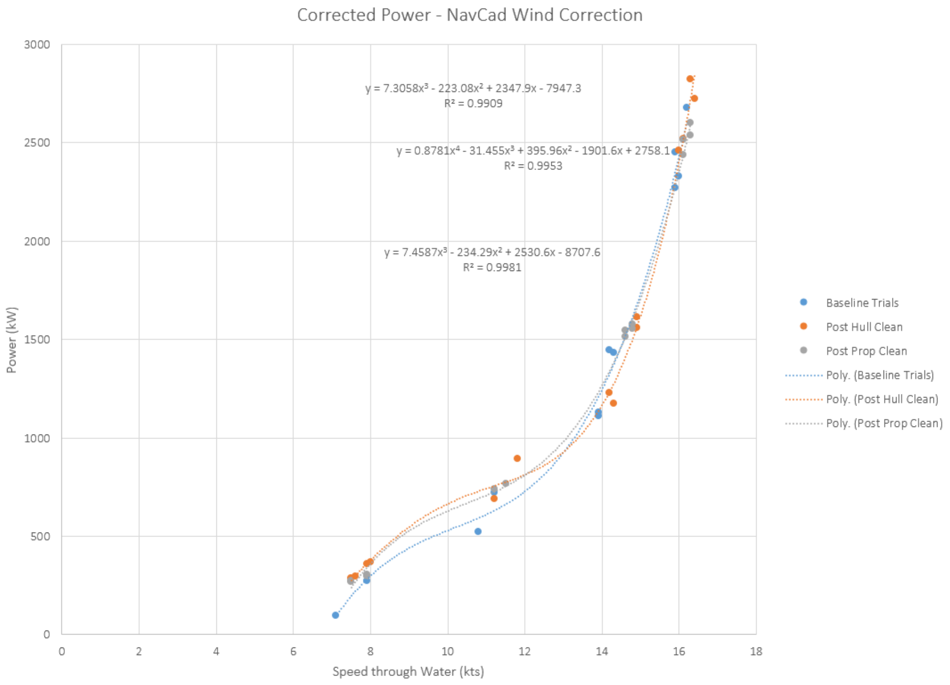


Figure 11. Corrected Power Results for All Trials – NavCad Wind Correction

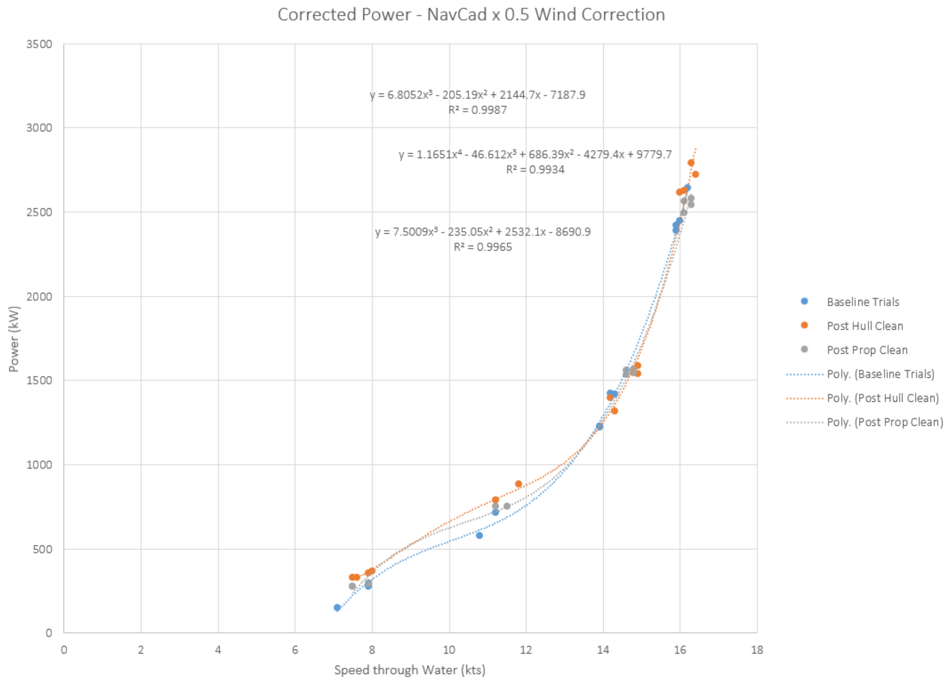


Figure 12. Corrected Power Results for All Trials – NavCad x 0.5 Wind Correction

7 Measured Data, Analysis and Results – Fuel Consumption and Speed

The measured total fuel consumption rate of both main engines was plotted against the speed through water for each test during each trial. The results from all trials were added to a single plot to allow comparison between the data sets. All data aligns relatively well to a single fuel consumption versus speed curve, though there is variability in the data sets. The post propeller cleaning trials have the least variability amongst the data points at a single engine setting, particularly at the higher engine settings tested. This was expected since the wind conditions during the post propeller cleaning trials were milder than the other two trials. The post hull cleaning points are slightly lower in terms of the fuel consumption rate that is required to attain a given speed when compared to the results of the other two trials. However, the post propeller cleaning points appear to be in line with the baseline trials results in terms of fuel consumption requirements for a given speed.

