Specialist Committee on Surface Treatment

Final report and recommendations to the 26th ITTC

1. Introduction

1.1. Membership

R. Anzböck, VMB, Austria, (Chairman)
M. Leer-Andersen, SSPA, Sweden, (Secretary)
M. Atlar, Newcastle University, UK
J. H. Jang, Samsung HI, Korea,
H. Kai, Yokohama National University, Japan
E. Carillo, CEHIPAR, Spain
M. Donnelly, NSWCCD, USA, left the committee on 29-01-2010

1.2. Meetings

The committee met 4 times:
November 24, 25, 2008, Vienna
May 11, 12, 2009, Madrid
February 1, 2, 2010, Daejeon
October 28,29, 2010, Gothenburg

1.3. Tasks

Below we list the tasks given to the committee by the 25th ITTC

1. Review state of the art of different surface treatment methods
2. Review the possible impact on ship performance in the following areas in the light of the recent rapid development of coating systems:
   a.) Resistance (friction line)
   b.) Propeller characteristics
   c.) Cavitation behavior
   d.) Comfort (propeller induced noise)
   e.) Acoustic signature
3. Review the existing measurement methods for surface roughness at model-scale and at full-scale
4. Propose methods that take into account surface roughness and other relevant characteristics of coating systems in model testing.
   a.) Check the need for changes to the existing extrapolation laws
   b.) Study the roughness allowance for high-speed and conventional ships (hull, appendages and propellers)

TASK 1: REVIEW STATE OF THE ART OF DIFFERENT SURFACE TREATMENT METHODS

The committee found practically no support from paint manufacturers; except brochures where they claim reduction of fuel consumption up to 10 % neither reliable measurements nor serious data were provided by the industry. In the following a short overview over the products of several paint manufacturers given and a few essential comments are added to the single products.

Hempel:

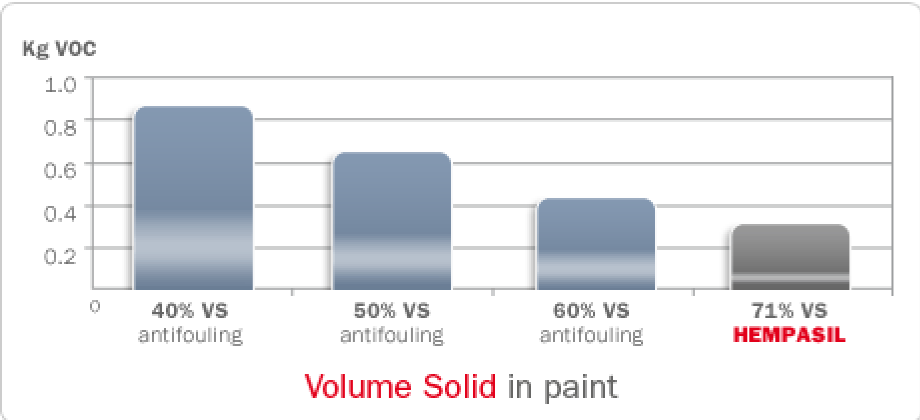
Hempasil X3

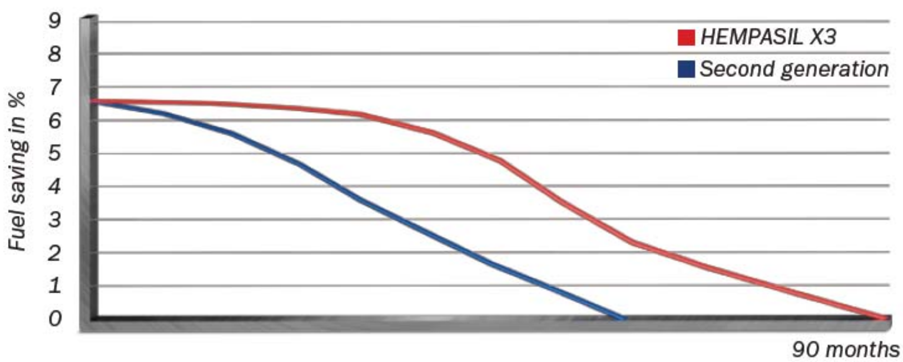
Type: Silicone Hydrogel, low surface energy

Toxicity: low toxicity, biocide free (VOC=Volatile organic compound)

Fouling: Self cleaning from 8knots. Silicon polymers form a hydrogel microlayer between the paint surface and the seawater, resulting in enhanced antifouling capability, and improved self-cleaning potential.
Service inter: 90months

Friction: Hempel does not claim reduction in frictional resistance per se, but claims reduced resistance due to less fouling. They claim 4-8% fuel savings (see XXXXXX). Tested at Force towing tank, plates of about 1m2. Have not obtained test report.





HEMPASIL 77500

Type: Silicone, water repellent low surface tension, second generation

Toxicity: biocide free
Fouling: Self cleaning above 8knots
Service inter: 40months

Friction: As seen below they claim big improvements in power, however underlying data must be investigated if possible. They claim AHR of 20micron compared to 125-150 for convetional

Vessel type	Power efficiency improvement of HEMPASIL	Service speed (Knots)
ROPAX	7.5%	22
Large container vessel	10,6%	24
Aframax tanker	11.3%	15
Bulk carrier	8.8%	15

Figure 1: Compared to self polishing antifouling

GLOBIC NCT

Type: Anti-fouling nanocapsule,
Toxicity: Cuprous oxide and other biosides

Fouling: self polishing toxic anti fouling self smoothing
*Service inter:*60months

Friction: self smoothing, exists in low (deep seae) and high polishing (coastal)

OLYMPIC

Type: Anti-fouling mineral fibres, high mechanical strength
Toxicity: Low level of VOC (400g/litres)

Fouling: self polishing toxic anti fouling self smoothing
Service inter:?

Friction: self smoothing, exists in low (deep sea) and high polishing (coastal)

OCEANIC

Type: Anti-fouling mineral fibres, medium mechanical strength
Toxicity:
Fouling:
*Service inter:*36month

Friction: self smoothing, exists in low (deep sea) and high polishing (coastal)

Comparison of Hempel paints

	Hempasil	GLOBAL NCT	OCEANIC	OLYMPIC
Mechanical	Exellent	Excellent	Very good	good
Fuel saving	Exellent	High	Fair	Neutral
Drydock inter	+60	60	60	36
Speed	>13kn	0-35knot	10-30knot	10-25knot
Self polishing	None	Excellent	Very good	good
VOC	275g/litre	400g/litre	430g/litre	450g/litre
Binder	Silicon	Nanocapsule	Zinc carboxylate	Natural rasin
Biocide efficiency	None	High	Medium	Fair

INTERNATIONAL

INTERSLEEK 700

Type: Silicone elastomer fouling release, self cleaning
Toxicity: None
Fouling:
Speed: 15-30knots
*Service inter:*36month

Friction: Claims 4% fuel savings compared to traditional SPC. Average AHR 100

INTERSLEEK 900

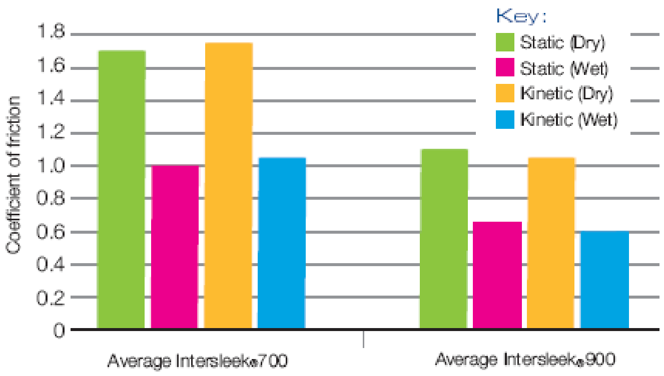
Type: Fluropolymer fouling release, self cleaning
Toxicity: None

Fouling: Hydrophobic waterreppelent surface, 40% lower barnacle shear adhesion strength than intersleek 700. Better slime repellent
Speed: >10knots
*Service inter:*36month

Friction: Claims 6% fuel savings compared to intersleek 700. Average AHR 75 (Intersleek 700 AHR=100, typical SPC(Self Polishing copolymer)=125micron. Also claims better efficiency parameter (wave length). With below method claiming 38% lower Cf than intersleek 700

The following graphs, which are copies of the manufacturer’s brochure, show, what “International” claims for their products “Intersleak 700” and “Intersleak 900”. They promise a reduction of the friction coefficient of 38% without any proof; nevertheless a fuel reduction of 6% is guaranteed ignoring the type of ship, the Froude numbers and the ratio of frictional resistance to total resistance.

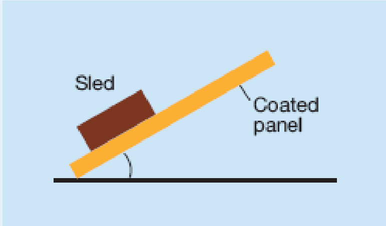
Frictional Coefficient of Intersleek®700 & Intersleek®900



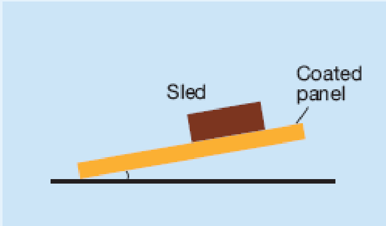
Summary of Measured Static and Kinetic Coefficient of Friction for Intersleek®700 and Intersleek®900

Intersleek®900 has an **average hull roughness of 75 microns** and an open textured surface reducing the coefficient of friction by 38% giving a predicted fuel and emissions saving of 6%

* Reference: ASTM D1894-06 'Static and Kinetic Coefficient of Friction'



Static: with the sled at rest on the incline, raise the incline until the sled starts to slide. The tangent of that threshold angle is a measure of the coefficient of static friction.



Kinetic: with the sled on the incline, raise the incline in steps and bump the sled gently to set it into motion. If it slows to a stop, then friction overcomes gravity. Repeat to find the angle at which it moves down the incline at constant speed. The tangent of that angle is a measure of the coefficient of kinetic friction.

INTERSWIFT 655

Type: Self polishing copolymer (SPC)
Toxicity: Copper Acrylate biocide release

Fouling: Biocide release
*Service inter:*36month
Friction: No info found

INTERSMOOTH 746

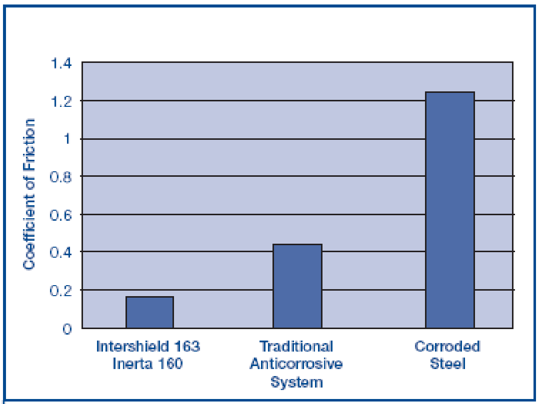
Type: Self polishing copolymer (SPC), lower solvent emission
Toxicity: Copper Acrylate biocide release

Fouling: Biocide release
*Service inter:*up to 60month
Friction: No info found

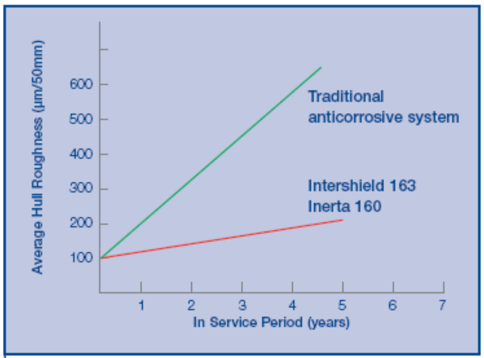
INTERSHIELD 163 INERTA 160

Type: Anti-corrosive, Ice resistant, no ice adhesion, high mechanical strength, low temperature
Toxicity: Low VOC (40g/litre)

Fouling: No anti fouling normally
*Service inter:*No information found
Friction: Claims 7-10% fuel saving compared to traditional ani corrosive paint.



Graph 2: Coefficient of Friction.



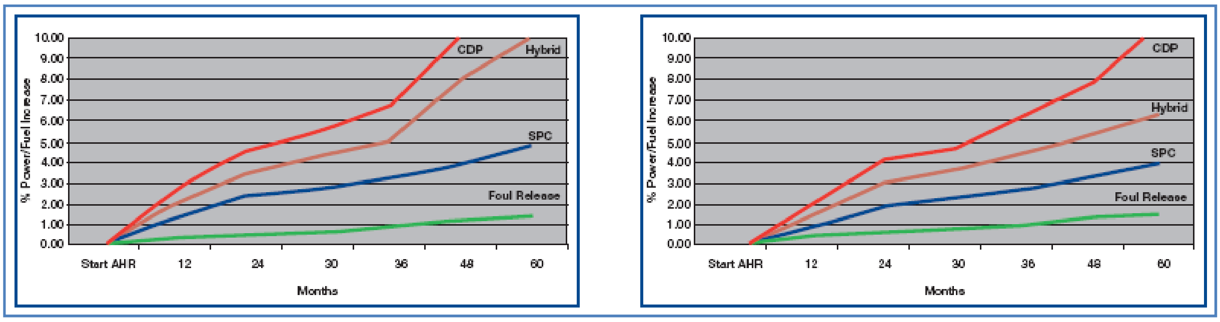
Graph 1: Average Hull Roughness (AHR).

Comparisons between International paints

Data taken from http://www.international-marine.com/Literature/HRPC_Folder_Paper.pdf "Hull roughness calculator"

	Intersmooth SPC	Intersleek 700	Intersleek 900
Paint cost ($)	320,000	516,000	755,000
Extra over SPC ($)	-	196,000	435,000
Fuel saving (%)	-	4%	6%
Fuel usage MT / Day	140	134.4	131.6
Fuel cost MT / Day	42,000	40,320	39,480
Days trading	310	310	310
Fuel cost pa	13,020,000	12,499,200	12,238,800
Savings pa	-	520,800	781,200
Fuel savings over 5 years	-	2,604,000	3,906,000
Nett savings over 5 years	-	2,408,000	3,471,000

Figure 2: Savings



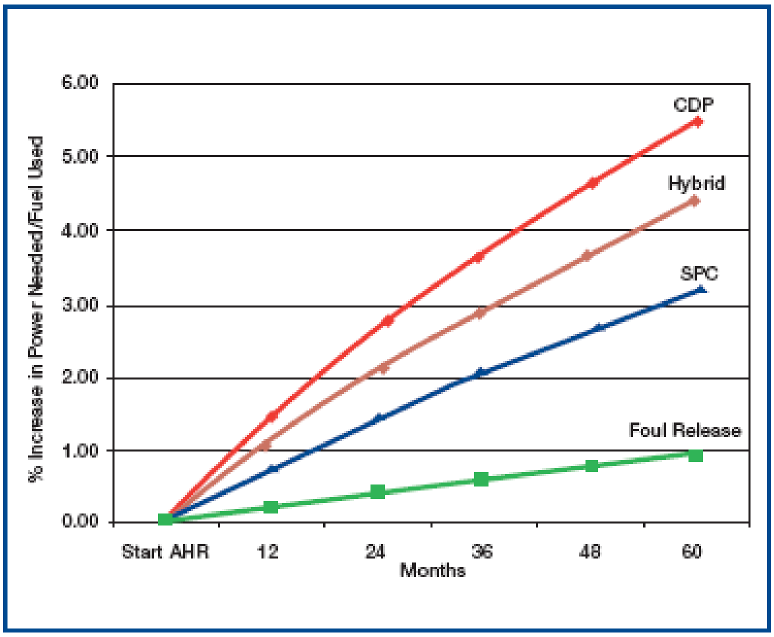


Figure 3: Fuel increase usage (hybrid= mix of CDP and SPC (Interswift), CDP=Controlled Depletion Polymer (Interspeed), SPC=Self polishing copolymer (Intersmooth), Foul release (Intersleek)) . All figures have same description?

JOTUN

Very little information found

SEALION

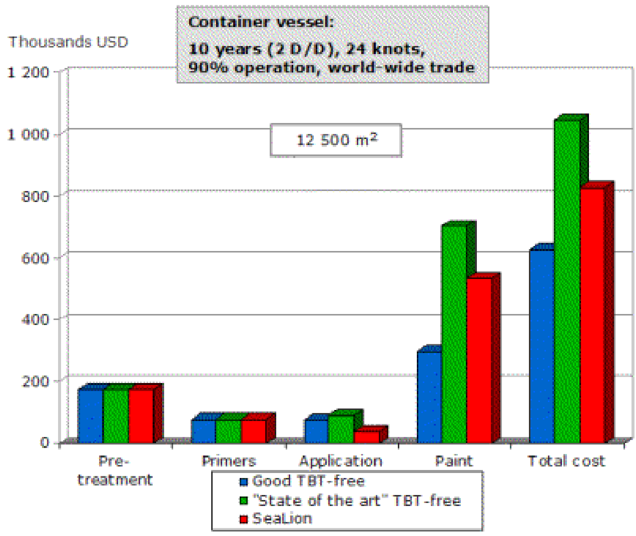
Type: Foul release Silicone elastomer

Toxicity:

Fouling:

Service inter:

Friction:



SeaQuantum

Type: Self smoothing and self polishing (SPC) Hydrolising

Toxicity:

Fouling:

Service inter:>60month

Friction: No information found

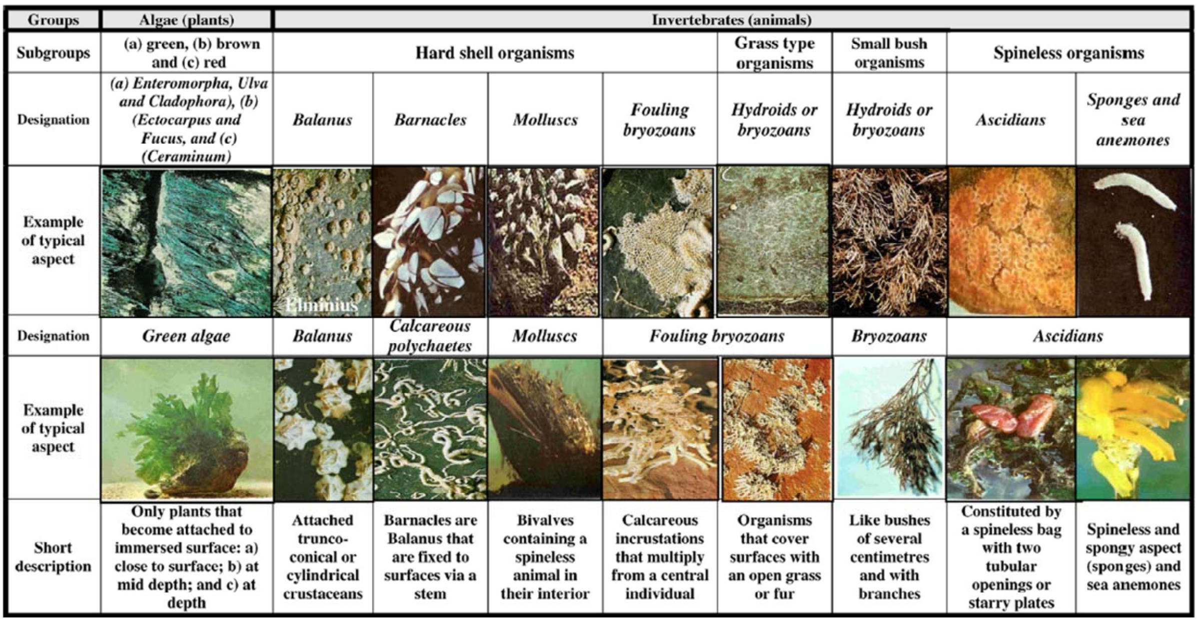
Paints for different application areas

Critical areas in ship painting	Main requirements	Typical paint systems
Sides and superstructures	Appearance, anticorrosive protection, washability, UV resistance	Pure or modified epoxy primer/epoxy topcoat Aliphatic polyurethane Aliphatic polyurethane/acrylic Polysiloxane/epoxy hybrid (anti-rust stain topcoat may be applied)
Decks	Appearance, anticorrosive protection, washability, UV resistance, non-slip	Zinc silicate followed by two-pack epoxy/polyurethane system Trowel- or roller-applied elastomer (1–3 mm) over high build primer Topcoat should include aggregates, e.g. aluminium oxide, silica or others to provide non-slip properties
Tanks		
Ballast	Resistance to alternating contact with sea water and with transported products	Modified epoxy Aluminium-pigmented pure epoxy Solvent-free epoxy Special waterborne asphaltic emulsion Cement-reinforced acrylic
Cargo Crude or petroleum Oils or hydrocarbons Very aggressive products	Resistance to contact with specific cargo types	High-solid or solvent-free polyamine-cured epoxy High-solid polyamine epoxy Epoxy-cyclosilicone

Figure 1: Typical paint systems for different application

Types of fouling

Several thousand species of marine organisms can foul the surface of a ship. Most will stay attach or release when the ship speed is above 4-5knots. Which organisms can attach is affected by many factors such as pH, temperature, salinity, dissolved salts and oxygen concentration.