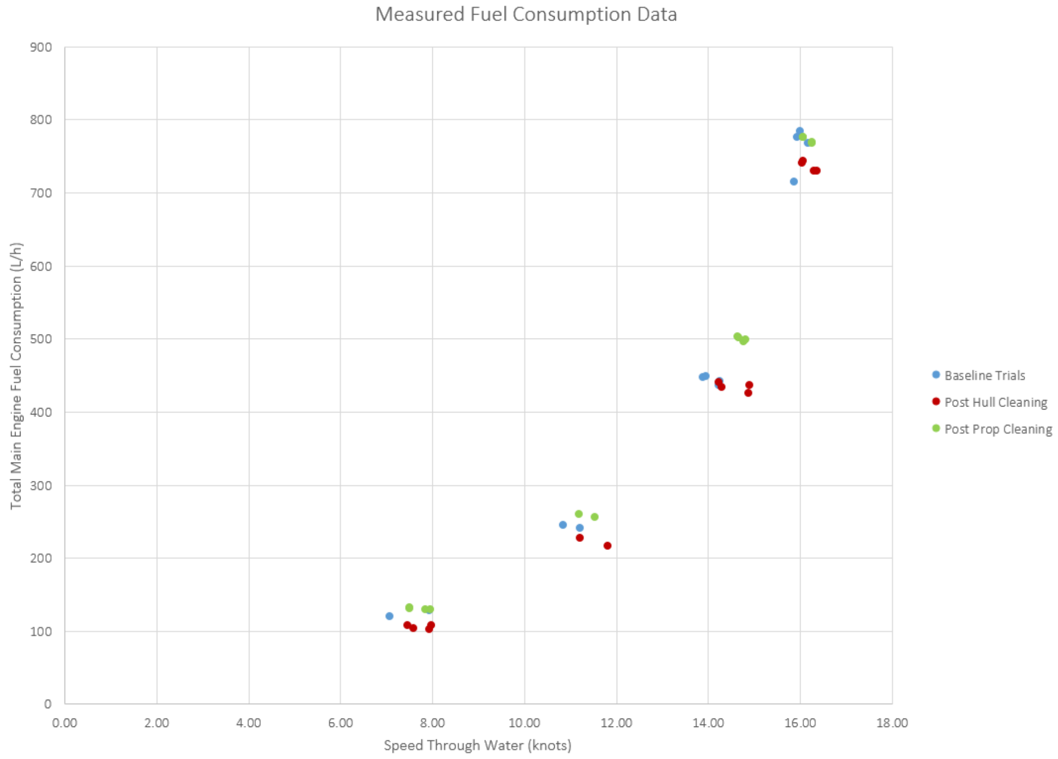


Figure 13. Uncorrected fuel consumption versus speed

The mean speed and fuel consumption rate at each engine setting was computed for each of the three trials. The mean fuel consumption values were plotted against the mean speed values and regression lines were fit through the data representing each trial. The results of this analysis is provided in Figure 14. The differences between the data sets from each trial, in terms of the relationship between fuel consumption and power, are clearer here. The fuel consumption savings as a result of cleaning the hull alone is larger than the fuel consumption savings resulting from cleaning the hull and propeller, which was unexpected.

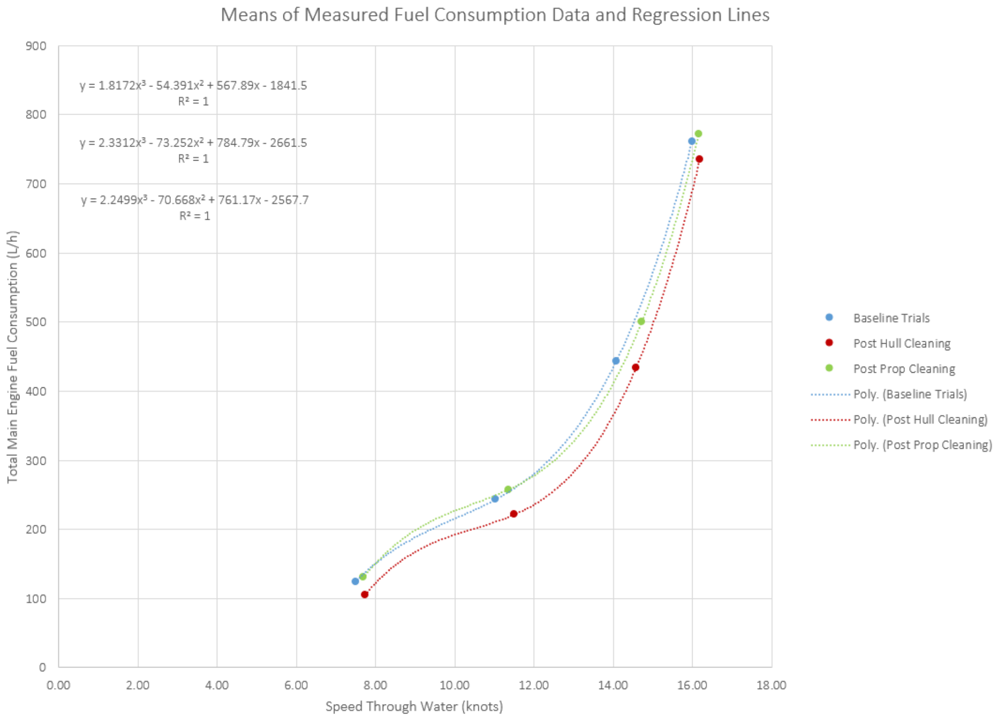


Figure 14. Means of Measured Data – Fuel Consumption versus Speed through Water

To investigate this further the total main engine fuel consumption versus shaft power was plotted for each trial. The fuel consumption versus power curve should be consistent for all trials since both fuel consumption and shaft power are not affected by external parameters such as environmental condition or hull and propeller condition. The speed attained however, does change as a result of variation in these external parameters. The measured total main engine fuel consumption versus power curve for all trials is shown in Figure 15. For each engine setting tested during trials, the baseline trials and post propeller cleaning trials data aligns well. However, there is an offset when it comes to the post hull cleaning trials data. For these trials there is less fuel required for a given power setting, particularly at higher power values. It is expected that there was some mechanical difference in the fuel measurement system that led to the discrepancy in the post hull cleaning fuel versus power data. A possibility is that one (or more) of the fuel flow meters surrounding one of the main engines was bypassed or partially bypassed or blocked during the post hull cleaning trials. However, the OpDAQ system bypass indicator did not highlight a complete bypass during this, or any of the trials.

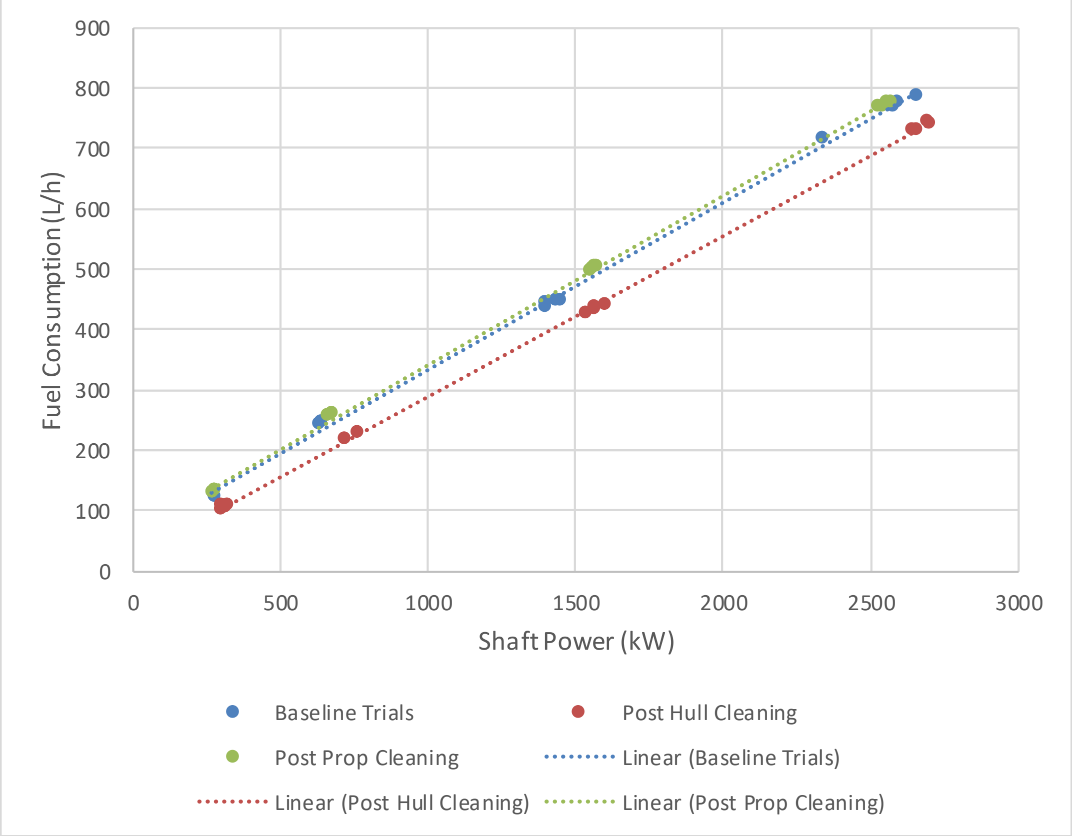


Figure 15. Uncorrected total main engine fuel consumption rate versus shaft power

The baseline and post propeller trials data for fuel consumption versus power was used to define the general fuel versus power curve for the Cygnus main engines. The post hull cleaning trials data was not used for this purpose due to the discrepancy from the other trials data. The general fuel versus power regression equation (regression equation listed in Figure 15) was used to calculate the "corrected" fuel consumption by adding the corrected power values at each engine setting for each trial. The power values corrected using the NavCad wind correction were used in this analysis. Once the "corrected" fuel consumption rate was identified for each test, the corrected fuel consumption versus speed was plotted for each specific trial so that the data could be easily compared (see Figure 16). There is no quantifiable difference between the fuel consumption rate and speed through water for the different sea trials. This is due to the level of variation in data at single test condition within a given trial and how data from different trials fall within this variability range. For example, at a throttle setting of 8.0, the baseline trials speed through water ranges from 13.9-14.3 knots and the corrected fuel consumption ranges from 373-475 L/h. At this same throttle setting, the post hull cleaning trials speed through water ranges from 14.2-14.9 knots and the corrected fuel consumption ranges from 393-526 L/h. There is overlap in the speed and fuel consumption variability ranges between trials for each engine setting.