Groups	Algae (plants)	Invertebrates (animals)							
Subgroups	(a) green, (b) brown and (c) red	Hard shell organisms				Grass type organisms	Small bush organisms	Spineless organisms	
Designation	*(a) Enteromorpha, Ulva and Cladophora), (b) (Ectocarpus and Fucus, and (c) (Ceraminum)*	*Balanus*	*Barnacles*	*Molluscs*	*Fouling bryozoans*	*Hydroids or bryozoans*	*Hydroids or bryozoans*	*Ascidians*	*Sponges and sea anemones*
Example of typical aspect		Elminius							
Designation	*Green algae*	*Balanus*	*Calcareous polychaetes*	*Molluscs*	*Fouling bryozoans*		*Bryozoans*	*Ascidians*	
Example of typical aspect									
Short description	Only plants that become attached to immersed surface: a) close to surface; b) at mid depth; and c) at depth	Attached trunco-conical or cylindrical crustaceans	Barnacles are Balanus that are fixed to surfaces via a stem	Bivalves containing a spineless animal in their interior	Calcareous incrustations that multiply from a central individual	Organisms that cover surfaces with an open grass or fur	Like bushes of several centimetres and with branches	Constituted by a spineless bag with two tubular openings or starry plates	Spineless and spongy aspect (sponges) and sea anemones

Figure 2: Main Marine fouling orgasms

Type of antifouling paints in second half of 20th century

Allthough these paints have been largely phased out some where still used until 2001 where IMO banned the use of TBT paints worldwide, because of their toxic effects on marine life.

TASK 2: REVIEW THE POSSIBLE IMPACT ON SHIP PERFORMANCE IN THE FOLLOWING AREAS IN THE LIGHT OF THE RECENT RAPID DEVELOPMENT OF COATING SYSTEMS

1. Resistance (friction line)
2. Propeller characteristics
3. Cavitation behavior
4. Comfort (propeller induced noise)

Task 2.1. Impact on the Resistance (friction line)

In the following an overview over the recent papers concerning the impact of coating systems on the resistance of a ship is given:

2.1.1. Ship resistance: Resistance Data are published

M. P. Schultz, "Effects of coating roughness and biofouling on ship resistance and powering", Biofouling, 2007, Vol. 23, No.5, pp.331-341

Increased resistance of full-scale ship by surface roughness is calculated in some roughness conditions. Calculation methods are based on model ship resistance results and boundary layer similarity law analysis. The calculation results show increased resistance in heavy calcareous fouling is up to 86%. Values of shaft power of full-scale ship obtained by trial data are given and compared to calculation results. Both results agree well with each other. The resistance coefficient Ct of typical naval ship is shown in Fig.1. However, the data in this figure is NOT so reliable.

T Munk, M Sc, "Fuel Conservation through Managing Hull Resistance", Motor ship Propulsion Conference, Copenhagen April 26th, 2006

In this paper, variations of increased resistance of some actual ships in service are shown. The data shows clearly the effect of dry-dock and propeller polishing. One example shows increase of resistance decreases over 20% thanks to dry-docking. Another example shows increase of resistance decreases about 10% due to propeller polishing. We can see the increase of resistance(%) to days for developments.

K. Yokoi, "On the Influence of Ship's Bottom Fouling upon Speed Performance", Toyama National College of Maritime Technology, Bulletin of Toyama National College of Maritime Technology in Japan2004

Speed trial data of training ship during past 8 years are shown. Variations of Ship speed, shaft horse power, fuel consumption are shown in order to estimate the effect of bottom fouling. The results show shaft horse power increases about 20% in full speed condition because of fouling. Trial data are analyzed and variations of friction resistance are also shown. We can see the shaft-horse power and fuel consumption versus days after dock with self-polish.

Leer-Andersen M, Larsson L, "An experimental/numerical approach for evaluating skin friction on full-scale ships with surface roughness", J. of Marine Science and Technology Vol. 8, No1, 2003

The authors evaluate the increased skin friction of full-scale ships by surface roughness. CFD code "SHIPFLOW" is modified and velocity shift function is used in order to take surface roughness effect into account. In order to determine the velocity shift function by surface roughness, experiment using long pipe in which the wall can be roughened is taken place. Full scale skin friction calculated by "SHIPFLOW" is shown in Fig.14. We can not see any reliable experiment data in this paper.

Lars-Erik Johansson, "The Local Effect of Hull Roughness on Skin Friction. Calculations Based on Floating Element Data and Three-dimensional Boundary Layer Theory", Read in London at a meeting oh the Royal Institution of Naval Architects on April 11, 1984

The effect of surface roughness on skin friction is calculated. The author takes place experiment using floating element and measure both skin friction and velocity profile in boundary layer. Using those data obtained, velocity shift is determined. A boundary layer program for three-dimensional turbulent boundary layers is employed. Roughness effect upon flat plate and two ship hulls are presented. Increase in viscous resistance due to roughness from painted surface of ship is shown in Fig.14.

2.1.2. Ship Resistance: Resistance Data are not published

Y. Yano, N. Wakabayashi : "Presumption of Bottom Fouling in Real Ship", J. of Japan Institute of Navigation , 2008

The authors attempted to presume the degree of bottom fouling of real ship by trial test. They conducted short stopping test with conventional paint and new type paint. From experimental data, they obtained coefficient of stain. From its value, the degree of bottom fouling was assumed and the effect of paint was investigated.

Townsin RL : "The ship hull fouling penalty", International Congress on Marine Corrosion and Fouling No11, San Diego, California , 2003

Friction drag by slime and shell and weed are discussed. Research history about them is shown. Methods to measure the hard paint roughness of antifouling coatings are summarized. The author refers to the relation between surface roughness and skin friction. Economic considerations are also made.

J. Willsher : "The Effect of Biocide Free Foul Release Systems on Vessel Performance", SHIP EFFENCY, 1st International Conference, Hamburg, October 8-9 , 2001

This paper firstly shows cause of hull roughness. The effect of coating on ship performance is calculated by some formula. The effect of biocide free foul release coating to fuel saving is shown. The author concludes foul release products give lower hull roughness than biocidal AF and lower environmental impact whereas higher initial costs.

H. Doi, O. Kikuchi : "Frictional Resistance Due to Surface Roughness (1st Report) - Effect on Reducing of Ship's speed by Roughness Models –", Journal of the Kansai Society of Naval Architects, Japan, No.194 , 1984

Five roughed plate which were obtained in hull of real ships were tested in the circulating water channel and measured frictional resistance coefficient. Speed decrease estimated by plate frictional resistance coefficient was 0.2 ~ 2 knot in case of blunt ships, and 0.3 ~ 3 knot in case of high speed ships.

Y. Yamazaki, H. Onogi, M. Nakato, Y. Himeno, I. Tanaka, T. Suzuki : "Resistance Increase due to Surface Roughness (2nd Report)", Journal of the

Society of Naval Architects of Japan, No.153 , 1984

Since hydrodynamic characteristics of sand roughened surface and painted surface were different in previous report, the author investigated this problem experimentally using simple wavy roughened surfaces. Frictional resistance and velocity distribution in boundary layer were measured in wavy surfaces. Roughness functions were obtained by experimental results.

Y. Yamazaki, H. Onogi, M. Nakato, Y. Himeno, I. Tanaka, T. Suzuki : "Resistance Increase due to Surface Roughness (1st Report)", Journal of the Society of Naval Architects of Japan, No..155 , 1983

The authors conducted experiments using roughened pipes in order to measure frictional resistance and velocity distribution in boundary layer. Relation between roughness height measured by BSRA analyzer and equivalent sand roughness was obtained. Velocity shift by surface roughness is used in order to get resistance increase.

K. Tokunaga, E. Baba :" Approximate Calculation of Ship Frictional Resistance Increase due to Surface Roughness", Journal of the Society of Naval Architects of Japan · No.152 , 1982

In order to calculate frictional resistance of a ship by surface roughness, the authors applied a-two dimensional turbulent boundary layer theory for rough surface to potential streamlines over the hull surface. Potential streamlines were calculated by Hess-Smith method. Increased resistance in full-scale ship was calculated.

M. Sone : "Influence of the Fouled Ship Bottom on the Propulsion Horsepower of the Seikan Ferry-boats", J. of the Marine Engineering Society in Japan, Vol.16, No.2 , 1981

Variations of Propulsion horsepower and fuel consumption of Seikan-Ferry boats were investigated in 10 years using measurement and abstract log-book data. This ship is docked every year and annual increase in delivered horse power due to the ship bottom fouling is about 8%. Since the paint was changed from higher-toxic one to lower toxic one, increase of propulsion horsepower seems to become higher.

H. Orido, M. Kakinuma : "Speed Decrease Due to Hull Surface Roughness (in Japanese)", Bulletin of the Society of Naval Architects of Japan · Vol.616 , 1980

The authors showed practical analysis using data of some ships in service. Relation between surface roughness and ship age was shown. Empirical approximate formula was also shown in the graph and compared with measured data. However, the accuracy of analysis seemed not to be high since the theory was not established enough.

2.1.3. Resistance of Flat Plates

M. Candries, M. Atlar : "Experimental Investigation of the Turbulent Boundary Layer of Surfaces Coated With Marine Antifoulings", 2005

Velocity distributions on turbulent boundary layers on flat plates coated with two different new generation marine antifouling paints were measured. The two paints were Foul Release paint and Tin-free SPC respectively. Smooth flat plate and plate covered with sand grit were also used in order to make sure the performance of two new paints. Remarkable point is that LDV measurements for marine coatings have been published in the open literature.

M. P. Schultz : “Frictional resistance of antifouling coating systems”, Journal of fluids engineering, vol. 126, No.6, 2004

Frictional resistance and velocity distribution on several ship hull coatings in the unfouled, fouled, ad cleaned conditions were measured. Test surface coated with silicone, ablative copper, SPC copper and SPC TBT were used. The experimental results indicated little difference in frictional resistance coefficient among the coatings in the unfouled condition, however, after 287 days of marine exposure, test surface coated with silicone showed the largest increases in frictional resistance coefficient.

M. P. Schultz :” The Relationship Between Frictional Resistance and Roughness for Surfaces Smoothed by Sanding”, Journal of Fluids Engineering, Vol.124, 2002

The effect of sanding on surface roughness was investigated. The author prepared 7 kinds of plates. One of them was not sanded and the others were sanded by different fineness. Plates were towed and frictional resistance was measured in each case. The results showed resistance increase of unsanded plate against polished one was 5% in average. Roughness function ΔU was shown of all plates.

M. Candries, M. Atlar, A. Guerrero and C.D. Anderson : “Lower frictional resistance characteristics of Foul Release systems”, Pro. of the 8th Int. Symp. on the PRADS, Vol. 1, 2001

The roughness and drag characteristics of surface painted with SPC (tin-free Self-Polishing Co-Polymer) and non-toxic Foul Release were investigated. Two plates coated with these two paints were towed in tank and drag was measured. The results showed total resistance of 6.3 m long plate coated with Foul Release coating was 1.4% lower on average than that coated with SPC. Roughness functions of two paintings were shown.

Candries M., Atlar, M. and Anderson, C.D. :” Low-energy surfaces on high-speed craft”, Proceedings HIPER '01, Hamburg, 2001

Towing test is carried out on three surface conditions in order to compare drag characteristics. The surface conditions are Aluminum, SPC and Foul Release coating respectively. From the experimental results, above Reynolds number 2 * 10^7, it is shown total drag coefficient of the foul release surface was on average 1.41% lower than the SPC surface.

M. P. Schultz : “Turbulent Boundary Layers on Surfaces Covered With Filamentous Algae”, Journal of fluids engineering, Vol. 122, No.2, 2000

The effect of algae to frictional resistance was investigated. The surfaces covered with filamentous algae were prepared and put in a closed return water tunnel. A two-component LDV was used to obtain velocity distribution in turbulent boundary layer. Significant increases in the skin friction coefficient for the algae-covered surfaces were measured.

M. P. Schultz and G. W. Swain : “The Effect of Biofilms on Turbulent Boundary Layers”, Journal of fluids engineering, Vol. 121, No.1, 1999

Turbulent boundary layers over natural marine biofilms and a smooth plate were compared. Profiles of the mean and turbulence velocity components were measured. An average increase in the skin friction coefficient was 33 to 187 % on the fouled specimens. The skin friction coefficient was found to be dependent on both biofilm thickness and shape of surface.

2.1.4. Resistance of Circular Cylinders

S.M. Mirabedini, S. Pazoki, M. Esfandeh, M. Mohseni, Z. Akbari : "Comparison of drag characteristics of self-polishing co-polymers and silicone foul release coatings: A study of wettability and surface roughness", Progress in organic coatings, Vol. 57, No.4, 2006

Drag on some surfaces coated with some paints is measured using a smooth aluminum cylinder connected to a rotor device. Downward shift of the velocity distributions and frictional resistance coefficients for each test cylinder by Reynolds number are also measured. The drag characteristics of a surface are affected by its free energy and roughness parameters.

Weinell CE, Olsen KN, Christoffersen MW, et al. : "Experimental study of drag resistance using a laboratory scale rotary set-up", Biofouling, International Congress on Marine Corrosion and Fouling No11, San Diego, California, 2003

A laboratory scale rotary set-up was used to measure the drag resistance, and the surface roughness of the samples was measured. Measurements on pure paint systems and measurements on large-scale irregularities were investigated. The contribution from a modern self-polishing antifouling or silicone based fouling-release paint was negligible compared to the one from irregularities of hull of ship.

Hisao TANAKA, Yasuyuki TODA, Kiyoaki HIGO, Kazuharu YAMASHITA : "Influence of Surface Properties of Coatings to Frictional Resistance", ournal of the Kansai Society of Naval Architects, Vol.239, Japan, 2003

In order to investigate effect of surface properties of coatings to frictional resistance, experiments were carried out using a rotating cylinder type dynamometer built by the authors. Frictional resistance and velocity distribution in turbulent boundary were measured. The aging effect of paints on surface roughness was shown.

2.1.5. Interaction Ship and Propeller

M. Miyamoto :" Estimation and Evaluation of Ship Performance in Actual Seas - Review and Evaluation of Fouling, Aging Effect and Sea Condition-", Journal of the Japan Society of Naval Architects and Ocean Engineers, Vol.4 2007

The author estimates the effect of fouling, aging effect and sea condition upon real ships. The approximate method exploited by the author is verified by comparing with measured data and data of abstract log-book. As a result, it is shown that the accuracy seems to be quantitatively practical. The approximate method could be applied to design stage.

A. Matsuyama, T. Nishiya, T. Araki , T. Imada :" Studies on Propulsive Performance by Marine Fouling of Ship-hull and Propeller", Bulletin of the Faculty of Fisheries, Nagasaki University No.83, 2001

In order to investigate the effect of marine fouling on ship hull and propeller, the author analyzed the log-book data from 1990 to 1998. Shaft horse power, amount of fuel consumption, admiralty coefficient and ship speed were investigated. It was recognized that fuel consumption increases up to 22% from the value of 1990.

K. Nagatomo, H. Matsushita, E. Inui, Y. Miyoshi : "Studies on Marine Fouling of the Bottom Plates and Propeller Surface – 1", The Journal of Shimonoseki Univ. of Fisheries, Vol.41, No.4, 1993

Bottom and propeller fouling of real ship was investigated through one year. It was known the kind of marine fouling organisms and process of attachment. The effect of marine fouling prevention by pouring sea water with dissolved innoxious copper-ion which was supplied by the system into the dome of bow-thruster was also investigated.

K. Sato, K. Inoue, E. Takeda, H. Akizawa, Y. Mine, Y. Koike, Y. Miyazaki : "Experimental Study of Prevention of Bottom and Propeller Foulings with Regard to Energy Saving of Fishing Boats", Journal of Tokyo Univ. of Fisheries, Vol.74, No.2, 1987

In order to investigate the effect of marine antifouling paints on propulsion performance of actual ships, firstly some test plates coated with some paints were put in seawater and performance of paints was studied. Secondly, speed trial tests were taken place. Variations of BHP and surface roughness just after painting, before docking, and after docking were shown.

E. Nishikawa, M. Uchida :" On Propulsion Property of FUKAE MARU Equipped CPP and its Deterioration due to Surface Fouling", Bulletin of Kobe Marchant Ship University Vol.33, 1985

The effect of surface fouling on the propeller and ship were investigated. Trial sea data of training ship equipped with CPP were obtained just before docking and just after docking in 3 years. Performances of propulsion property with and without fouling were compared. The results showed change of propulsion performance with CPP was different from the one with FPP.

N. Nakai, S. Suzuki : "On the Presumption of Bottom's Roughness with Making Use of Propeller Efficiency on CPP", Bulletin of Kobe Marchant Ship University Vol.32, Japan, 1984

In order to estimate the bottom fouling of real ship, practical method was presented. The speed trial test was taken place before and after docking. Surface roughness in fouled condition was estimated by the increase of frictional resistance using Bowden formulation. The results showed after docking, surface roughness became about 6.2 mm from 145 μ m in cleaned condition.

N. Nakai, S. Suzuki : "The Effect of Marine Fouling -On the Result of Actual Experiments with the Ship Installed CPP-", J. of Japan Institute of Navigation, 1983

The increased resistance caused by adhesion of barnacle to propeller was calculated. Firstly, the situation of foul of propeller was measured. The measurement results showed barnacle adhered near trailing edge near boss. Barnacles were approximated as a half-cylinder solid and loss-horse power was calculated. The calculation results showed loss horse power was over 1%.

N. Nakai, S. Suzuki : "On the Effect for Propelling Performance in Consequence of Marine Fouling and the Practical Method of Presumption of Bottom's Roughness on FUKAE MARU before Autumnal Docking", Bulletin of Kobe Marchant Ship University Vol.32, Japan , 1983

The foul condition on bottom and propeller of real ship was investigated. Because of long-time mooring during August to October, fouling was progressed so much. According to speed trial, ship speed became about 70% compared to cleaned condition. The cause of speed decrease came from ship hull fouling by two-third; the rest came from propeller fouling.

2.1.6. Further Papers of possible Interest

2.1.6.1.Paint

Elisabete Almeida, Teresa C. Diamantino, Orlando de Sousa :" Marine paints: The particular case of antifouling paints", 2007

The authors presented a general overview of marine antifouling paints. Firstly, interaction between ship hull and sea water was explained. Marine organisms that adhere to ship hull were shown. The history of the development of antifouling technology was explained. As a next generation marine paints, more environment and man-friendly antifouling paints, such as CDPs, TF-SPCs and Biocide-free paints were shown.

Chambers LD, Stokes KR, Walsh FC, et al. : "Modern approaches to marine antifouling coatings", 2006

This article reviews the development of marine antifouling coatings. Historic antifouling methods were shown. Over 100 papers were review in it. Among them, 10 major paper were chosen and introduced. Performances of some coatings are compared. Tin-free self-polishing copolymer (SPC) and foul release technologies are current applications however many alternatives have been suggested.

Casse F, Swain GW : "The development of microfouling on four commercial antifouling coatings under static and dynamic immersion", 2006

Four test panels coated with paints were immersed in seawater in order to compare their performance against microfouling under static and dynamic immersion. Three paints were biocide based (tributylin self-polishing, copper self-polishing, copper ablative) and one was biocide free (silicone fouling release). It was know that total bacteria counts were similar on all coatings after static immersion, but after dynamic immersion the largest decrease in numbers was seen on the fouling release coating.

Tetsuya SENDA : "Ship Bottom Anti Fouling Coating and Marine Environment (in Japanese)", 2006

History of development of anti-fouling coating is summarized. Since restrictions against toxic coating have become harder in recent years in terms of protection of marine environment, the author evaluates the environmental risk for anti-fouling coating. The author says it is necessary to establish the way to evaluate properly environmental effects of anti-fouling substances, and to find some low-risk substances.

Anderson, C.D., Atlar, M., Candries, C., Callow, M.E., Milne, A. and Townsin, R.J : "The development of Foul Release coatings for seagoing vessels", 2004

This paper describes the history of development of antifouling paint. Firstly, some marine fouling organisms are explained. Secondly, some explanation about antifouling painting is done. The method how fluid drag on foul-release coating is calculated is explained. Lastly, performance of antifouling coating is shown. Reading this paper, reader can get the overall knowledge of antifouling painting.

Kazuya OGAWA : "The Prevention of Marine Fouling on FRP Ship Hull by Coating a Non-polluting and Anti-fouling Paint 2 - Relation between Preventative Performance and Physical Properties of Silicone Coated Film-", 1996

In the second report, the author investigates the reason why the proposed new coating method has an effectiveness for the prevention of bio-foulings on FRP ship hulls. The physical properties of the coated film are investigated. The author measures a contact angle and a sliding angle of a drop of water on the silicone coated film. The author also observes the repelling appearance of colored water sprayer on this film.

Kazuya OGAWA : "The Prevention of Marine Fouling on FRP Ship Hull by Coating a Non-polluting and Anti-fouling Paint 1 - Effectiveness of Silicone Coated Film against Marine fouling-", 1996

In the first report, the author develops new coating method by using a nontoxic paint instead of toxic paints. FRP test plane with some coating are put in sea for several month and antifouling performance are compared with each other. The paint which shows the best antifouling performance is painted to real ship and its performance is confirmed.

Nobuyoshi HIROTA : "Non-Toxic Anti Fouling Coating without Adhesion of Marine Creatures (in Japanese)", 1985

Development and application of non-toxic anti fouling coating called "Bioclean" developed by CHUGOKU MARINE PAINTS LTD is explained. In case of the application to the propeller of the 200 thousand DW ore carrier, it is reported that no adhesion of marine creatures occurred in half year after launching. In case of the application to the propeller of the support ship of national defense ministry, it is reported that no adhesion of marine creatures occurred in one year.

2.1.6.2.Marine Creature

Schultz MP, Kavanagh CJ, Swain GW : "Hydrodynamic forces on barnacles: Implications on detachment from fouling-release surfaces", 1999

In this paper, lift and drag acting on barnacles were measured. The results were compared to the results obtained by hemisphere, cube and pyramid. Lift coefficient remained nearly constant over the range of Reynolds numbers tested, however drag coefficient decreased slightly with increasing Reynolds number.

A table of the literature checked for task 2a is attached in appendix 1 to this report.

TASK 2.2: IMPACT OF PROPELLER COATING SYSTEMS ON PROPELLER CHARACTERISTICS

2.2.1. Introduction

This section gives a background on propeller coating systems and their influence on propeller characteristics. In item 2.2.2. the important aspect of the propeller surface measurements and representation are reviewed. This is followed by 2.2.3. where the review of reasons and associated different coating methods reported in the open literature are given. Based on this review since the Foul Release (FR) coating systems have been developing as the prime propeller coating system, in 2.2.4 a brief background to this coating system is given with a view to the propeller coating. Item 2.2.5. presents the recent applications and review of the effect of the FR coatings on the efficiency, cavitation and underwater acoustics of propellers as well as the interaction of this coating system with bio-fouling. Finally, 2.2.6. presents the concluding remarks from the review and recommendations for further research on propeller coating.

When the loss in ship performance is associated with the condition of the ship hull, the effect of the propeller surface condition is often overlooked. **Mosaad (1986)** stated that in absolute terms, the effect of the propeller surface condition is less important than the hull condition, but significantly more important in terms of energy loss per unit area. In economic terms, high return of a relatively cheap investment can be obtained by propeller maintenance. This has been well recognised by cautious ship operators who regularly polish the propellers of their vessels. While this is a good practice, the inconvenience of finding suitable time and place as well as the associated cost favour for the alternative means of keeping propellers clean by coating, especially after the recent introduction of Foul Release (FR) type coating. Besides, there has always been an interest to the coating of propellers to avoid or reduce fouling growth and galvanic corrosion of ship hull and as well as to resist to cavitation erosion if it is ever possible.

Propeller coating applications have been growing with increasing applications of foul release (FR) coatings on ship hulls during the last fifteen years or so, especially on the propellers of large cargo vessels. According to the data base of one of the major coating manufacturers, the current breakdown of the ship antifouling applications, about a 5% of their hull coating applications is with the FR type and this ratio has been increasing considerably due to environmental scrutiny and competitions amongst newly emerging other FR brands. This type of coating is favoured for the propeller applications due to their smoother finish and improved application as well as longevity relative to the Self-Polishing Copolymer (SPC) types. In fact some paint manufacturers have been offering free of charge paint applications to ship owners who are willing to paint their vessels by FR coating. Again, according to the data base of the above mentioned major paint manufacturer the number of the coated propellers has reached to more than 250 during the last 10 years.

The main objective of propeller coating is to control fouling growth beside other potential benefits in association with improved condition of the blade surfaces including propeller efficiency, cavitation and noise. However prior to exploring these effects, one needs to clarify differences amongst surface deterioration and fouling. Surface deterioration may be caused by corrosion, impingement attack, cavitation erosion or improper maintenance whilst fouling is mainly due to marine growth of the animal type, acorn barnacles and tubeworms as well as the slime type, **Atlar et al (2002).** Depending upon its extent while the surface deterioration can be represented by surface roughness the representation of fouling is rather complex and hence its effect upon the propeller is difficult to quantify since very little theoretical and experimental work done on the subject. However it is a well-known fact that, whether it is a surface deterioration or fouling, any micro or macro level change in the blades surfaces will increase the propeller loss due to the viscous friction effect in addition to the potential axial and rotational losses. The frictional loss can be as high as 15% of the total propeller losses depending upon the propeller's loading condition, **Glover (1991).** It is therefore beneficial to keep the propeller surface free from marine fouling and as smooth as possible to reduce the frictional loss beside other consequences of these causes that may lead onto undesirable earlier inception and further development of cavitation as well as increased underwater noise.

2.2.2. Measurement and representation of propeller surface condition

Before the effects of roughness upon the performance of a propeller can be quantified the roughness of the surface has to be measured. There are various methods for doing this, such as using a propeller roughness comparator, by using a portable stylus instrument or by taking a replica of the surface of the blades and measuring it with laboratory equipment such as optical measurement systems. A detailed description of both the stylus (by mechanical contact with the surface) and optical measurement systems can be found in e.g. **Thomas (1999).** On the other hand the propeller roughness comparator is a simple gauge by which the roughness of a propeller can be compared to a surface of known roughness. The most well-known example of this is the Rubert propeller roughness comparator. The gauge consists of six examples (A, B, C, D, E and F) of surface finish that range from an average meanline roughness amplitude Ra = 0.65μm to an amplitude of Ra = 29.9μm, see, e.g. **Carlton (2008).** The examples represent the surfaces of actual uncoated propeller blades. Examples A and B represent the surface roughness of new or reconditioned propeller blades while the remaining examples are replicas of surface roughness taken from propellers eroded by periods of service. C, D, E and F can be used to assess and report upon the propeller blade surface condition after periods of service.

The measurement of propeller roughness, whichever method is used, presents a number of problems which are similar problems to those of measuring hull roughness. They stem from the very nature of propeller blade roughness, with its wide variety of amplitudes, textures and locations. **Townsin et al (1981)** discussed the propeller roughness measurement problems and concluded the following: any one small area of a blade will give a wide range of values for all roughness parameters; therefore for any point on the blade, an average of many samples is needed to reach a representative figure. However these values of average roughness will vary hugely over the blades surface, meaning that the roughness needs to be measured at many locations. This is important as the same level of roughness will cause very different effects on section drag, depending upon where on the blade it is located. Fouling and damage, such as galvanic or cavitation erosion, can have a massive effect upon the roughness measured and hence the section drag. Most importantly, there was no agreed standard methodology for measuring roughness, no matter how arbitrarily defined.

In an attempt to establish a standard methodology for the propeller roughness measurements **Townsin et al. (1985)** proposed the following procedure: each blade surface is divided into a number of roughly uniform radial strips, for each of which 3 measurements were taken with a cut-off length of 2.5mm. At that time this was designed for use a stylus type roughness device, the Surtronic 3 instrument, so Ra (the mean line average roughness amplitude) and Pc (the Peak Count per unit length, which is a texture parameter) were recorded for later conversion into Musker's "Apparent" or "Characteristic" roughness parameter, h', by the approximation below.

$$h' \approx 0.0147\, R_a^2 (2.5) P_C$$

This was then used to calculate a value for the Average Propeller Roughness (APR). This is a weighted average, so the roughness closer to the tip has a much greater influence than the same roughness would, if placed nearer the blade root. Five sections were suggested and given the weights shown in Table 1.

Table 1. Weights suggested for calculating APR, based on 5 sections.

i	Region	Weight
1	0.2 - 0.5	0.07
2	0.5 - 0.7	0.22
3	0.7 - 0.8	0.21
4	0.8 - 0.9	0.27
5	0.9 - tip	0.23

By assuming h' is constant within each weighting band; APR for the 5 bands is given by,

$$APR = \left[\sum_{1}^{5} W_i (h'_i)^{1/3} \right]^3$$

A more generalized form for APR, suitable if a survey of the entire blade roughness is not available (the missing values should not just be assumed to be zero) is given by

$$APR = \left[\frac{\sum_{m}^{n} W_i (h'_i)^{1/3}}{\sum_{m}^{n} W_i} \right]^3 \qquad m < n < 5$$

The weights are evaluated such that for a uniform distribution of roughness, APR = h'.

In the above procedure "characteristic" roughness parameter h' was obtained from a drag-roughness correlation with replicated coated surfaces based on **Mosaad's (1986)** extensive measurements. This parameter was originally proposed by **Musker (1977)** to characterize a surface by a single parameter taking both the amplitude and texture of the roughness into account. At this point it must be noted that a single parameter (such as average roughness height) as those measured by **Broersma and Tasseron (1967)** or equivalent sand roughness height (k_s) of the fully turbulent frictional drag expression for the propeller blade surfaces in ITTC'78 procedure, will not be suitable for representing the effect of coatings on propellers. This is not only on the ground that this expression is based on the Nikuradse approach of sand roughness, since actual propeller roughness is different than the sand roughness, but also on the ground of neglecting the effect of surface texture. Although a surface may have relatively large average roughness amplitude its texture may have a long wave length sinusoidal texture. This type of surface may cause lower drag when compared to a surface consisting of smaller amplitudes but with a jagged texture consisting of closely packed sharp peaks surface as claimed by **Grigson (1982).** This claim was further proved by **Candries (2001)** through comprehensive boundary layer, drag and roughness measurements and analysis of flat plates coated with two different marine coatings which were a commercial FR and a tin free Self-Polishing Copolymer (SPC) type. In this study it was shown that the FR coated system belonged to the former surface type while the SPC coated surface belonged to the second type suggested by Grigson as typified in their comparative roughness profiles shown in Figure 1. It can be seen that when long-wavelength waviness, which is unlikely to have any effect upon the drag, has been filtered out, two striking features appear: not only are the amplitude parameters (i.e. Ra, Rq, Rt) of the FR profiles typically lower, the texture parameter of the surface, which is represented by the slope (Sa), is significantly lower. In metrological terms this type of texture is known as "open" whereas the spikier texture of a tin-free SPC surface is known as "closed".

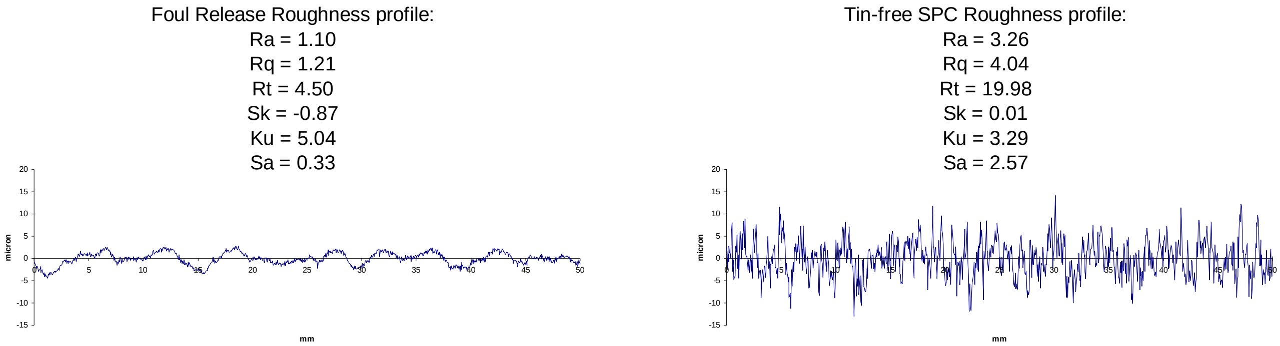


Figure 1 – Characteristics of a typical foul release (Intersleek 700 – on the left) and tin-free SPC (Ecoloflex – on the right) roughness profiles taken by laser profilometry, **Candries et al (2001)**.

As it is noted in the above review, an accurate representation of blades surfaces by characteristic roughness parameter requires relatively sophisticated measurement devices for proper analysis of the surfaces. These devices are preferred to be optical and portable as well as practical that can be used in dry docks etc. Unfortunately such systems currently are not available although there are increased activities in this field especially after the introduction of the FR coatings. As discussed earlier these coatings do not readily allow themselves to be measured by practical stylus type devices although they are currently being used on based on certain skills involving some errors in measurements. Although taking replica (print) from the actual blade surfaces is relatively direct and hence more accurate way measurement method, it is rather impractical and it has its own problems. At this point, until such devices are available, it is plausible to think of establishing a new comparator system, which is based on a similar idea to the Rubert comparator. However this new comparator can be developed for foul release coated sample surfaces which are graded based on different paint applications varying from good to bad since the application grade is an important parameter in the texture and roughness parameters for newly applied coatings. Of course these samples will be indirect and will not necessarily represent the actual coated blades after a period in service. However, as long as they are not damaged, FR coating systems can maintain they roughness and texture characteristics similar to the new condition except the effect of slime. There may be ways including this effect but requiring further research.

2.2.3. Review of propeller coatings

The idea of coating a marine propeller is not a new one. The first recorded idea was by **Holzapel (1904)** who claimed two major reasons for the coating of marine propellers, as true today, namely to prevent fouling and to reduce galvanic corrosion. Unfortunately his comments were not taken up at the time and further investigation into the concept of coating marine propellers was not conducted for some time. It was not until the second World War that further development of protective coatings for marine propellers was conducted in order to conserve the scarce alloys usually used for propellers. Cast steel is much cheaper than bronze, can be easier to coat and requires less exacting manufacturing technology, so was proposed as an alternative. At least 4 ships had coated steel propellers installed during the war. Three of them were sunk and unfortunately no follow-up was made on the fourth **Dashnaw et al., (1980**).