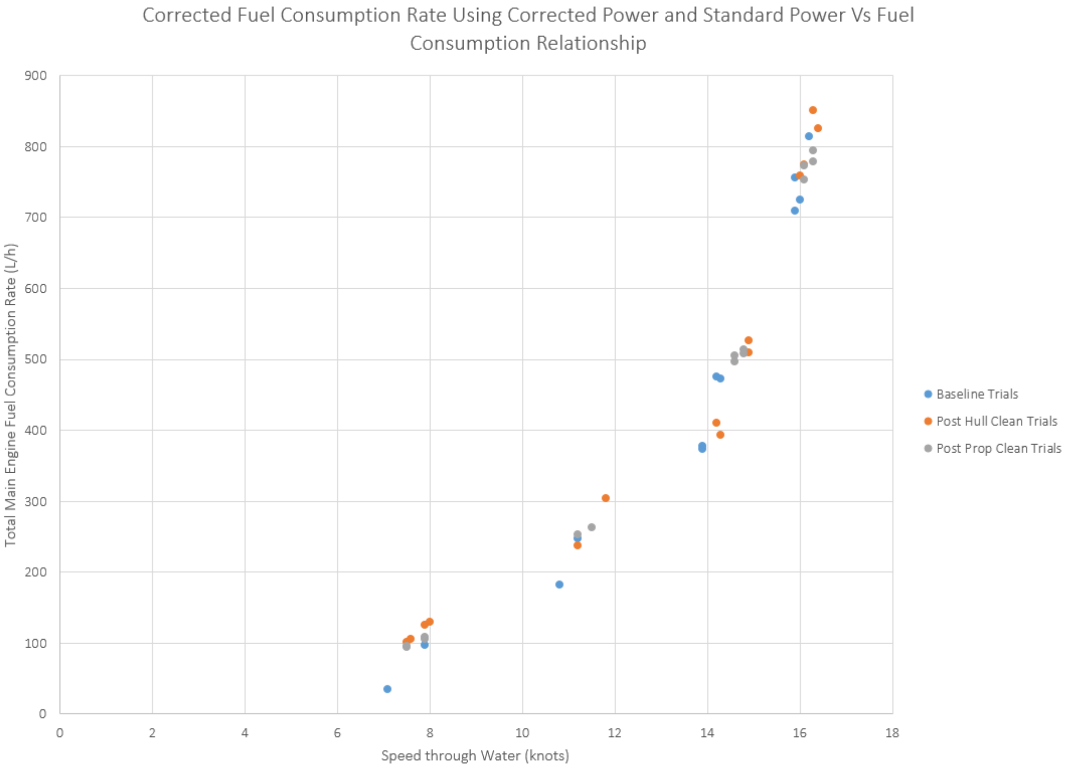


Figure 16. Corrected total main engine fuel consumption rate versus speed

8 Condition of Cygnus Hull in September 2018

The CCGS Cygnus was taken into dry dock on September 11, 2018 to perform vessel maintenance. When in dry dock, the hull was observed to have a relatively high level of fouling on one side in particular (port). The level of fouling present on the port side was similar to the amount that was present during the underwater survey conducted in May, 2018, prior to cleaning the hull. Specifically, there was slime and sea grass covering a large portion of the underwater hull (see Figure 17). These observations were unexpected for two reasons. The first relates to the speed of fouling taking place on the Cygnus hull. Prior to the May hull cleaning, the Cygnus hull had not been cleaned in two years. It was anticipated that the level of fouling present in September, just 3.5 months post hull cleaning, would be much less than that observed during the May survey. Some reasons that could have led to rapid fouling growth during this short period include the relatively warm temperatures during summer 2018 in the region and a depletion in anti-fouling coating.

Figure 17. Images of port side of hull during September, 2018 dry dock

The second oddity relating to the September hull condition is that the level of fouling differed on the port and starboard sides of the vessel with the starboard side having a higher level of fouling. The May survey results indicated that the starboard side of the hull had a slightly worse level of fouling. It was anticipated that if one side was more fouled than the other in September, it would have been the starboard side to be consistent with earlier results. Increased fouling on one side of the vessel could result from frequent docking on one side (fouling occurs more on side subject to sunlight) or lower quality of anti-fouling coating on one side of vessel. Cygnus Captains were consulted and it was confirmed that the docking side varies. The anti-fouling paint was noted to be highly depleted in September, on both sides of the vessel (see Figure 18). This likely played a role in the high fouling accumulation rate during the summer period.

Note that the anti-fouling paint is the black paint that can be observed in Figure 18. This image indicates the level of depletion of the anti-fouling paint after the biofouling was removed using a pressure washer in dry dock. The anti-fouling paint adhesion was investigated by brushing it lightly by hand using a scouring pad. This resulted in the anti-fouling paint flaking off as a result of the brushing. It is possible that the May and September hull cleaning events enhanced this level of depletion. However, if the anti-fouling paint had adhered properly upon initial application, it would not flake away so easily.