In demonstrating the effect of fouling on propellers and its prevention by coating **Kan et al (1958)** investigated the characteristics of a fouled propeller using self-propulsion tests and full-scale trials with the propeller covered in various rubber sheets to mimic the fouling. They found that small increases in roughness will cause large increases in delivered horsepower (DHP), producing a worse effect on propulsive efficiency than hull fouling but the reduction in thrust due to roughness was very small. These experiments, however, did not give very good agreement with their full-scale results. The full-scale measurements showed that the rate of increase of DHP will decrease as the roughness increases; the initial roughness has the greatest effect on performance. Because of propeller fouling, the DHP decreases by 20% and from these results, it can be seen that the effects of propeller fouling in terms of a power penalty are much greater than those of surface roughness.

Further work was conducted from the 50's to the 80's particularly focusing upon the prevention of cavitation damage e.g. by **Heathcock et al. (1979), Angell et al (1979)** and **Akhtar (1982)**. These mostly used ceramic coatings and were not just interested in propellers but also, rudders, A-brackets and turbine blades.

Dashnaw et al. (1980) published their work studying a large number of coatings and surface finishes, in order to investigate those that might prevent cavitation damage and corrosion while still providing a smooth surface to minimise the hydrodynamic drag. Their theory being that, if a suitable covering system could be found it might be possible to replace the expensive materials propellers that are usually made from by cheaper steel. They conducted tests using a 24 inch rotating disc apparatus and found that certain urethane coatings could produce less drag than bare steel discs even with a higher value of the root-mean-squared roughness amplitude, Rq. They concluded that there was a 10% change in drag approximating to a 1% change in power at the propeller, although no explanation as to how they arrived at these figures was presented. Three coatings were proposed for further evaluation and were coated onto blades of a 6.5m bronze propeller. The two coatings were polyurethane formulations and one was an undisclosed formulation (known as Y-1). They were inspected after 2 and 11 months in service. It was found that the polyurethanes had quickly delaminated from the propeller. Y-1 had fared better. From these trials they realised that for any propeller coating, the bond strength of the adhesive/primer was of fundamental importance. They recommended that for the broad surface area of the blades, under low hydrodynamic loading, the coating needed an adhesion strength of at least 8.92 kN/m (50 lb/in.) of width. Near the edges of the blades, where the surface was under high and dynamic hydrodynamic loading, a much higher strength would be needed.

Foster (1989) described trials on 2 Canadian naval vessels that had their propellers coated with a 3-layer vinyl antifouling system that used a cuprous oxide containing topcoat. This was at the time the standard system used on the hulls of the Canadian naval fleet. The first vessel, *CFAV Endeavour*, found that, after 2 years in service, the coated propeller (the ship had twin screws and only was one coated) was fouling free and only had small amounts of paint loss on the leading edges of the blades. They also found that the shaft grounding current of the coated propeller was reduced to about a third of the uncoated one (the information on current demand was taken from the monthly cathodic protection reports of both ships). The second ship, the naval frigate *HMCS MacKenzie* had both of her propellers coated. They were examined by divers after 6 months and again in dry-dock after 2.5 years in service. The divers found that the coating was fouling free and almost intact except for some detachment along the leading edges and some small isolated spots on the back of the blades. They also noted that the coating was still red in color suggesting that little copper had leached out. Once in dry-dock, it was found that while still free from fouling, the damage had grown. The small isolated spots on the back of the blade, most likely caused by cavitation, had grown to a diameter of 5-30mm. A 30mm wide strip had been eroded along the trailing edge and the top-coat had been removed from the leading edge back to about the mid-chord. The cathodic protection reports showed that the current demand had dropped by about 30% while at rest and at sea by about 20% compared to the pre-coated condition. They maintained these figures throughout the 2.5 years in service.

Coldron and Condé (1990) reported on the *Shell Engineer*, a 1300dwt coastal tanker, generating 905kw at 250rpm through a 4 bladed nickel-aluminum-bronze propeller, 2.44m in diameter. In 1983 it was selected to trial the effect of a TBT-SPC based coating on its propeller. This system was suggested by the wealth of published data on the coatings performance on ships hulls. The propeller was removed, faired, wet blasted and then dried before the coating system was applied. Two alternate blades were coated with a vinyl shop primer and 2 with a 2 layer epoxy primer. The whole propeller was then coated with two layers of the TBT-SPC system (an extra coating was also added to the outer half of the blades. The roughness of the propeller before and after coating can be seen in Table 2.

Table 2. A comparison in the roughness of the surface both before and after painting

Coldron and Conde (1990)

	Ra (2.5)	**Rtm (2.5)**
Prior to Painting	23.2μm	110.3μm
After Painting	14.2μm	43.7μm
% Change	38.79%	60.38%

The propeller was inspected after both 6 and 12 weeks and was found that the TBT-SPC coatings had rapidly been removed from the vinyl primer. The SPC on the epoxy performed better with only some mechanical damage to the tip. The polishing rate of the SPC was found to be very low when compared to that expected of a ship's hull. The epoxy was slowly 'stripped' back along the suction side from the tip inwards so that 25% had been removed after only 3 months. In 1989, after 6 years in service, 20% of the epoxy, near the blade roots, still remained on the propeller

Further trials were conducted, this time using a ceramic coating, in order to try and prevent a problem with localized but random cracking of the propellers of the *Shell Marketer* class of vessels **Coldron and Condé (1990**). Two blades were, cleaned, degreased, preheated and the grit blasted before being coated not more than 40 mins after the surface preparation. The coating used was a ceramic mix, with an alumina base, with 13% titanium added (this improves the impact resistance but reduces the electrical resistance). The coating was applied using a plasma flame spray system with argon/hydrogen plasma gas. The two remaining blades were prepared to the manufacturer's standard finish. After a period of 4 years, the propeller was inspected to find that the coated blades had actually become smoother compared to their initial roughness after coating. The uncoated blades, however, had deteriorated to a surface about 50% rougher than their initial value. The coating had managed to remain attached, even in an area where mechanical damage had removed part of the coating, there was no evidence of 'creep back'. Although it should be considered highly unreliable, due to the complex nature of the effect of propeller condition on ship performance, it was also noted that the *Shell Marketeer* was performing 6% (in terms of nautical miles per tonnes of fuel) better than its sister-ship, the *Shell Seafarer*, whose blades had not been coated, but were of a similar roughness to the *Shell Marketeer's* blades prior to their coating.

Matsushita et al. (1993) noted that because the training ship of the Yuge National College of Maritime Technology in Japan, the *Yuge-Maru*, was at anchor for long periods, the propeller had a serious problem with biofouling. The seawater around its home port ranged from 8-9°C to 27-28°C, a wide variety of adhesive sea life were present in the surrounding waters, including at many different species of barnacle (such as *Tintinnabulum rosa*, *Amphitrite tesselatus* and *Amphitrite hawaiiensis*), Bryozoans (calcarious colonial animals, similar to corals), Serpulids (a type of tubeworm), mussels, oysters, algae and bacterial biofilm. Therefore researchers at the college, as part of a wider investigation into the effect of a non toxic coating of silicone resin decided to coat the ship's propeller. The coating system had been developed as an industrial, non-polluting paint in such areas as seawater suction pipes and cooling pipes of nuclear plants. Since there was no toxin present in the coating chemistry it was considered safe to the environment. The surface had similar properties to the modern Foul Release properties, with a low surface energy and high water repellence. The antifouling ability was derived from the low attachment strength of marine fouling organisms to the surface. This was then the first reported experiment with a FR coating on a marine propeller. The propeller was first cleaned and then allowed to foul over a six month period. Upon inspection after this period it was found that the propeller was heavily coated in fouling (mostly bryozoans and serpulids) particularly in areas of slow flow speed over the surface e.g. the boss and blade roots. After the inspection the propeller was then re-cleaned and coated with silicone resin paint. 6 months after coating, the propeller was again inspected. The coating was found to be intact and free from fouling except for a few flat bryozoans on the root. After a further 6 months the propeller was inspected a third time, again no damage to the coating was found, there was however, some bryozoans and slime fouling present. These results were the first to show that a foul release coating can remain attached to a propeller and achieve effective antifouling in actual service.

In addition to the propeller inspections described above the fuel consumption was recorded for both the un-coated and coated propellers were recorded over the course of three months during the summer fouling breeding season. It was found that the fuel consumption with the 6.2% lower when the propeller was coated although the lack of details about the change in hull condition over the trial period mean that this change cannot be attributed to the condition of the propeller alone.

The *Yuge-Maru* also had a large number of sacrificial zinc anodes attached around the hull to protect the hull from electrochemical corrosion by galvanic action in seawater, caused by the copper alloy propeller. Each side of the ship has 23 anodes attached to the shell plating, one in the bow thruster tunnel, one on each of the upper and lower bearings of the rudder post and one at the end of the stern tube, see Figure 2.

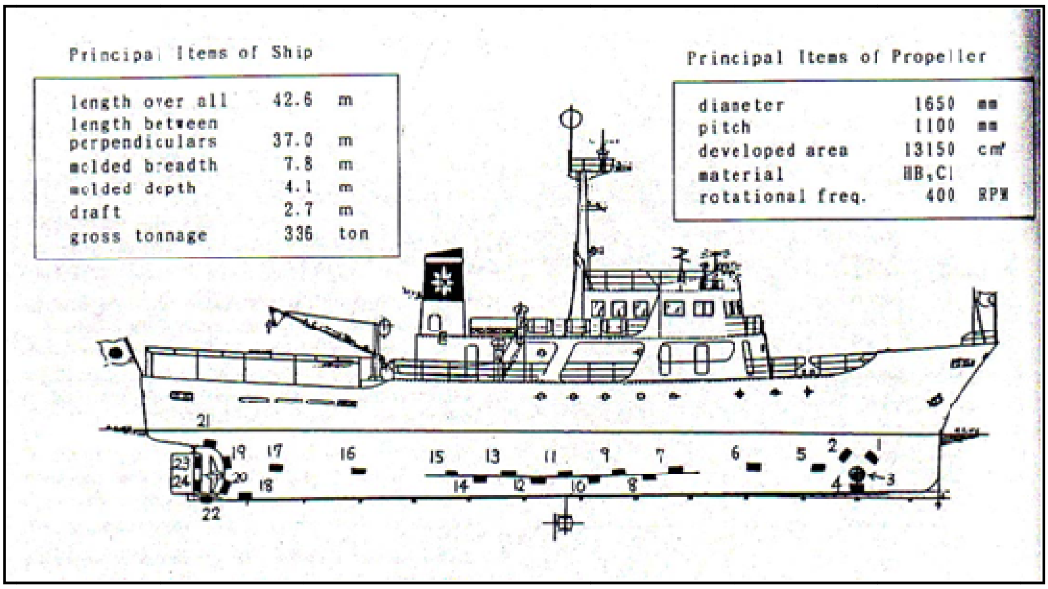


Figure 2 - Arrangement of Sacrificial Anodes (Zn Plates) on ship body of *Yuge-Maru* **(Matsushita et al., 1993)**.

Table 3 shows the amount of degradation of the anodes of the course of a year without the propeller being coating and as a comparison the levels of degradation of the replacement anodes over a year once the propeller was coated. The level of deterioration was low for both cases (less than 5%); suggesting that the number of anodes attached to the ship was excessive. The results did show however, as expected, the anodes near the propeller were the most reduced (except number 3, inside the bow thruster tunnel). The difference between anode degradation in the uncoated and coated propeller condition was approximately 30% in favour of the coated propeller condition. This suggests that the propeller coating stopped or significantly reduced the galvanic current. In fact this has since been confirmed by more recent research by **Anderson et al. (2003)** who conducted further testing of new generation FR system, on the propellers (and replacement metal discs) of a 100th detailed scale model of a frigate, to investigate the effect of a propeller coating upon the current output of an Impressed Current Cathodic Protection (ICCP) system. They found that the use of the coating *"markedly reduced"* the ICCP current output. When the coating was damaged, there was an increase in the output, but this was still much lower than the current output of the uncoated disc. Although done on a small scale, this is further strong evidence that the coating will reduce the galvanic current caused by the propeller.

Within the framework of galvanic corrosion **Atlar (2004)** noted that some ship owners and propeller manufacturers may think that partially coated propellers, which can represent possible damage to paint or a paint failure, could be subjected to complex corrosion effect due to inherent differences in two surfaces. Although such corrosive damage has not been reported in any of the vessels with coated propellers, within the capability of modern cathodic protection systems this should not be a problem. His consultation with a major UK propeller manufacturer revealed that the final surface finish of a large propeller by hand may take about a month of time while with a machine this will take at least a half of this period. In the mean time, the application of coating on propeller surface would require relatively rough surface, which is obtained by grid blasting, to provide the coatings with a necessary grip to stick on the surface. Based upon this requirement, the propeller manufacturer does not perform the final finish, and hence save labour cost and delivery time, while the paint manufacturer will apply grid blasting directly on this surface. This way all three parties: the owner; propeller manufacturer and paint manufacturer can benefit as well as the environment

Table 3. Consumption of Sacrificial Anodes (Zn plates) of the TS Yuge-Maru. **(Matsushita et al., 1993)**

Non-Propeller Coating (07.03.1989-28.02.1990)			Propeller Coating (10.03.1990-04.03.1992)		
Zinc Anode Position Number	New Zinc Weight (Kg)	Rate of Zinc Consumption (%)	Zinc Anode Position Number	New Zinc Weight (Kg)	Rate of Zinc Consumption (%)
1	3.5	2.1	1	3.5	3.1
2	3.5	2.1	2	3.5	3.6
3	3.5	14.2	3	3.5	14.9
4	3.5	3.5	4	3.5	3.0
5	3.5	2.4	5	3.5	3.4
6	3.5	2.7	6	3.5	4.3
7	3.5	3.0	7	3.5	3.6
8	3.5	3.1	8	3.5	3.9
9	3.5	3.4	9	3.5	2.7
10	3.5	2.5	10	3.5	3.1
11	3.5	2.7	11	3.5	2.5
12	3.5	2.3	12	3.5	1.9
13	3.5	1.4	13	3.5	2.2
14	3.5	1.2	14	3.5	2.6
15	3.5	1.5	15	3.5	3.1
16	3.5	3.1	16	3.5	4.3
17	3.5	4.6	17	3.5	3.9
18	3.5	2.9	18	3.5	2.9
19	3.5	8.9	19	3.5	0.4
20	3.5	9.1	20	3.5	3.1
21	3.5	2.5	21	3.5	2.1
22	3.5	6.1	22	3.5	3.0
23	3.5	9.6	23	3.5	4.7
24	3.5	13.6	24	3.5	4.9
Subtotal	84.0	4.5	**Subtotal**	84.0	3.65
A	5.2	12.6	**A**	5.2	4.5
B	2.2	2.2	**B**	2.2	8.4
C	4.0	4.0	**C**	4.0	6.2
Total	**95.4**	**5.5**	**Total**	**95.4**	**3.95**

1-24	=	Shell Plate (B-4)
A	=	Upper Gudgeon
B	=	Lower Gudgeon
C	=	End of Stern Tube

Another Japanese trial was conducted, this time using the training ship *Kakuyo Maru* **Araki et al., (2000)** and **Araki et al. (2001)**. The ship's 2.85m diameter propeller was coated with a silicone resin (Bioclean DX – Chugoku Marine Paint Company Ltd.). After 1 year in service, the propeller was inspected to find only light slime on the blades, with only a little paint having been removed from the tips of the blades. Improvements were also noted in the rate of fuel oil consumption, fuel oil pump index, and shaft horse power required, compared to the fouled propeller, although it was unlikely that this was due to the condition of the propeller alone.

Over the years propeller coatings have been tested that have a wide range of properties that effect propeller performance and durability of coating. In the search for the perfect propeller coating a number of attributes have been highlighted as desirable. **Coldron and Condé (1990)** defined the attributes of an ideal propeller coating as follows:-

- Exhibit adequate erosion, abrasion, corrosion and cavitation resistance and be resistant to impact damage and penetration.
- Posses anti-fouling characteristics or be smooth to simplify removal of marine biofouling.
- Retain an acceptable level of properties when exposed to seawater with low water permeability to prevent degradation of bond strength by corrosion of the coating/substrate interface.
- Possess adequate bond strength initially and after prolonged seawater immersion to withstand the operating conditions, including maintenance procedures.
- Be non-conducting to reduce cathodic protection current requirements by limiting the cathodic area.
- The materials should be cheap, readily available, and relatively easy to apply and repair.
- The coating must be capable of inspection for quality assurance purposes.
- The coating must be sufficiently thin that it can be applied within the blade thickness tolerance range and not require expensive re-design of the propeller. In practice this implies a coating in the thickness range of 100 to 250μm.

To the above list it can be added two further attributes, that have become more desirable in the years since Coldron and Condé published their list:

- The coating must be as environmentally benign as possible.
- Preferred to reduce any radiated signatures emanating from the propeller as much as possible (especially important for naval vessels and cruise ships).

A number of possible propeller coating types have been developed that each have some of the above attributes but not all of them. The possible types were listed by **Coldron and Condé (1990)** as in the following

Organic Coatings

This is a wide ranging group of coating types that includes both current SPC technology and Foul Release antifouling coating technologies, epoxies, vinyls, neoprenes, urethanes and polyamides (nylons). There are a wide range of possible application methods such as airless spray, brush and roller. Some can even be coated onto the propeller in either a fluid or powdered state and then autoclaved to give the final coating, although such methods are hard to use for large modern merchant propellers, due to the need for an autoclave of sufficient size.

Metallic Coatings

A wide variety of metallic coating could be considered for marine propellers. Some may even have antifouling properties, if they contain compounds metals with known antifouling properties such as Copper, Zinc, Tin or other heavy metals. They could, in theory, be deposited a number of different methods, such as by electroplating, thermal spray, weld overlay or vapour deposition. This group could also include, laser surface melting, when a thin layer of the surface is heating to improve the surfaces resistance to cavitation, e.g. **Tang et al., (2004, 2005)**. The development of these coating would require large scale facilities to allow merchant propeller, typically of 5-10m diameter to be treated economically. Metallic coatings also suffer from the problem of, if two dissimilar metals are in contact, a galvanic cell will form causing accelerated corrosion. This is why little research has been done on this type of coating for use on propellers.

Ceramic Coatings

This type of coating are created a powdered mix of mineral substances including clays and metal oxides (aluminum, chrome and titanium oxides are widely used) that are then fired (or specialist techniques, such as thermal spray processes can be used) to produce a dense, low porosity coatings. The properties vary widely, depending on what chemicals are what proportions of each chemical are used. They can be insulating or semi-conducting and the hardness can be varied. They are

usually inert in seawater but not all can withstand high levels of cavitation. Expensive research into the ideal chemical formula would be needed before their use as a propeller coating will become widespread.

No coating has yet been found to have all the attributes in the list, so the perfect coating is still elusive. The current leading contenders for a suitable propeller coating and their properties compared to the above requirements can be seen (not in any order of importance) in Table 4.

Table 4**.** The four systems currently most likely to be developed as a propeller coating are the two leading types of antifouling system (silicone based foul release and copper based SPC) and metallic and ceramic type coatings. The qualities of each coating system compared to the desired attributes are shown. Those coloured green indicate that the system exhibits that attribute successfully, orange indicates that the system may exhibit that attribute or no evidence for the system displaying that attribute was available and red indicates that the attribute is not exhibited.

	Silicone Foul Release	Copper SPC	Metallic Coating	Ceramic Coating
Resilience to Damage	Softer coating	Hard coating	Hard coating	Hard coating
Antifouling Ability	Proven antifouling ability	Proven antifouling ability	Unproven, possible with some metals	Unproven, No mechanism known
Inert in Seawater	Inert in seawater	Leaches away with time	Depends upon the chemistry used	Inert in seawater
Strong Attachment	Proven attachment to propellers	Proven attachment to propellers	Unknown attachment ability	Proven attachment to propellers
Non Conducting	Non conductor	Unknown, may conduct	Likely to be conductor	Depends upon ceramic used
Cheap to develop and produce	Already in production	Already in production	Development and material costs required	Development and material costs required
Inspection of Coating	Coating easy to inspect	Coating easy to inspect	Depends on coating used	Depends on coating used
Thickness of Coating	~350mic, 3 layer system	Coating thins over time	Thin coating likely	Thin coating likely
Noise Reduction	Pliable, may reduce Noise	No effect likely	No effect likely	No effect likely
Harmful to environment	Non toxic	Toxic leachate	Depends upon coating used	Non toxic

From the table it can be seen that silicone based fouling release systems displays more of the attributes when compared to the other types of coating as will be discussed further in the next.

2.2.4. Review of foul release coating technology

Foul Release (FR) coating technology is the fore runner of the modern coating systems for ship propellers. In comparison to traditional antifouling technologies, FR technology relies on a fundamentally different concept of fouling prevention. Instead of using the slow release of a biocide into the surrounding water, FR coatings work by providing a surface to which fouling species find it difficult to attach securely, this is known to be “low free surface energy” surface. The fouling is then removed from the surface by hydrodynamic shear force.

The free energy of a surface, which is commonly referred to as “surface energy” or “surface tension”, is the excess energy of the molecules on the surface compared with the molecules in the thermodynamically homogenous interior. The size of the surface energy represents the capability of the surface to interact spontaneously with other materials, **Brady (1997).** The surface energy and the critical surface tension of surface are determined by comprehensive contact angle analysis, using a variety of diagnostic liquids, measuring the angles that the liquid droplets make with the coated surface. It is the surface tension of a polymer which is the property that has most commonly been correlated with resistance to befouling, **Brady and Singer (2000).** A generalised relationship between Surface Tension and the Relative amount of bio Adhesion has been established and presented in a graph commonly known as the “Baier curve”, which does not display the minimum relative bio adhesion (22~24 mN/m) at the lowest surface energy. A variety of explanations has been given to account for this including the effects of elastic modulus (E), thickness and surface chemistry of coatings as discussed by **Anderson et al (2002).** Elastic modulus is key factor in bio adhesion and hence ability of organisms to “release” from a coating, **Brady and Singer (2000)** and **Berling et al (2003).** The calculated Critical Free Surface Energy (γ_c) for a range of different polymers indicated that there was a better correlation between the relative bio adhesion and $(\gamma_c E)^{1/2}$ than with either surface energy or elastic modulus,

Brady and Singer (2000). Thickness is another characteristic of low surface energy coatings that plays an important role in bio adhesion. It has been found that below ~100µm dry film thickness barnacles can "cut through" to the underlying coats and thus establish firm adhesion. Above this thickness there is no marked increase in FR properties. The majority of current FR coatings are based on the molecule Polydimethylsiloxane (PDMS) which are generally formed by a condensation mechanism. This long chain polymer has a long flexible 'backbone' that, along with the low intermolecular forces between the methyl groups, allows it to adopt the lowest surface energy configuration. PDMS has, in air, a surface energy of 23-35 mN/m and such lower value of surface energy and its elastic nature makes PDMS perfectly suited for use as a FR type coating, **Brady and Singer (2000)**. In fact, for PDMS and other silicone material, $\sqrt{\gamma_C E}$, was found to be at least an order of magnitude lower than that of other materials (**Singer et al., 2000**). It has been found that incorporation oils can enhance the FR properties of PDMS polymers, **Milne (1977).** Oils, by their nature, are lubricants and therefore should decrease the friction, but this is not the main reason for the efficacy of PDMS. This is thought to be due to the surface tension and hydrophobicity changes that the oils effect during the curing process and after immersion, **Truby et al (2003).**

When Foul Release coatings were commercially introduced in the mid-1990s and applied to a high-speed catamaran ferry, replacing a toxic Controlled Depletion Polymer (CDP) antifouling, the recorded fuel consumption was lower at the same service speed, implying lower drag characteristics as reported by **Millett and Anderson (1997)**. As a consequence a research project was set up at Newcastle University with the objective of collecting data on the drag, boundary-layer and roughness characteristics of Foul Release and tin-free SPC coatings, and to compare them systematically, **Candries (2001)** The coatings used were a PDMS Foul Release and a tin-free copper-pigmented acrylic SPC that contained zinc pyrithione as a booster biocide.

Drag measurements were carried out in towing tank experiments with two friction planes of different size (2.5m and 6.3m long), which showed that the Foul Release system exhibits less drag than the tin-free SPC system when similarly applied. The difference in frictional resistance varied between ca. 2 and 23%, depending on the quality of application as reported by **Candries et al. (2001).** Rotor experiments were also carried out to measure the difference in torque between uncoated and variously coated cylinders. In addition to coatings applied by spraying, a Foul Release surface applied by rollering was included because there were indications that this type of application might affect the drag characteristics. The measurements indicated an average 3.6% difference in local frictional resistance coefficient between the sprayed Foul Release and the sprayed tin-free SPC, but the difference between the rollered Foul Release and the sprayed tin-free SPC was only 2.2%, **Candries et al. (2003)**

The friction of a surface in fluid flow is caused by the viscous effects and turbulence production in the boundary layer close to the surface. A study of the boundary-layer characteristics of the coatings was therefore carried out in two different water tunnels using four-beam two-component Laser Doppler Velocimetry (LDV) and the coatings were applied on 1m long test sections that were fitted in a 2.1m long flat plate set-up, **Candries and Atlar (2005).** Velocity profiles were measured at five different streamwise locations and at five different free-stream velocities. A rollered surface and a sprayed Foul Release surface were tested to investigate the effect of application method. The measurements showed that the friction velocity for Foul Release surfaces is significantly lower than for tin-free SPC surfaces, when similarly applied. This indicated that at the same streamwise Reynolds number the ratio of the inner layer to the outer layer is smaller for Foul Release surfaces. The inner layer is that part of the boundary layer where major turbulence (and hence drag) production occurs. Statistical analysis of the values of the roughness function obtained by means of multiple pairwise comparison, using Tukey's test, indicated that the roughness function for Foul Release surfaces is significantly lower than for tin-free SPC surfaces at a 95% confidence level. These findings are consistent with the drag characteristics measured in the water tunnel and rotor experiments

In addition to the difference in frictional resistance and the roughness function, the roughness characteristics of each of the surfaces were investigated. The average values of their roughness were measured using the BMT Hull Roughness Analyser, which is the stylus instrument in common use in dry-docks or underwater, for standardised hull roughness measurement. It measures R_t (50), which is the highest peak to lowest valley roughness height over a sampling length of 50mm. Successive values are averaged over a surface. It is clear from the rotor experiments and the large plate towing tank experiments that this single amplitude parameter does not correlate with the measured drag increase for Foul Release surfaces, as it does with SPC surfaces.

A detailed non-contact roughness analysis was carried out with an optical measurement system fitted with a 3mW laser. Measurements were taken on sample plates coated alongside the surfaces tested in the towing tank and water tunnel, and were thus assumed representative of the test surface characteristics. In the case of the cylinders used in the rotor experiments, sections were cut from the cylinders after testing, for use in the optical measurements. A moving average was applied to filter long-wavelength curvature. The upper bandwidth limit or cut-off length was set at 2.5 and 5mm, whereas the lower bandwidth limit or sampling interval was set at 50mm.

The detailed roughness analysis revealed that when long-wavelength curvature has been filtered out, the amplitude parameters of the sprayed Foul Release surfaces are in general lower than those of the rollered Foul Release surfaces and the SPC surfaces. However, the rollered Foul Release surfaces display a roughness height distribution which is considerably more leptokurtic (i.e. exhibits a larger number of sharp roughness peaks) than the sprayed Foul Release surfaces. The greater number of high peaks on the rollered Foul Release surfaces is expected to engender higher drag than sprayed Foul Release surfaces.

The main difference between the Foul Release and the tin-free SPC systems lies in the texture characteristics, as shown in Figure 3 for two typical roughness profilogram of such coatings, applied by spraying. Whereas the tin-free SPC surface displays a spiky "closed" texture, the wavy "open" texture of the Foul Release surface is characterised by a smaller proportion of short-wavelength roughness. This is particularly evident in texture parameters such as the mean absolute slope and the fractal dimension. There is relatively little data available in the literature of irregularly rough surfaces on the influence of texture only on drag. Grigson **(1982)** has mentioned explicitly that open textures have a beneficial effect on drag.

It is clear that in order to correlate with drag, the roughness of the generality of irregularly rough surfaces needs to take both amplitude and texture parameters into account, e.g. **Musker (1977)** and **Townsin and Dey (1990)**. Based on the experiments presented, it was thought that the rheology of the paint, which is significantly different for foul-release and tin-free SPC coatings, had a direct effect on its texture, whereas amplitudes depend significantly on the application quality. A correlation analysis of the texture parameters with the amplitude parameters, however, has shown that the two are inter-related, so that bad application can be expected to have a knock-on effect on the texture parameters

At present, the procedure adopted by the International Towing Tank Committee (ITTC) to correlate roughness with drag only accounts for a single roughness amplitude parameter, **ITTC (1990).** The procedure hinges on the use of a practical formula for the added ship resistance (or roughness correlation allowance), which was proposed by **Townsin and Dey (1990)** in terms of Average Hull Roughness for the moderately rough ship range where Rt(50) is less than 230µm. Unfortunately, this procedure may not work for foul-release surfaces, unless a texture parameter is included in the roughness characterisation. For a selection of 41 different coated surfaces, including 8 newly applied foul-release surfaces, **Candries and Atlar (2003)** found that the measured drag correlated reasonably well best when the roughness measure, h, is characterised by h = 1/2Ra.Δa where Ra is the average roughness amplitude while Δa is the mean absolute slope. There was a need for further testing and correlation studies to provide further support for this correlation.

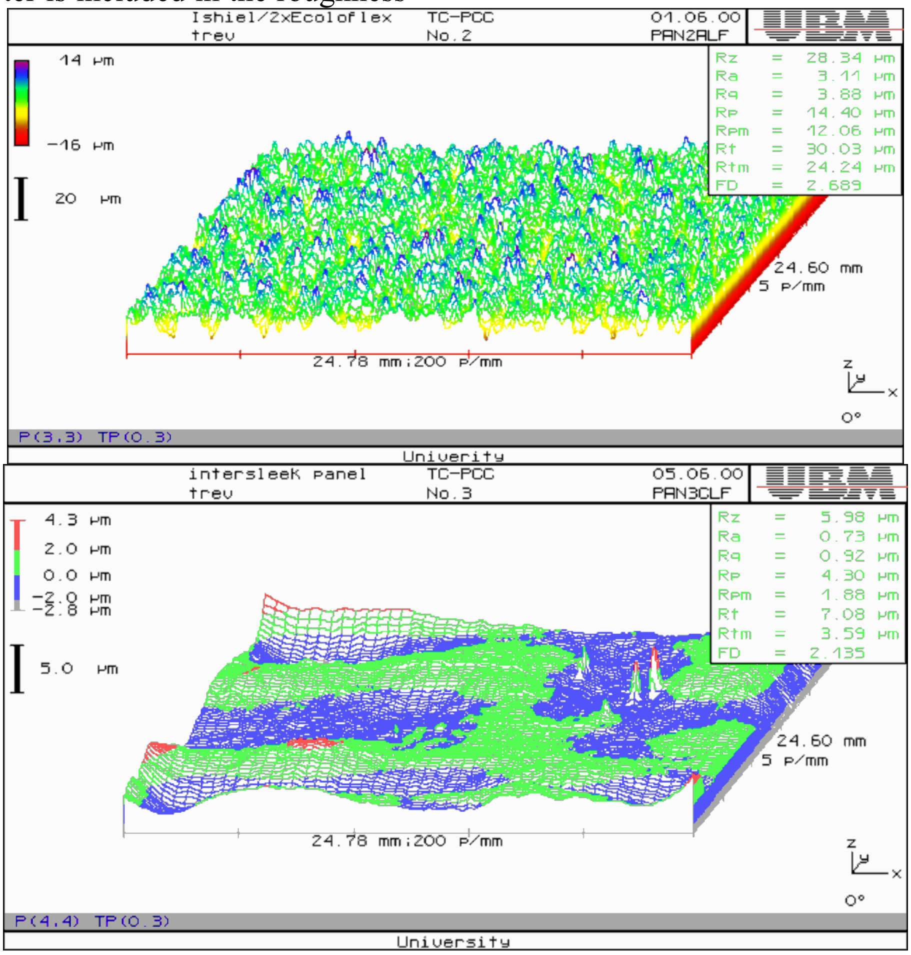


Figure 3. Typical roughness profilograms taken from a tin free SPC coated surface, Ecoloflex, (above) and Foul Release, Intrersleek 700, coated surface (below) using laser profilometry, **Candries and Atlar (2003)**

2.2.5. Foul release coating research – as applied to propellers

While the earlier summarized research on the FR coatings was continuing to understand their general drag reduction mechanism, there was further interest from industry to research on the application of these coating systems on propellers in the following two areas: (1) if the FR coatings can successfully stay on yacht propellers in arduous conditions; (2) if the FR coatings can display any performance benefit for a large commercial vessel propeller that was coated with the earlier mentioned FR system, Intersleek 700 (IS700). In addressing at the first investigation area (1), a pilot experimental study was conducted with a 3-bladed, 300mm diameter, aluminum alloy model of a commercial motorboat propeller. The model was coated by IS700 using a rollering technique as opposed to spraying to simulate a real life scenario for small craft owners. Open water tests were conducted in the Emerson Cavitation Tunnel of Newcastle University in atmospheric and reduced vacuum condition. In the latter case the propeller was exposed to several hours of cavitating condition to check on the adherence resilience of the FR system. In the atmospheric condition a slight increase in propeller efficiency of 0.16% was recorded. In a vacuum condition (equivalent to the scaled service condition of the propeller) a slight drop in efficiency (2.48%) was noted. Neither of these values was large enough to say that the coating made a significant change to the propeller efficiency beyond that of experimental error. It was noted that with the coating the inception of the tip vortex cavitation appeared at approximately a 5% lower value of the rpm for the uncoated propeller, although this could easily be due to the poor application of the coating (applied by brush) or mechanical damage on the leading edges of the blades. No adverse effect of the coating to the extent of the cavitation was noted whilst the coating stayed intact until the end of these tests except small peeling off at the sharp edges, **Candries et al. (1999).** In addressing at the second stage investigations (2) more through and long term research was planned. This has involved numerical and experimental investigations as well as full-scale trials / observations to demonstrate if there were any benefits or disadvantages of applying FR coating on propellers in terms of propeller efficiency, effect on cavitation inception, type and extent of cavitation and underwater noise emission from propellers. The following section gives a brief review and findindgs from these investigations.

2.2.6. Effects on propeller efficiency

Based upon some plausible fuel saving reports after the application of IS700 coating on the propeller of a 100,000 DWT tanker, it was decided to use the propeller of this vessel as the benchmark propeller for the Newcastle University propeller coating research, and some numerical and experimental work was conducted with the scaled model of this propeller with the following main particulars given in Table 5 and operating conditions given in Table 6.

Table 5. Main particulars of the basis vessel and propeller

Propeller		**Vessel**	
Diameter, D	6.85 m	Ship type	Medium sized tanker
Pitch Ratio, P/D	0.699	Deadweight	96920 tonnes
Expanded Blade Area Ratio, A_E/A_0	0.524	Length Overall, L_{OA}	243.28 m

Number of Blades, Z	4	Max Draught, T	13.62 m
Design Advance Coefficient, J_A	0.48	Speed	14.86 knots
Direction of rotation	Right/H	Power(installed)	9893 kW
Scale ratio, λ	19.57	Year built	1992

Table 6. Operational conditions

	Fully Loaded Condition	**Ballast Condition**
Cavitation number, σ	0.520	0.334
Propeller immersion, H (m)	10	4.66
Propeller speed (RPM)	100	104
Design J_A	0.48	0.486
J range tested	0.75, 0.70, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40	

Atlar et al (2002) conducted numerical investigations on the open water performance analysis of this propeller by using a boundary element theory based lifting surface analysis tool in which the effect of the FR coating was simulated in the appropriately selected drag coefficients of the propeller blade section. In this selection the increase in section frictional drag due to roughness was represented by the expression given by **Mosaad (1986)** as:

$$1000\Delta C_F = 8.1\,\mathrm{Re}^{0.093}\left[\frac{1}{3}(h'/c) - 4.5\,\mathrm{Re}^{-1/3}\right]$$

Where Re is the blade section Reynolds' Number; c is the section chord length; h' is the roughness parameter as defined by Musker described earlier. Values for h' for the various Rubert surfaces were calculated by Mosaad and are given in Table 7.

Table 7. Musker's characteristic roughness measure of Rubert gauge surfaces.