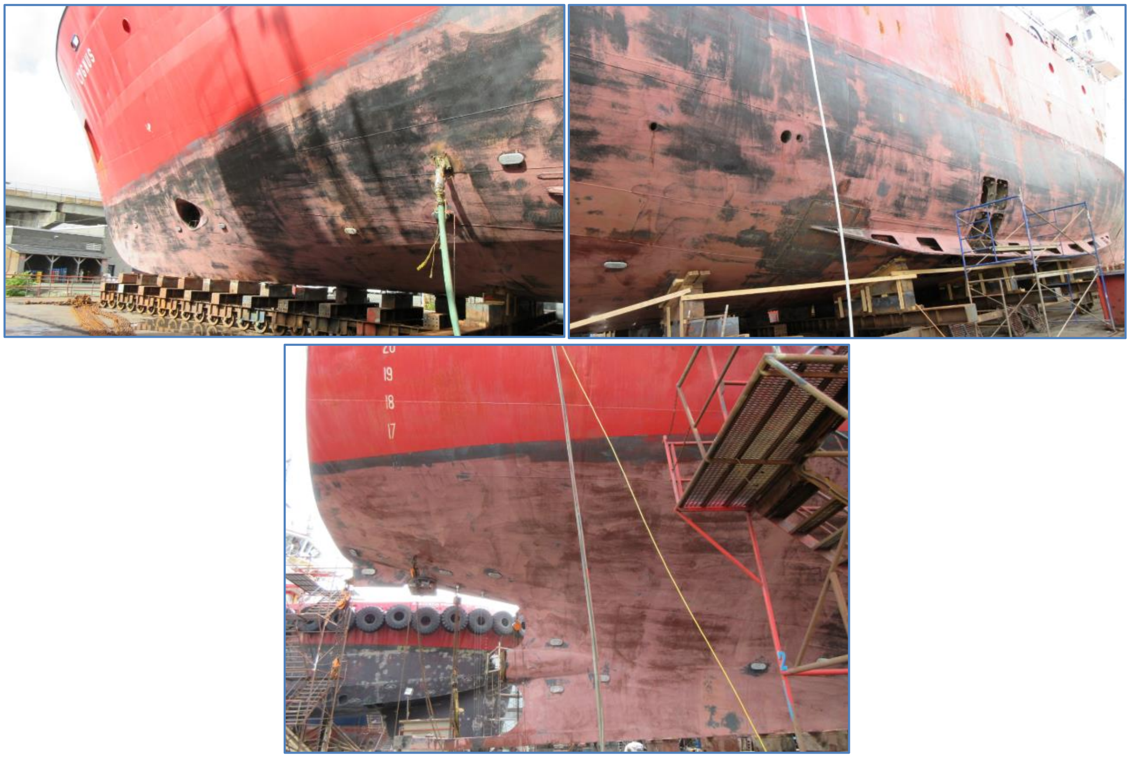


Figure 18. Images of Anti-fouling coating after biofouling was removed

The status of the anti-fouling paint was considered further by consulting with the Canadian Navy. A Canadian Navy biofouling Subject Matter Expert (SME) noted that the level of depletion of anti-fouling coating on the CCGS Cygnus was not typical given that the anti-coating was applied to the vessel only two years prior. The Canadian Navy SME indicated that this level of depletion was not seen on Navy vessels even after 5 years of use. They suggested to check on conditions during application and noted that application during high humidity levels could lead to faster depletion of coating. They also indicated that the type of coating used on the CCGS Cygnus was different than that used on Navy vessels and recommended that the CCG use an alternative coating.

The relatively high level of fouling present in September likely has an impact on the results presented in this report since there may have been a level of fouling present on the hull during post cleaning trials. This is particularly true for the post propeller cleaning trials which were not conducted until August 1, 2018. Unfortunately, there is no way to quantify the amount of fouling present during the post hull cleaning and post propeller cleaning trials. In general, if fouling was present during the post hull cleaning trials the analysis would indicate a lower level of power and fuel savings than the actual values. Also, if more fouling was present during post propeller cleaning trials than during post hull cleaning trials, the discrepancy between the measured savings potential and the actual savings potential would differ between trials and be larger for the post propeller cleaning trials. This could relate to the unexpected result of the post propeller trials found from the ITTC analysis methods.

9 Discussion and Recommendations

The measured results indicated a 4.1% savings in terms of required power to attain a given speed as a result of cleaning the hull and a 5.0% savings as a result of cleaning the propeller, for speeds between 12.5 and 16 knots. However, there were variations in the environmental conditions and condition of the vessel between trials and these differences have an influence on vessel performance. The wind, wave and water temperature variations between trials were corrected based on ITTC guidelines. The wind correction was also made using two variations of the ITTC recommended wind resistance correction method for comparison. The discrepancy between vessel displacement during the different trials was not corrected for since there was no standard guideline available to correct for this when the displacement varied by more than 2%. It was estimated that the displacement between trials varied by approximately 8%. The hull condition also varied between trials in that there was likely some level of fouling present during both the post hull clean and post propeller clean trials. Therefore there is some uncertainty in level of fouling between the post hull and post propeller cleaning trials. Based on the data that was corrected for wind (NavCad correction method), waves and water temperature, there is an average of 5% savings in terms of power required to attain a given speed as a result of cleaning the hull, for speeds between 13.5 and 16 knots. The performance decreases after the propeller polishing in this same speed range based on this analysis. To correct for wind, wave and temperature variation a number of parameters (e.g. wind resistance coefficient, propeller pitch for each trial, hull underwater area) had to be estimated. As a result, there is uncertainty involved in the corrected power values.

In terms of fuel consumption, there appeared to be a measurement error during the post hull cleaning trials which led to lower fuel consumption rates for a given power setting. This could be a result of partially closed fuel valve(s) surrounding one of the main engines. Therefore, it was impossible to quantify fuel savings resulting from cleaning the hull directly from the measured data. The general fuel consumption rate versus shaft power regression equation was used to calculate the corrected fuel consumption rates for each trial using the corrected (NavCad wind, ITTC wave and sea temperature) power values. This resulted in a corrected fuel consumption rate versus speed through water plot for each set of sea trials. The results for each trial were very similar and there were no quantifiable differences in the three curves.

9.1 Sources of Variation and Correction Consequences

As noted, three main sources of variation between the trials includes environmental conditions, vessel displacement and the hull fouling condition. Corrections for wind, wave and sea temperature variation were made and resulted in power versus speed curves that were lower (less power required for a given speed) for both the baseline and post hull cleaning trials. The post propeller cleaning trials were not as affected by this correction due to the relatively small wind and wave conditions during trials. This correction pushed the power versus speed curves for the baseline and post hull trials towards and even lower than that of the post propeller polishing trials as can be seen when comparing Figure 6 and Figure 11. The variation in displacement was not corrected for but it should be noted that the displacement during baseline trials was approximately 8% higher than that of the other two trials. If this discrepancy between trials was corrected for the power versus speed curve for the baseline trials would be lower (less power required to attain a given speed) and the power versus speed curves for the post hull and post propeller cleaning trials would be relatively unaffected. This would reduce the gap between the baseline and post cleaning trials, indicating less performance increase subsequent to cleaning. The variation in hull fouling condition was also not accounted for. This was the variable factor in this study since the goal is to quantify changes to vessel speed and power performance prior to and subsequent to cleaning the hull and propeller. However, it was not anticipated that there would be some level of fouling present on the hull during the post hull cleaning and post propeller cleaning trials. It is probable that some fouling was present at the time of the final two trials given the condition of the hull in early September 2018. If the results were corrected to account for slight fouling present during the post cleaning trials the power versus speed curves for these two trials would be lower, pushing these curves further away from the baseline trials curve and indicating better performance post cleaning.