Rubert Surface	*h' (μm)*
A	1.32
B	3.4
C	14.8
D	49.2
E	160
F	252

The total drag coefficient was represented by the sum of the frictional drag and the form drag as in the following where t is being the thickness of the blade section:

$$\Delta C_D = 2(1 + t/c)\Delta C_F$$

In consultation with a major UK propeller manufacturer, it was assumed that a roughness equivalent to Rubert A represented a degree of smoothness unlikely to be achieved in practice. Rubert B was considered characteristic of a new or well polished propeller and Rubert D to E would be equivalent to the blade roughness after 1 to 2 years in service. In the numerical analysis it was assumed that the new or polished propeller had Rubert B blade surfaces, the drag of which was represented by the design C_D values taken from **Burrill (1955-56)**. The increase in C_D caused by blade roughening was then given by the difference between the ΔC_D values corresponding to the Rubert surface in question and that for Rubert B. The effect of the increased roughness on the drag coefficient for the section at r/R = 0.7 is shown in Table 8.

Table 8. Drag coefficients of Rubert surfaces (Design = Rubert B).

Surface	*Design*	*Rubert D*	*Rubert E*	*Rubert F*
C_D	0.008338	0.01003	0.01138	0.01206
% Increase		19.7	35.8	43.9

The key decision on this analysis was the determination of characteristic roughness values (h') for the foul release coated blade surfaces. In this decision the measurements made with the FR coated flat plates by **Candries (2001)** played an important role. The surface characteristics of 5 different applications were studied using a UBM Optical Measurement System from which it was found that the roughness measure h' varied between 0.5 and 5µm. The quality of application ranged from excellent to good, so that it was considered appropriate to assume a value of h' = 5µm. The calculated values were negligibly different from those calculated when using the Design C_D values. From this it can be inferred that a foul release coated blade surface was equivalent to the new or well polished blade surface.

Based on the above assumption the sectional drag coefficients in the numerical tool was modified and the propeller performance with the design C_D values was first was calculated for varying operating (advance coefficient) conditions and this procedure was then repeated with the drag coefficients corresponding to Rubert D, E and F surfaces for the same conditions. The results of the comparisons were presented in the open water curves of this propeller as shown in Figure 4 where the predominant effect of an increase in the roughness of the propeller blades was an increase in the propeller torque. The decrease in propeller thrust that accompanies the increased torque was too small to be obvious on the figure's scale.

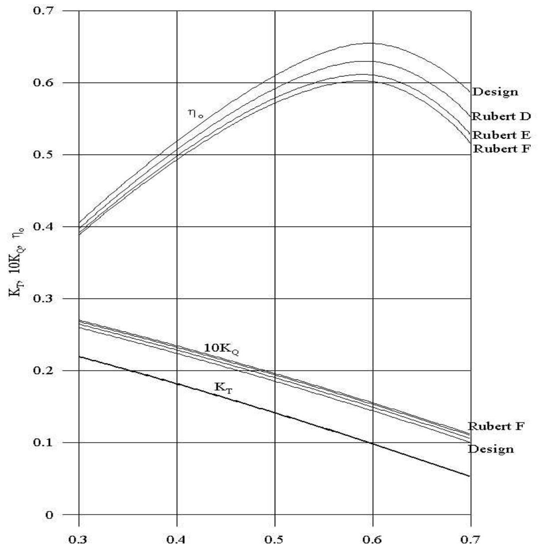


Figure 4. Propeller open water characteristics for various values of blade surface roughness, **Atlar et al (2002).**

The loss in propeller efficiency (η_o) as the propeller blades roughen, to a base J, is shown by Figure 5. Performance data for the subject vessel from which the propeller was modelled showed that on average propeller worked at a value of J = 0.48. As shown in Figure 3 the propeller efficiency losses due to blade roughening (or gains by keeping propeller clean) were about 3%, 5% and 6%for surfaces of roughness represented by Rubert D, E and F, respectively. In summary, this numerical investigation showed that significant losses in propulsive efficiency resulting from blade roughening can be regained by cleaning and polishing of the blades. Alternatively, the efficiency losses could be avoided, perhaps indefinitely, by the application of a paint system that gives a surface finish equivalent to that of a new or well-polished propeller. A foul release coating could be such a paint system.

Atlar et al (2003) conducted the similar analysis, this time applied on high-speed and large surface area propellers. The simulations for the open water performance of the Gawn-Burrill Series based propeller of a twin-screw patrol gun boat indicated rather plausible efficiency gain (or loss) which was almost twice the maximum efficiency gain (or loss) obtained with the earlier reported tanker propeller. This was related to the high speed and larger blade surface area of the propeller.

While the above described numerical investigations revealed attractive potential of the FR coating for efficiency gain, experimental investigations were conducted to confirm on this potential with a scaled model of the earlier described basis tanker propeller in the Emerson Cavitation Tunnel. The model was constructed from aluminium to a scale of 1:19.57 so that multiple sets of blades, manufactured with great accuracy can be installed or replaced easily.

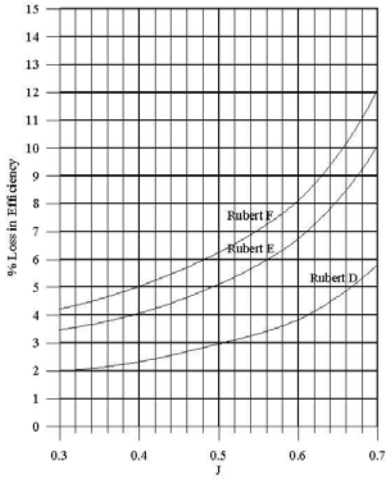


Figure 5. Loss in efficiency in going from Design Drag Coefficient to specified Rubert Surfaces, **Atlar et al (2002)**.

This allowed rapid and reversible changes between the coated and uncoated condition. One set of blades was coated with the IS700 FR system which was a three layer system consisting of an epoxy basecoat, a silicon polymer top coat and a tie coat between these two for good bonding. The whole system dried to a film thickness of between 320 and 360mic. The uncoated and coated propeller model can be seen in Figure 6.

Figure 6. Model Propeller with uncoated (left) and coated (right) blades, **Mutton et al (2005)**

Results from the tests were discussed by **Mutton et al (2005)** and Figure 7 shows the findings from the open water tests. As shown in this figure there was little difference between the coated and uncoated condition for the favour of the coated condition at higher values of advance coefficients. The slight change was due to the slight decrease in the measured torque as observed in the numerical simulations. The open water tests were repeated at a reduced vacuum, which corresponded to the fully-loaded condition of the vessel. This did not show any change in the efficiency at the design operating condition.

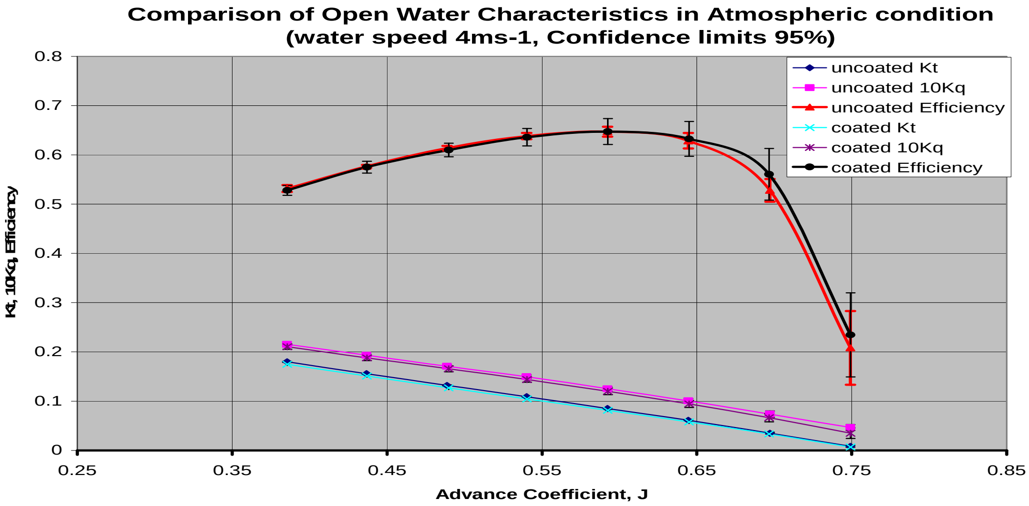


Figure 7. Open water curves for the uncoated and coated propeller. A slight reduction in torque at higher advance coefficient has led to an increase in efficiency for the coated propeller. The design operating condition for this propeller is J=0.48; no difference is detected in performance at this condition, **Mutton et al (2005).**

Examination of full-scale propellers coated with FR systems has demonstrated that, like all propeller coatings, the Foul Release coating is prone to suffering damage from to cavitation and hitting objects in the water. This is usually about 5-10% of the coating surface area and predominantly on the blades leading edge, trailing edge and tip regions. It was suggested that this damage may significantly affect the performance of the propeller as well as promoting early cavitation inception and encourage further cavitation development in the damaged areas. To investigate these effects **Mutton et al (2005)** imparted different levels of typical damages onto this model propeller's coating to investigate the damage effects. These tests indicated that the damage to the coating had to be extensive before significant reduction in efficiency to occur.

One of the important aspects affecting the foul releasing ability of these coatings is the lower threshold of a vessel's continuous operational speed. Early generation FR coatings had relatively high threshold (e.g. 18 knots and beyond) to be effective whilst this limit has been reducing (e.g. 12 knots and below) with recent development in this coating technology. In parallel to this development, in the early stages of the above described research at Newcastle University the commercial FR system used was International Paint's Intersleek 700 (IS700). After the introduction of the recent commercial product, Intersleek 900 (IS900), the above propeller performance tests were repeated with this latest coating system applied on the same model propeller by **Korkut and Atlar (2009).** Using the latest application technology it was possibly to achieve a dry film thickness of 250μm with the three layer coating system as opposed to a 350μm thickness of the earlier tests. The open water performance tests revealed an average 1% difference in the efficiency values over the entire J range for the favour of uncoated blades. Both thrust and torque values were slightly increased by 1.9% and 0.9% with the effect of coating, respectively. In overall the difference in the average efficiency was within the uncertainty level of the open water tests which was 3%, similar to the conclusions by **Mutton et al (2005)** although the trend in the previous tests was in favour of coated blades.

However in their experimental study, **Korkut and Atlar (2009)** withdrew attention on the applied paint thickness such that, owing to the practical limitation of the application technique of the particular coating, which was airless spraying, the coating thickness applied on the model propeller was almost similar to the coating thickness at full-scale. This would require further investigation on scaled coating thickness and appropriate scaling law.

Within the same framework another recent experimental investigation on the application of new FR coating on model propeller performance was reported by **Atlar et al (2010)** as part of the recently completed EC-FP6 integrated R&D project AMBIO which aimed to develop non-toxic antifouling benefited from nano technology engineering to prevent or reduce the growth of biofouling in the marine environment, **AMBIO (2010).** In this project, one of many newly formulated and tested FR coatings was TNO-008 which was based on nano-engineered Sol-gel technology by TNO. This coating was applied on the earlier described benchmark model propeller using spraying technique and cured by heating up to 125 deg. The nature of the coating and the application technology enabled to apply this coating at a desired thickness such that it was possible to achieve an average roughness which was 54% less than the roughness achieved with the Intersleek 900 (IS900). The comparisons of the open water test results of the model propeller with the IS900 and TNO-E008 coatings showed similar torque characteristics, with little difference observed between the 2 coatings. However the TNO-E008 coating gave a higher thrust value for the same rpm when compared to the IS900 coating such that the efficiency increase could be as high as 4% when compared to the IS900 at the maximum efficiency. Whilst this finding appears to be too plausible requiring further investigations at least by applying on other types of propellers and to test, the most interesting nature of this new coating technology was the flexibility in the application thickness that can be adjusted to meet a scaling criterion that can be found between the model and full-scale paint thickness.

In order to investigate the effect of propeller coating on ship's performance in full-scale and controlled manner, **Mutton et al (2003)** conducted a series of comparative dedicated full scale trials for the first time with the FR coated and uncoated propellers. This was over a measured mile with Newcastle University's Ex-R/V Bernicia which was based on the design of a fishing vessel and mainly used for estuarine and coastal research. The main particulars of the R/V and its single screw are given in Table 8 and 9, respectively.

Table 9. The general particulars of RV Bernicia

Overall length	16.2 m
Beeam	4.72m
Draft	2.59m
Gross tonnage	46.25 tons
Engine (MCR)	150HP @ 1500rpm
Gear box ratio	3.4:1
Maximum ship speed	9 knots

Table 10. Main particulars of the R/V Bernicia propeller

Diameter	1.14m
Mean face pitch	0.9m
Expanded BAR	0.466
Blade numbere	4
Rotation	Right hand
Max rpm	440

The initial trials were conducted with its clean but uncoated propeller before being placed on the slip and its propeller removed to be coated by IS700 using spraying at the paint manufacturer's site. Another series of measured mile trials were then conducted for the same loading conditions applied with the uncoated propeller trials. Shaft torque, shaft/vessel speeds and all other relevant parameter measurements were recorded for analysis and further corrections. The conduct of the trials and analyses were carried out using the BSRA standard procedure and details of these measurements can be found in **Mutton et al (2003).** As shown in Figure 8, despite the weather affecting the coated trials, the results showed little difference between the shaft power performance of the coated and uncoated propellers.

Although the sea trials proved inconclusive due to poor weather, in measuring the short term increase in performance due to the application of the coating, in the first three years since the trials took place, the propeller was inspected at both 12, 24 and 36 months' The state of the propellers at these inspections are shown at pictures in Figure 9, **Mutton et al (2005)**.

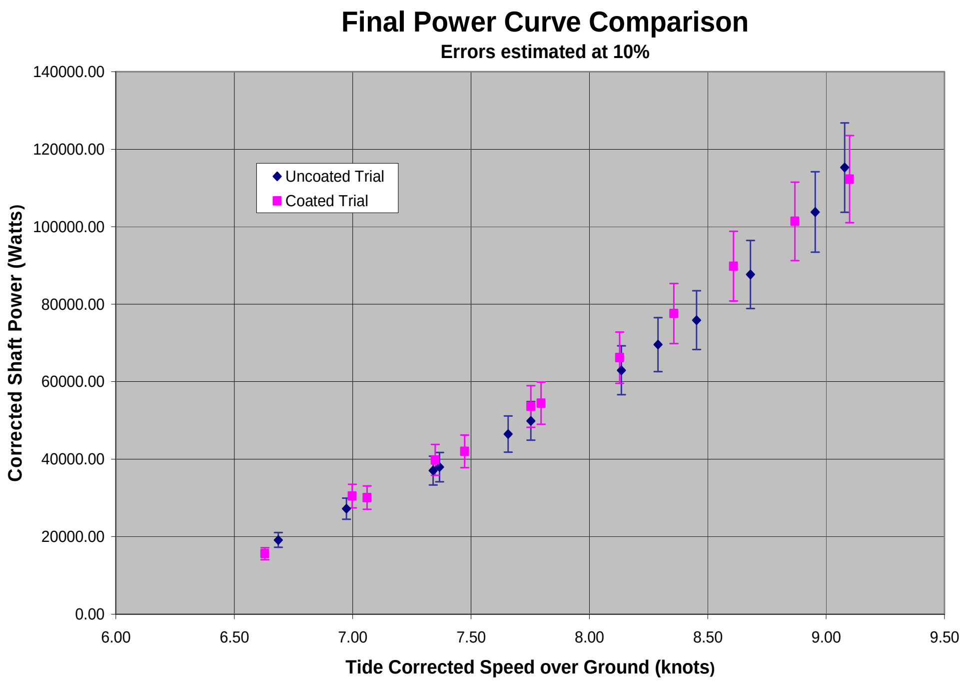


Figure 8: The final Results of the Bernicia sea trials show no statistical difference between the two curves. The trials were particularly affected by the weather leading to large error estimates and making the results inconclusive, **Mutton et al (2005).**

As shown in these pictures the coating was found to be in good condition, 95% intact, except for slight removal of the coating at the edges and tip of the blades. The results have shown that despite the vessel operating in a heavy fouling, coastal and estuarine environment, little fouling was returned to the propeller. What fouling was returned is a light 'slime' layer that could be easily removed with a damp cloth. This was very different for the uncoated propeller where after 14 months in service after a polish, hard shelled barnacles were present to about half the blade radius that can only be removed by scrubbing..

12 months

24 months

36 months (back)

Figure 9.: The coated propeller of Bernicia after 12, 24 and 36 months in service, **Mutton et al (2005)**

Roughness measurements were taken on the Bernicia propeller using stylus type roughness gauge (Surtronic 3+) before and after the coating applied as well as after 1 year vessel was in service with the coated propeller. As shown in Figure 10 the average of the mean roughness amplitude (Ra, with a cut-off length of 2.5mm) and its distribution was significantly different in favour of the coated propeller. There was some measured difference between the newly applied coating and the coating after 12 months in service. This was mostly due to the presence of the slime layer on the blades which can easily be removed and some slight mechanical damage to the coating.

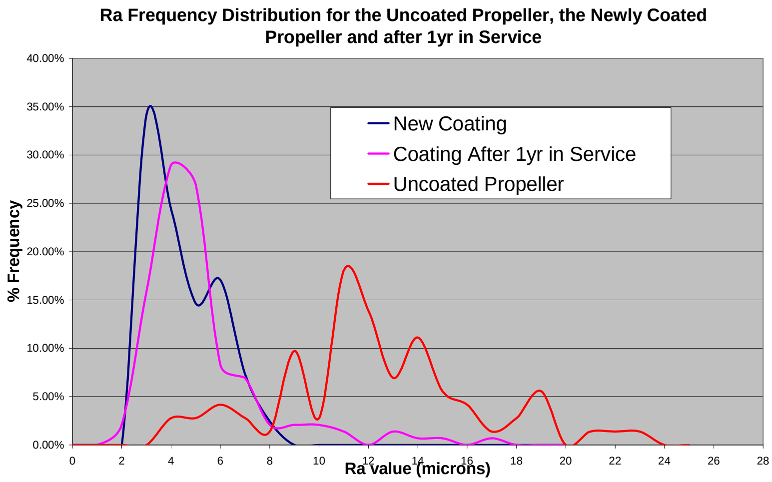


Figure 10. The mean roughness amplitude, Ra, frequency distributions measured on the propeller of R/V Bernicia before coating, after coating and after a period with the coating in service.

Figure 11 shows the mean spacing distance between profile peaks frequency distribution (Sm) measured on the Bernicia's propeller. This is a measure of the surface texture where the larger the value, the more 'open' the texture. The coated propeller exhibits a much wider range of mean spacing, while the uncoated propeller had a much smaller range. As shown in Figure 11, after a year in service the frequency distribution of Sm has changed little and still exhibited the wider range. **Mutton et al (2005)** concluded that the coating significantly changed the roughness characteristics of the propeller blade surface and that the roughness did not change significantly after 12 months in service. The coating had the effect of preventing the increases in roughness usually seen with uncoated propellers as well as keeping the R/V propeller remarkably free from major fouling more than 3 years which was impossible with her uncoated propeller.

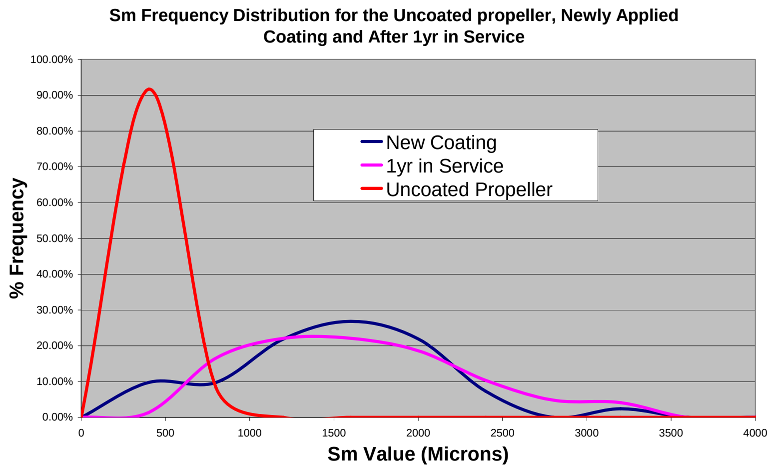


Figure 11. The mean spacing between profile peaks, Sm, frequency distribution. Measured on the propeller of Bernicia before coating, after coating and after a period with the coating in service.

Task 2.3. The Effect of Coating on the Cavitation Behaviour

The effect of coating on the cavitation performance of a propeller can be as important as on its efficiency or even more for a quiet propeller. Nevertheless, there is hardly any data reported on this subject in the open literature except some anecdotal reporting from full-scale and limited experimental investigations conducted at Newcastle University. These investigations have focused on the effect of different types FR coatings on the cavitation inception, and type and extent of fully developed cavitation observed on the earlier mentioned bench mark tanker propeller tests summarised in the following.

Cavitation inception is a complex phenomenon which is far from being completely understood at present. The mechanisms underlying this phenomenon are thought to be threefold: (1) water quality (mainly nuclei content and its statistics); (2) the growth of the boundary layer over the blade sections; and (3) type of cavitation to be developed. Amongst them, it is most likely that the growth of the boundary layer will be most affected by the presence of coating while the type of cavitation may also be affected.

In the case of a “surface” cavitation, as oppose to a “vortex” type, inception occurs in the region of the boundary layer transition. In this respect, propeller blade roughness stimulates the transition of the boundary layer from laminar to turbulent flow and hence causes cavitation inception. The Foul Release coatings are expected to delay such transition from the laminar to the turbulent flow and hence the associated delay in cavitation inception will also be expected. However, this effect may not be so important for full-scale propellers which operate in fully turbulent regime. Even if it is limited to the leading edge regions, this effect can be important for special propellers designed to avoid cavitation. Another interesting nature of the visco-elastic materials, like the silicon coating, is their effect to alter the turbulence characteristics of the flow near the wall and even “re-laminarise” the turbulent flow. This will not only affect the cavitation inception but also influence the characteristics of the developed cavitation. In contrast, the protuberances of uncoated and not well-maintained rough blade surfaces are expected to destabilise the vortices more quickly and creating bubble residence locations, and hence reduce the cavitation strength of the water.

In the case of "vortex" type cavitation, particularly in the tip vortex type, the nature of the vortex is strongly dependent upon the nature of the boundary layer over blade in the tip region, which can be affected by the coating. If the boundary layer separates near the tip then the tip vortex will be attached to the blade while the preservation of a laminar flow near the tip can avoid the detachment of tip vortices.

The effect of FR coating on the cavitation inception was first reported by **Mutton et al (2006)** on the tests conducted in the Emerson Cavitation Tunnel with the earlier described benchmark tanker propeller. The model of this propeller was tested with its blades uncoated and coated with Intersleek 700 (IS700) in uniform flow at reduced vacuum levels simulating the loaded and ballast operating conditions of the tanker. Careful recordings of the cavitation inception of a thin unattached tip vortex indicated slight delay in inception due to the FR coating in the loaded condition whilst this trend was somehow reversed in the ballast condition. In overall it was concluded that the effect of coating on cavitation inception was not significant. On the other hand, the nature and extent of the developed cavitation patterns, which were mainly tip vortex and sheet cavitations, were somehow different such that the uncoated propeller tip vortex was thicker while the extent of sheet cavitation was relatively large compared to the coated propeller blade cavitations. However, the uncoated propeller cavitation pattern was more stable compared to the coated one. The unstable nature of the coated sheet cavitation sometimes caused it to break up into misty and cloud types of cavitation along the lower boundary of the cavity sheet. Although it was not published the effect of coating damage on cavitation was also explored by various scenarios and no evidence was found that the coating damage would cause further cavitation on this propeller model.

In a recent follow up investigation to the above study, **Korkut and Atlar (2009)** conducted further experimental investigations onto the effect of coatings on the cavitation inception and cavitation extent on the same benchmark propeller but using latest commercial FR product, IS900. Furthermore they also explored the effect of non-uniform flow by testing the model propeller behind a wake screen. The results of the inception/desinence test are shown in Table 11 where the cavitation inceptin number is defined based on the resultant flow velocity combined with the advance speed and rotational speed at 0.7R.

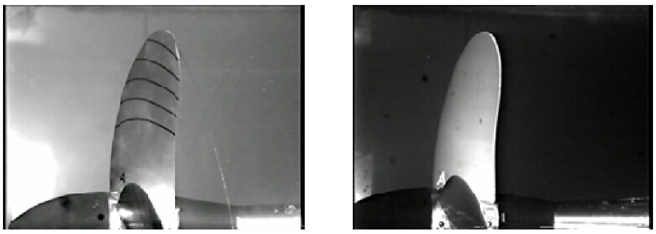
Table 11. Cavitation inception test results with uncoated and coated blades in uniform and non-uniform flow cases, **Korkut & Atlar (2009)**

	Uniform		**Non-Uniform**	
Cavitation Type	**Uncoated**	**Coated**	**Uncoated**	**Coated**
Unattached tip vortex cavitation-inception	0.685	0.679	0.982	0.984
Unattached tip vortex cavitation-desinence	0.683	0.677	0.980	0.983
Attached to all blades	0.606	0.611	0.701	0.695

As shown in the table the coating of the blade did not change the cavitation inception characteristics of the model propeller (difference is less than 1%), if the coating applied correctly (i.e. avoiding sagging of paint at sharp blade edges that may cause unrealistic cavitation pattaern and singing). Korkut and Atlar related this to the similar roughness and surface texture characteristics of both uncoated and coated blades measured with the model. However this may not be the case in full-scale applications, where some advantage of smooth FR surface finish can be expected, by delaying the inception of cavitation.

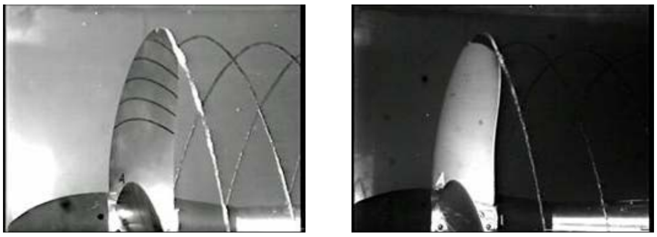
As far as the cavitation extent was concerned, the uncoated blades displayed slightly more extended cavitation than those of the coated blades from tip vortex to sheet vortex type for both loading conditions as shown in Figure 12 for the fully loaded condition.

In a recent study by **Sampson and Atlar (2010)** the cavitation inception and extent characteristics of the same model propeller were compared as uncoated, coated with IS900 and the earlier described AMBIO project coating (TNO-E008). These tests indicated some delay in cavitation inception for IS900 compared to the uncoated and TNO-008 coated blades. Analysis of the cavitation patterns was subjective owing to the resolution of the video camera. The predominant cavitation on the blade was steady sheet cavitation and developed tip vortex cavitation in the propeller slipstream which had greater extent on the uncoated blade and similar but slightly less presence on the coated blades with non-discernable difference between them as shown in Figure 13.

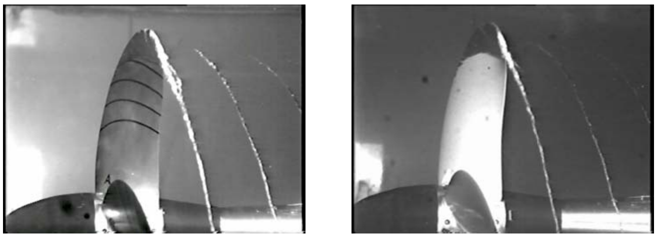


J=0.50 Uniform

J=0.50 Non-Uniform



J=0.40 Uniform



J=0.40 Non-Uniform

(a) **(b)**

Figure 12. Cavitation developments in uniform and non-uniform flow conditions at varying advance coefficients for fully loaded condition: (a) uncoated; (b) coated by IS900.
Korkut & Atlar (2009)

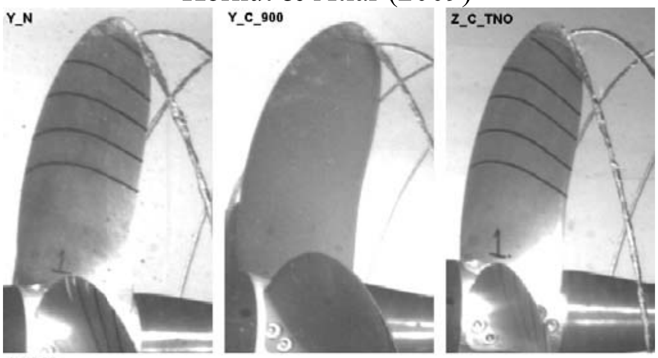


Figure 13. Cavitation comparison of the 3 blades (Uncoated, IP900, TNO-E008) at J = 0.35 and atmospheric condition. Atlar et al (2010)

Task 2.4. The effect of Coating on Comfort (Propeller noise)

Similar to the lack of research on cavitation, virtually there is also no published data on the effect of FR coating on propeller noise available in the open literature, apart from the limited investigation conducted at Newcastle University by **Mutton et al (2006)** and **Korkut & Atlar (2009).**

There are four principal mechanisms by which a propeller can generate sound pressures in water, **Carlton (2009).** These are associated with: (1) the displacement of the water by the blade profiles; (2) immigration of flow from the pressure to the suction side of the blades in developing thrust; (3) fluctuating volume of cavitation on the blades when cavitation develops on the blades of propeller operating in non-uniform wake flow; and (4) collapse of cavitating bubble and/or bursting of a cavitating vortex.

Of the above four mechanisms of generating propeller noise the first two are associated with “non-cavitating” propeller flow while the latter two with the “cavitating” flow. The non-cavitating component of sound pressures will have distinct tones – known as the blade rate noise- associated with discrete (lower) blade frequencies together with a broad-band noise at higher frequencies. The blade rate noise is closely associated with the unsteadiness caused by circumferentially varying wake field in which the propeller operates. This causes a fluctuation in the angle of attack of the propeller blade sections and hence sound pressure. However this can hardly be affected by the presence of the coating. On the other hand the broad-band noise is mostly affected by the level of turbulence in the incident flow and its interaction with the wall boundary layer which will be affected by the coating. One of the important mechanisms contributing to the broad-band noise is the trailing edge noise, which is perhaps the least well understood mechanism. The role of the turbulence in the boundary layer is a crucial parameter, which will be affected by the presence of coating, while this noise component would suffer from the effect of possible fouling with uncoated propeller as well as from hydro-elastic effects of the coated blades. The collapse of cavitation bubbles creates shock waves and hence cavitation noise. This is manifested as mostly ‘white noise’ in a frequency band up to around 1MHz. It is thought that the coating will mostly affect the trailing edge noise and may even act as a damper by absorbing the energy of cavitation noise due to its flexible nature.

The investigation of the effect of FR coating on propeller noise was also part of the experimental work on the efficiency and cavitation investigations with the benchmark propeller reviewed earlier. The noise investigations therefore conducted at two experimental campaigns: in the first, the benchmark model propeller uncoated and coated with IS700 tested in uniform flow; in the second campaign the same model propeller coated with IS90 and tested behind non-uniform flow as well as the uniform flow.

The comparative results of the first experimental measurements, which were analysed using the ITTC analysis and correction procedure, presented as the net sound pressure level of the propeller against the centre frequencies for the uncoated and coated blades at the fully loaded and ballast conditions as reported by **Mutton et al (2006)**. The comparisons indicated that there was some effect of the coating and the beneficial effect appeared limited to the broadband frequencies and the higher advance coefficients. At smaller values of advance coefficients, which covered the design advance coefficient, the uncoated propeller exhibited reduced noise levels compared to the coated one. In the discrete frequency range there was hardly any discernable difference between the two. As the cavitation increased (as in the ballast condition) the difference between the noise levels of the uncoated and coated propeller at smaller advance coefficient diminished.

The recent follow up investigations by **Korkut and Atlar (2009)** measured the comparative noise levels of the benchmark model propeller, and analysed and presented in the similar manner to the previous investigation. However they used IS900 to coat the blades and also included the effect of flow non-uniformity by wake screen. Typical comparative presentation of their measurements in uniform flow is shown in Figure 14 for fully loaded condition. From these measurements it was concluded that whilst the coating of the blades reduced the noise levels in non-cavitating condition (i.e. higher advance coefficients, J=0.75-0.60), it slightly increased in the developed cavitation condition. This finding applied to both fully loading and ballast condition in uniform and non-uniform flows.

Interaction with bio-fouling

As stated earlier the effect of fouling is a rather important but complex phenomenon and hence to prevent and reduce the fouling settlement on any surfaces, including propeller blades, should be the prime target rather than assessing or modelling of the fouling effects. Within this framework numerous end-user-testimonies and 4 years of monitoring of the Newcastle University R/V Bernicia propeller reveal that FR coating can effectively stay on blades more than 3 years almost 85-90% percent of the coating intact. For example, Figure 14 shows the state of the FR coating (IS700) on the propeller of the earlier mentioned tanker vessel after 37 months in service. During this period the coating has clearly prevented the major fouling development except the slime fouling.

This beneficial effect was even more obvious on the Newcastle University R/V propeller as shown in Figure 15 where the uncoated propeller (after 14 months) is compared with the FR (IS700) coated propeller (after 24 months). It was noted that the uncoated propeller was covered with hard shelled barnacles that had to be removed by abrasive means or scrapers, **Mutton et al (2003).** In contrast the slime or even barnacles that may be attached to FR coated surfaces could be removed by pressure washing or gentle sweeping action.

The effect of slime on any type anti-fouling is a pretty well-known and complex issue, and experience so far with FR coatings indicates that this coating type suffers more from the slime compared to other types, since slime film will attach more strongly to foul release surfaces than other fouling organisms. Experimental studies with FR coatings indicated that increasing the flow shear can reduce the thickness of the slime layer but not remove completely, e.g. **Klijsnstra et al (2002).** While this may compromise the initial drag benefits of FR coatings, at higher speeds that propeller blades operate, this benefit may still persists due to thinner layer of slime film as discussed by **Candries et al (2003).** This is a rather topical issue currently attracting much research supported by paint manufacturers and ship owners.

In an attempt to model the coating roughness including the bio-fouling effect on ship resistance the recent study by **Schultz (2007)** is worthy to note. In this study the resistance-roughness characteristics of some coating types on flat surfaces, which are exposed to different grades of roughness and bio-fouling (varying from slime to heavy calcareous types) settled in a controlled environment, have been established by using a similarity law scaling procedure proposed by **Granville (1958)** and **(1987)** based on the similarity between smooth and rough wall boundary layers.

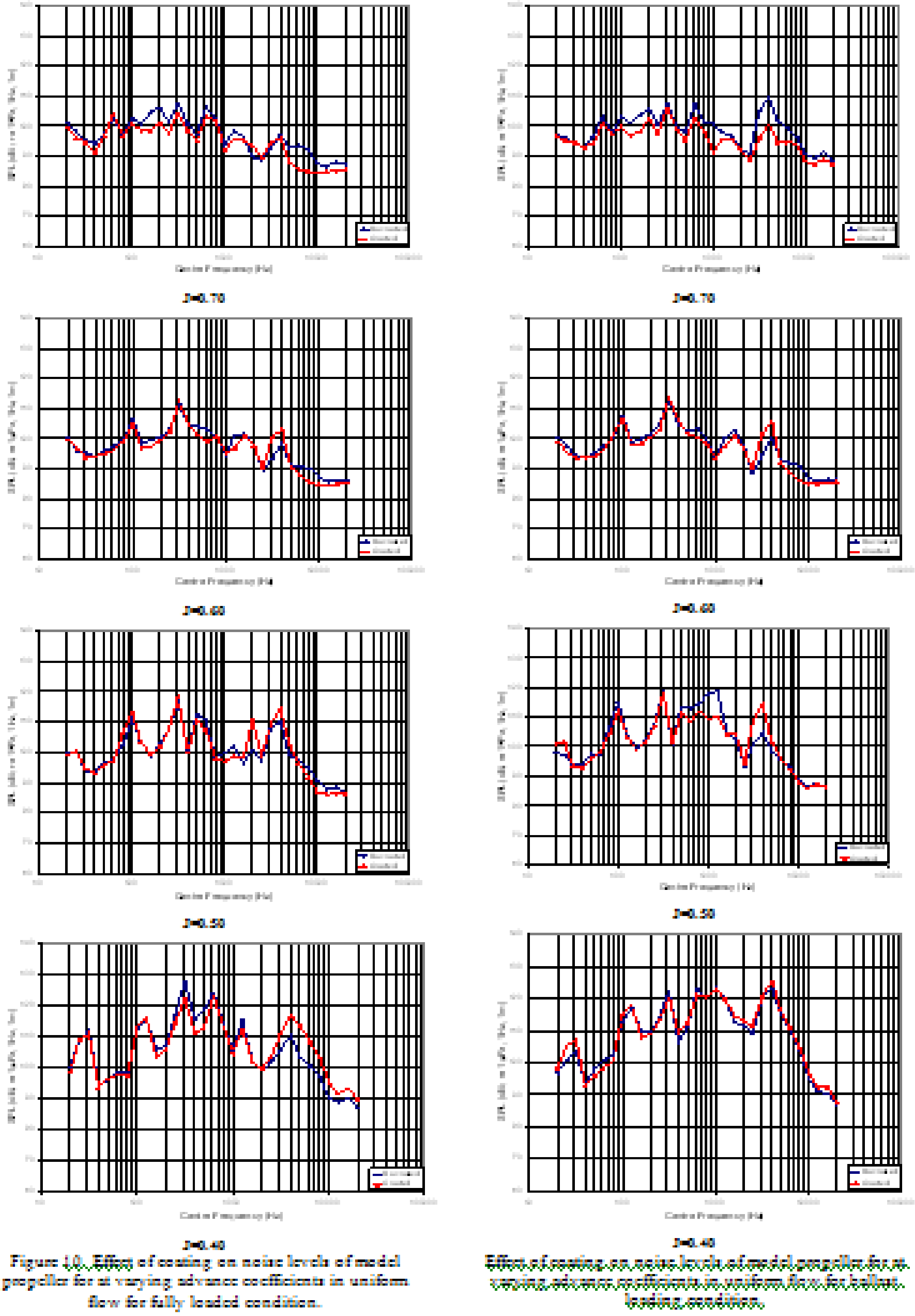


Figure 14. Effect of coating on noise levels of model propeller for at varying advance coefficients in uniform flow for fully loaded condition.