In terms of both the power and fuel consumption, there is a range in the measured values at a given throttle setting during each of the sea trials. There is also a range in the speed through water values between the different tests at each throttle setting. There is some overlap between these ranges across the baseline, post hull and post propeller cleaning trials which makes it difficult to quantify power and fuel performance changes between trials. However, multiple tests were conducted at each throttle setting and the means of the data from each of these tests was used to define regression equations describing each of the sea trials. These mean based regression equations were used to quantify the variation between trials.

9.2 Recommendations to Reduce Uncertainty and Gain Result Clarity

There were a number of recommendations identified for conducting a similar study in the future which would lead to lower uncertainty in the data and more clarity in the results. These are summarized in point form below.

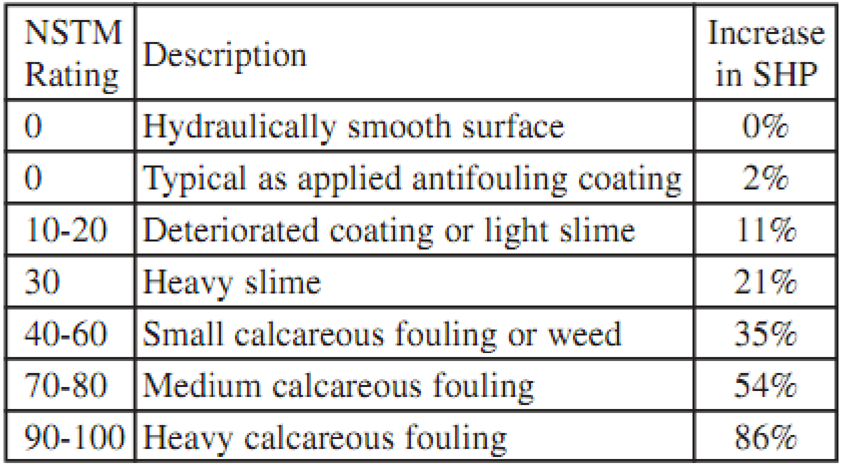
1. Conduct all tests in very low wind and wave conditions. In this project the baseline trials and post hull cleaning trials were conducted in similar conditions which were high in terms of the environmental condition limit. The post propeller cleaning trials were conducted in relatively mild conditions. The methods to correct for wind and wave conditions lead to uncertainty in the results since certain parameters need to be estimated. In mild conditions these corrections are much smaller and therefore less significant.
2. Conduct all tests at the same displacement. Variations in displacement lead to changes in vessel performance. In this project it was attempted to complete all trials at the same draft levels. However, since the Cygnus is an operational vessel and trials were completed weeks apart this was difficult to manage. As such, there was a variation in the draft (and displacement) and the effect of this on the results was not quantified. Trials at the same displacement would not have this source of variation and would lead to increased confidence in results.
3. Select vessel that has available propeller open water curves, wind tunnel test data and model resistance test data. This would reduce the number of parameters estimated in the data correction analysis and lead to lower uncertainty in the results.
4. Conduct tests closer together in time. The three tests involved in this test were completed between May – August of 2018. During this time there was some level of fouling that developed on the hull between trials and subsequent to the hull cleaning. This leads to a lower level of confidence in the results since there may have been some fouling present during both post hull and post propeller cleaning trials. If the trials had occurred closer together in time (e.g. days apart rather than months) this would limit the potential for fouling to develop on the hull or propeller between trials.
5. Conduct study on a vessel that has an off-season or longer alongside duration. The CCGS Cygnus is continuously in operation throughout the year and has a short, 2 day, layover period between operations. This gives limited time for the accumulation of biofouling and as such it was expected that the amount of fouling present initially on the Cygnus would be relatively low. The performance increase as a result of cleaning the hull and propeller would be larger for a vessel with more fouling in the baseline condition. A good candidate

would be a vessel that does not operate for a portion of the year, during which time fouling would accumulate faster than during operations.

9.3 Comparisons to Similar Publically Available Data

A brief literature search was completed to compare the results of this study to data available in the public domain. There were no directly comparable results identified in the literature in terms of comparable vessel size or initial level of fouling. However there were guidelines identified that provided insight as to what performance increases could be expected from cleaning the hull based on different initial levels of fouling (Schultz, 2007). These guidelines are based on model scale drag measurements and boundary layer similarity law analysis and were made for a mid-sized naval combatant at two speeds, 15 and 30 knots. Different fouling ratings (FR) as per the Naval Ships Technical Manual (2006) were used in this study. Table 10 summarizes the results of this study for a vessel speed of 15 knots in terms of increase in shaft power resulting from different levels of fouling. As discussed in Section 3, the fouled (baseline) condition of the CCGS Cygnus was mostly FR 20 with some areas having FR 30 (~15% of vessel). The corrected (for wind, wave and temperature) results indicate that the baseline trials required approximately 5 % more power than trials during which the hull was clean, for speeds greater than 13.5 knots. This is smaller than the 11% estimated increase in power for FR 10-20 as outlined in Table 10. However, the baseline condition was not a hydraulically smooth surface and was better described as a somewhat deteriorated coating. Therefore, it is reasonable to expect a lower power savings when comparing the two conditions.

Table 10. Expected performance changes as a result of hull fouling (From Shultz, 2007)



NSTM Rating	Description	Increase in SHP
0	Hydraulically smooth surface	0%
0	Typical as applied antifouling coating	2%
10-20	Deteriorated coating or light slime	11%
30	Heavy slime	21%
40-60	Small calcareous fouling or weed	35%
70-80	Medium calcareous fouling	54%
90-100	Heavy calcareous fouling	86%

Giorgiutti et al. (2014) conducted a study to investigate the impact of fouling on a crude oil tanker. This study investigated the effects of fouling on the hull and propeller separately and involved several sea trials. The data from sea trials was analyzed using ITTC analysis guidelines and complimented with other recommended methods. The analysis involved corrections for wind, wave, sea temperature and displacement variation. Details on the displacement during each trial or how this was corrected for were not provided. In this study the level of fouling at baseline condition was much higher on both the hull and propeller than that which was present on the Cygnus. The fouling was not rated as per Naval Guidelines however it was indicated that there was severe hard, calcareous fouling that was difficult to remove covering the majority of the propeller and underwater hull surface. The savings resulting from cleaning the hull and propeller were approximately 45 % in terms of reduced power at cruising speed. This study included both propeller cleaning and polishing.

A Computational Fluid Dynamics (CFD) based study was presented by Demirel et al. (2016) in the Journal of Applied Ocean Research. This investigation predicted the effect of biofouling on resistance and power requirements of a container ship based on full scale simulations. These predictions indicated an increase in power by 18.1% for the ship fouled with light slime and an increase by 38% for the ship fouled with heavy slime. There were no full scale sea trials used to compare or validate the CFD results. However, model test data was compared to the non-fouled predictions and they compared well.

In general, there is limited comparison data available in the public domain for this type of study, particularly data resulting from sea trials. The data that does exist can be compared generally but not directly since the hull forms and initial level of fouling vary. In addition, there are gaps in the methodologies applied for data analysis and trial corrections for the comparative data that is available in the literature.

9.4 Concluding Remarks

The primary goal of this study was to quantify the effects of cleaning the hull and propeller on the vessel performance in terms of speed and power, for the CCGS Cygnus. The corrected sea trials data indicated a reduction in power required to attain a given speed by an average of 5% between the speed ranges of 13.5-16 knots. However, these results were not corrected for variation in displacement across trials or the presence of slight fouling during the post cleaning trials. The results compare reasonably to estimations of power increase for a mid-sized Naval frigate for similar baseline and fouled conditions.

This study provided insight towards steps that could be taken to increase the value of future tests of a similar nature. These recommendations should be considered when planning future work to increase the level of confidence in results.

10 Acknowledgement

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Appendix A – Trials Test Logs

Baseline trial:

Measured or observed data														
1	Main engine output setting		50%		65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12
3	Heading	(deg)	229.41	48.71	227.16	48.79	228.08	47.99	226.88	46.72	227.71	48.04	227.58	47.23
4	Mid time of each run	(hour)	12:57:00	13:15:00	16:11:00	13:47:00	14:04:00	14:19:00	14:34:00	14:50:00	15:08:00	15:24:00	15:39:00	15:55:00
5	Ship speed over ground	(knots)	6.91	8.02	10.77	11.23	13.73	14.45	13.84	14.38	16.10	16.41	16.01	16.06
6	Ship speed through water	(knots)	7.06	7.93	10.84	11.22	13.89	14.23	13.95	14.26	16.00	16.17	15.93	15.86
7	Current velocity	(knots)	-0.15	0.09	-0.07	0.01	-0.16	0.21	-0.11	0.13	0.10	0.24	0.09	0.20
8	Propeller shaft speed	(rpm)	172.21	174.04	198.03	199.33	223.18	223.33	223.31	223.08	249.82	249.81	249.84	248.99
9	Propeller shaft torque	(kN-m)	15.29	14.56	30.70	30.15	61.87	59.65	61.27	59.64	101.39	98.39	99.07	89.66
10	Propeller shaft power	(kW)	275.73	265.30	636.67	629.25	1446.04	1395.13	1432.80	1393.31	2652.58	2573.89	2592.02	2337.86
11	Fuel Consumption	(l/hr)	120.28	128.85	245.58	241.22	447.69	436.83	448.54	442.33	785.00	768.62	776.80	714.65
12	Relative wind velocity	(knots)	31.97	12.59	29.05	6.10	35.43	2.65	33.90	0.55	35.40	0.12	34.53	-0.45
13	Relative wind direction	(deg)	-11.45	158.18	-4.25	147.81	-6.21	115.15	-6.00	108.35	-1.93	75.15	5.47	80.16
14	True wind velocity	(knots)	25.24	20.26	18.33	16.71	21.83	15.76	20.19	14.57	19.32	16.38	18.66	16.14
15	True wind direction	(deg)	214.84	215.35	220.42	217.58	217.97	219.24	216.77	224.66	224.18	227.64	237.74	228.79
16	Wind resistance coefficient		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17	Mean wave period	(s)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
18	Significant wave height	(m)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
19	Mean wave direction	(deg)	214.84	215.35	220.42	217.58	217.97	219.24	216.77	224.66	224.18	227.64	237.74	228.79
20	Incident angle of waves	(deg)	14.57	-166.64	6.74	-168.79	10.11	-171.25	10.11	-177.94	3.53	-179.60	-10.16	-181.56

Post hull cleaning trial:

Measured or observed data																
1	Main engine output setting		50%				65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Heading	(deg)	228.71	46.68	229.59	48.48	232.50	52.85	229.54	48.41	229.48	48.27	227.50	47.41	228.35	46.03
4	Mid time of each run	(hour)	10:30:00	10:45:00	11:00:00	11:16:00	11:32:00	11:46:00	12:04:00	12:20:00	12:36:00	12:52:00	13:08:00	13:25:00	13:41:00	13:58:00
5	Ship speed over ground	(knots)	7.81	7.88	7.63	7.86	11.30	11.69	14.53	14.78	14.45	14.86	16.36	16.40	16.39	16.39
6	Ship speed through water	(knots)	7.58	7.94	7.46	7.99	11.20	11.81	14.24	14.88	14.29	14.90	16.03	16.31	16.06	16.35
7	Current velocity	(knots)	0.23	-0.06	0.17	-0.12	0.10	-0.12	0.30	-0.09	0.15	-0.04	0.32	0.10	0.34	0.03
8	Propeller shaft speed	(rpm)	173.66	173.73	173.85	173.70	201.71	201.72	227.31	227.50	226.36	228.28	249.94	249.97	249.94	249.92
9	Propeller shaft torque	(kN-m)	17.07	16.46	17.56	16.47	36.02	33.86	67.28	64.52	65.96	65.39	103.22	101.39	102.92	100.83
10	Propeller shaft power	(kW)	310.36	299.51	319.63	299.60	760.72	715.20	1601.45	1537.08	1563.32	1563.15	2701.52	2653.77	2693.55	2638.58
11	Fuel Consumption	(l/hr)	103.52	102.41	108.23	107.42	226.94	216.41	440.20	425.90	433.36	436.39	740.38	729.48	742.93	730.64
12	Relative wind velocity	(knots)	23.61	7.91	27.76	6.72	35.91	10.41	41.59	7.22	39.99	0.12	38.47	3.08	37.05	5.66
13	Relative wind direction	(deg)	-8.15	153.49	-13.78	160.60	-9.62	140.10	-8.29	142.46	-7.90	130.43	-2.00	98.48	-8.90	108.27
14	True wind velocity	(knots)	15.92	15.37	20.43	14.37	24.83	20.78	27.29	20.98	25.76	14.94	22.13	17.13	21.01	18.94
15	True wind direction	(deg)	216.57	213.41	210.70	219.54	218.52	214.12	216.85	216.29	217.15	227.91	224.02	217.19	212.52	209.55
16	Wind resistance coefficient		0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9
17	Mean wave period	(s)	2.50	2.25	2.00	2.10	2.20	2.30	2.40	2.45	2.50	2.85	3.20	3.20	3.20	2.90
18	Significant wave height	(m)	0.18	0.20	0.21	0.24	0.27	0.32	0.36	0.36	0.36	0.38	0.40	0.39	0.38	0.36
19	Mean wave direction	(deg)	242.00	241.00	240.00	238.50	237.00	239.00	241.00	244.00	247.00	246.00	245.00	245.00	245.00	243.00
20	Incident angle of waves	(deg)	-13.29	-194.32	-10.41	-190.02	-4.50	-186.15	-11.46	-195.59	-17.52	-197.73	-17.50	-197.59	-16.65	-196.97

Post propeller cleaning trial:

	Measured or observed data															
1	Main engine output setting		50%				65%		80%				100%			
2	Run number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	Heading	(deg)	49.52	229.46	50.05	230.90	49.60	232.30	51.21	232.13	50.59	232.04	52.51	232.94	52.96	233.72
4	Mid time of each run	(hour)	11:50:00	12:05:00	12:24:00	12:39:00	12:56:00	13:10:00	13:25:00	13:38:00	13:51:00	14:04:00	14:19:00	14:33:00	14:47:00	15:00:00
5	Ship speed over ground	(knots)	7.68	7.66	7.70	7.73	11.11	11.47	14.40	15.02	14.50	14.95	16.09	16.49	16.10	16.46
6	Ship speed through water	(knots)	7.85	7.50	7.95	7.50	11.54	11.18	14.77	14.65	14.82	14.63	16.26	16.07	16.25	16.05
7	Current velocity	(knots)	-0.17	0.16	-0.25	0.23	-0.43	0.29	-0.37	0.37	-0.32	0.32	-0.17	0.42	-0.15	0.40
8	Propeller shaft speed	(rpm)	172.80	172.88	172.71	172.68	200.07	200.14	228.96	229.02	229.02	228.99	249.82	249.80	249.83	249.83
9	Propeller shaft torque	(kN-m)	14.72	15.12	14.62	15.05	31.30	32.06	64.59	65.54	64.76	65.30	97.10	98.13	96.58	97.58
10	Propeller shaft power	(kW)	266.38	273.68	264.39	272.21	655.70	671.88	1548.65	1571.79	1553.17	1565.75	2540.21	2566.80	2526.67	2552.92
11	Fuel Consumption	(l/hr)	129.18	131.08	130.03	132.11	256.19	259.37	496.24	502.18	498.96	503.07	769.33	776.50	767.61	776.35
12	Relative wind velocity	(knots)	2.64	14.10	1.78	14.25	3.88	18.96	10.01	18.86	10.44	20.16	9.14	24.69	6.13	24.91
13	Relative wind direction	(deg)	80.64	-13.04	86.27	-7.61	56.94	-9.50	37.94	-9.09	32.57	-6.13	25.35	6.42	13.93	11.89
14	True wind velocity	(knots)	7.71	6.86	7.78	6.67	9.56	7.88	8.95	4.68	8.01	5.53	8.76	8.50	10.26	9.43
15	True wind direction	(deg)	209.78	201.82	216.90	214.45	209.70	208.89	187.80	192.53	186.01	209.13	205.98	251.89	224.68	266.66
16	Wind resistance coefficient		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17	Mean wave period	(s)	12.70	12.70	6.70	6.70	6.90	6.90	6.40	6.40	7.80	7.80	7.40	7.40	7.00	7.00
18	Significant wave height	(m)	0.35	0.35	0.53	0.53	0.46	0.46	0.47	0.47	0.57	0.57	0.54	0.54	0.59	0.59
19	Mean wave direction	(deg)	242.00	241.00	240.00	238.50	237.00	239.00	241.00	244.00	247.00	246.00	245.00	245.00	245.00	243.00
20	Incident angle of waves	(deg)	-192.48	-11.54	-189.95	-7.60	-187.40	-6.70	-189.79	-11.87	-196.41	-13.96	-192.49	-12.06	-192.04	-9.28