Figure 14. Face and back view of the benchmark tanker propeller painted by IS700 FR coating after 37 months in service without any cleaning

Figure 15. R/V Bernicia propeller uncoated after 14 months in service (left); coated by IS700 after 36 months in service without cleaning (right)

This procedure enabled Schultz to predict the effect of a given roughness on the frictional resistance of a plate of arbitrary length (i.e. representing ship surface) based on laboratory-scale measurements of the frictional resistance and roughness function of a smaller flat plate covered with the same roughness. Schultz applied this procedure to predict the roughness and fouling penalties of a US frigate demonstrating as high as 86% penalty for the heavy calcareous fouling case.

Concluding remarks

Although this study is only representative and requires further proof, its potential implication in assessing performance losses due to deteriorated blade surfaces including various grades of bio-fouling can be plausible since the procedure is generic and technically can be applied to the blade sections based on the flat plate approach as applied in e.g. **Atlar et al (2002)**. However further roughness data of different types of coating in controlled environment may be required for the simulation of typical propeller surfaces.

- Propeller coating has always been interest to ship owners by multiple reasons amongst which the prevention/reduction of galvanic corrosion and that of bio-fouling are the well recognised ones. Recent developments in foul release coating technology and increasing number of FR coated propellers indicates that these coatings have most of the desired properties of propeller coating and currently the most suitable system for development of a propeller coating.

- In spite of various anecdotal claims there has been no credible evidence from full-scale to demonstrate any gain/loss from a vessel fitted with newly polished propeller and FR coated one. However there is limited evidence that these coatings can provide the propeller surface with roughness and texture levels similar to newly polished surfaces for a long time after its applications. This will provide savings in propeller efficiency and maintenance cost relative to the efficiency and cost of unpolished propellers in-service.

- There is no published report of dedicated trial or model test on the comparative efficiency, cavitation and noise emission characteristics of a propeller as uncoated and coated with FR coatings apart from a single source. Limited amount of tests conducted in this source with a model propeller with the coated and uncoated blades have not revealed any remarkable difference in the open water efficiency, cavitation inception and extent as well as the measured noise levels despite some small variations in these characteristics due to the effect of coating.

- Propeller model tests with coated blades suffer from appropriate paint thickness at model scale due to practical limitation of the application method with commercial FR coatings. This requires further investigations.

- Semi-empirical expressions used for the frictional drag coefficient of uncoated propeller blade sections need to be modified to take into account surface roughness effect of coated sections properly. This will in turn require drag-roughness correlation studies with foul release coated surfaces, preferably including the effect of slime.

- Validation and verification studies involving model and full-scale performance of coated propeller will require standard measurement procedures and reliable measurement tools, which are preferably optical and practical to use in model and full-scale, for the measurement of appropriate blade surface characteristics.

- There is a need for dedicated comparative full-scale trials and observations to accurately assess the effect of coatings on the propeller efficiency, cavitation and noise emission.

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Task 3: Review the existing measurement methods for surface roughness at modelscale and at full scale

3.1. Roughness Parameters

Surface roughness in general is a measure of the of the texture of a surface. It is quantified by the vertical deviation of the real surface from its ideal form; in case of large deviations we speak about a rough surface. Roughness values can either be calculated on a profile or on a surface. Profile roughness parameters (Ra, Rq….) are more common whereas area roughness parameters (Sa, Sq,….) give more significant values.

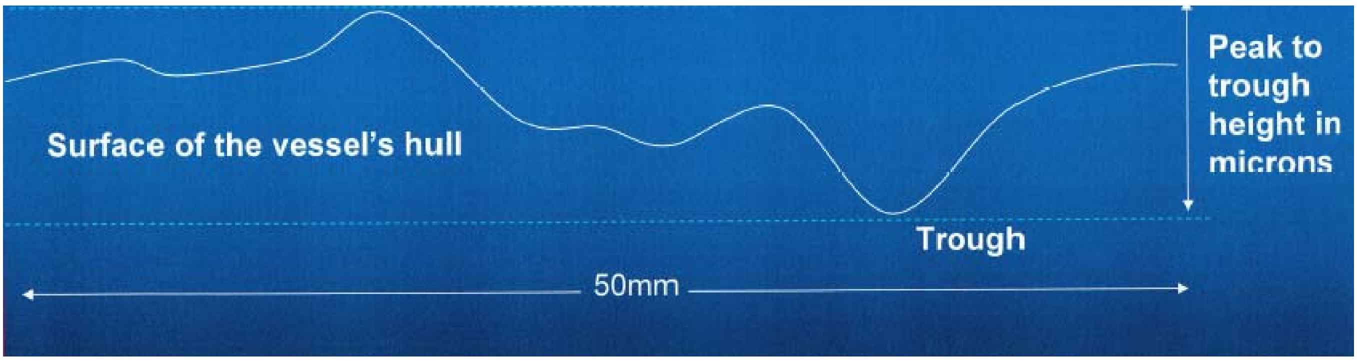
There are many different roughness parameters in use, but Ra (Rah) is by far the most common one. Since these parameters reduce all of the information in a profile to a single number great care must be taken in applying and interpreting them.

The following table gives an overview over the most common formulas how to calculate roughness. Each of the formulas listed in the table assumes that the roughness profile has been filtered from the raw profile data and the mean line has been calculated. The roughness profile contains n ordered, equally spaced points along the trace where y_i represents the vertical distance from the mean line to the i^{th} data point.

Parameter	Description	Formula
R_a[1] R_{aa}, R_{yni}	arithmetic average of absolute values	$R_a = \frac{1}{n}\sum_{i=1}^{n} \lvert y_i \rvert$[1]
R_q, R_{RMS}[1]	root mean squared	$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$[1]
R_v	maximum valley depth	$R_v = \min_i y_i$
R_p	maximum peak height	$R_p = \max_i y_i$
R_t	Maximum Height of the Profile	$R_t = R_p - R_v$
R_{sk}	skewness	$R_{sk} = \frac{1}{nR_q^3}\sum_{i=1}^{n} y_i^3$
R_{ku}	kurtosis	$R_{ku} = \frac{1}{nR_q^4}\sum_{i=1}^{n} y_i^4$
R_{zDIN}, R_{tm}	average distance between the highest peak and lowest valley in each sampling length, ASME Y14.36M - 1996 Surface Texture Symbols	$R_{zDIN} = \frac{1}{s}\sum_{i=1}^{s} R_{ti}$, where s is the number of sampling lengths, and R_{ti} is R_t for the i^{th} sampling length.
R_{zJIS}	Japanese Industrial Standard for R_z, based on the five highest peaks and lowest valleys over the entire sampling length.	$R_{zJIS} = \frac{1}{5}\sum_{i=1}^{5} R_{pi} - R_{vi}$, where R_{pi} R_{vi} are the i^{th} highest peak, and lowest valley respectively.

The most commonly used roughness parameter is the Average Hull Roughness parameter Rah representing the mean of all the vessel's hull roughness readings.

The standard roughness unit is the peak to trough height in microns per sample (one sample is of 50 mm length of the underwater hull).

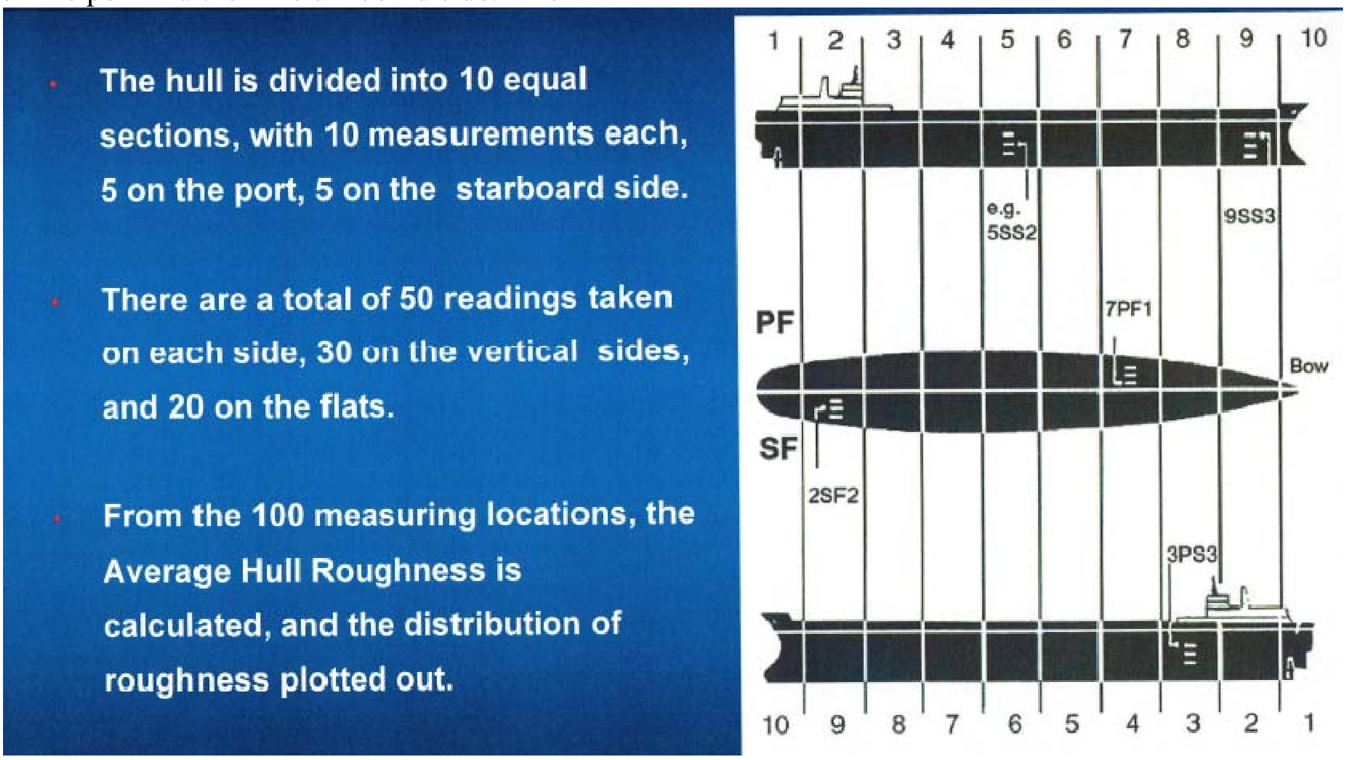


3.2. Measurement Techniques

For the measurement of roughness stylus instruments and optical instruments are in use. In the shipbuilding industry the BMT Sea Tech Hull Roughness Analyser (a stylus instrument with a surface probe) is accepted as the industry standard instrument for the measurement of hull roughness.

3.3. Full Scale Measurements

The hull roughness normally is measured in the way that the hull is divided into 10 equal sections with 10 measurements each, 5 on the port and 5 on the starboard side. A total of 50 readings are taken on each side, 30 on the vertical sides and 20 on the flats. From the 100 measuring locations, the Average Hull Roughness is calculated.



3.4. Roughness Measurements on Ship Models

Roughness measurements on ship models are carried out (e.g. MARIN, SSPA) but the results of the measurements are used for quality assurance and not for further investigation.
Most of the Model Basins do not measure the roughness of the model's hull.

Task 4: Propose methods that take into account surface roughness and other relevant characteristics of coating systems; check the need for changes to the existing extrapolation laws.

This chapter will outline recommendations regarding procedures in measuring skin friction on rough surfaces aimed at the maritime sector.

1. Measurement equipment

Several different techniques can be used for measuring skin friction on rough surfaces some better suited than others. In no specific order the following can be mentioned:

Flat plate in towing tank

Flat plate in cavitation tank

Flat plate in open water channel
Pipe friction device
Flow cell
Couette cell
Other shapes than flat plate in towing tank or the like such as ax symmetric body or model ship
Full scale tests

1.1.Flat plate in towing tank

In the committees opinion the best combination of accuracy and complexity. Usually a quite large surface can be coated, and if care is taken with the setup and rigging of the plate, reproducibility is usually excellent.

The longer and thinner the plate is the better, as skin friction resistance ratio to total resistance will increase with those parameters. Towing speed is limited (to usually around 5m/s) which does require some more extrapolation to full scale than for instance cavitation tank.

Re-rigging after a new surface has been applied can be quite sensitive, therefore control of reproducibility is very important. Time between tows can also be important as a flat plat (especially if towed horizontally) is sensitive to small changes to angle of attack caused by vortical flow remaining in the towing tank after a test.

1.2.Flate plate in Cavitation tank

Skin friction measurements can be achieved by two methods.

1.2.1. Floating element measurements

A plate is built with the sample coated on the plate (and/or before the plate), with a very small gap between the measurement plate and the flush surrounding plate. This plate is suspended in such a way that it is fixed, but shear forces can recorded, usually by strain gauges.

To avoid edge effects the gap is critical, and step changes in roughness should be avoided by coating before and after the test section.

1.2.2. Boundary layer measurements

Measuring the boundary layer by for instance LDV (Laser Doppler Velocimeter), the velocity shift in logarithmic boundary layer can be recorded.

$$U^+ = \frac{1}{\kappa}\ln y^+ + B - \Delta U^+ - \frac{\Pi}{\kappa}\omega(\eta)$$

where U^+ is the non-dimensional wall velocity, y^+ the wall distance and ΔU^+ is the velocity shift function, also known as the roughness function. Critical is the extraction of the friction velocity u_τ and several methods have been proposed. This committee has no recommendations regarding which one to use.

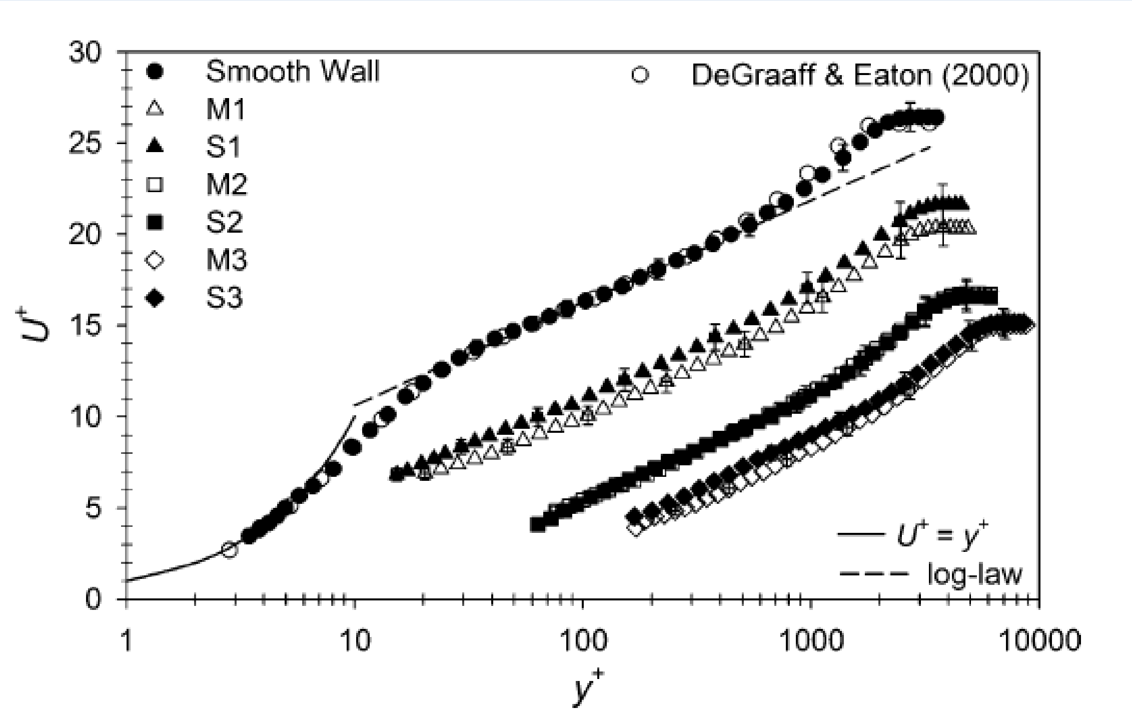


Figure 4: Velocity profile measurements on different rough surfaces

Once the velocity shift function is established by boundary layer measurements, it relates to the skin friction coefficient as

$$\Delta U^+ = \left(\sqrt{\frac{2}{C_f}}\right)_s - \left(\sqrt{\frac{2}{C_f}}\right)_r$$

where s and r refers to smooth and rough respectively. Therefore for all boundary layer measurements (and skin friction measurements in general) it is important to measure the hydraulically smooth case. The above equation is a simplification of integration of the log-law boundary layer equation, and assumes that the displacement thickness is constant. Depending on the type of measurement, care must be taken to either ensure that the assumption holds, or otherwise correct for the simplification. For boundary layer measurements for example momentum or outer similarity methods can be used, but will not be described further in this report, see for example.

Finally, skin friction can be related roughness by the non-dimensional roughness height

$$\Delta U^+ = f(h^+) = \frac{1}{\kappa}\ln(\mathrm{h}^+ + 1) = \frac{1}{\kappa}\ln\left(\frac{\mathrm{hu}_\tau}{\nu} + 1\right) = \left(\sqrt{\frac{2}{C_f}}\right)_s - \left(\sqrt{\frac{2}{C_f}}\right)_r$$

or if boundary layer measurements are not available (as for instance towed plate or floating element measurements)

$$\Delta U^+ = f(h^+) = \frac{1}{\kappa}\ln(\mathrm{h}^+ + 1) = \frac{1}{\kappa}\ln\left(\sqrt{\frac{C_{f\,r}}{2}}\frac{\mathrm{hU}}{\nu} + 1\right) = \left(\sqrt{\frac{2}{C_f}}\right)_s - \left(\sqrt{\frac{2}{C_f}}\right)_r$$

The above equations can be used for any type of skin friction measurements, the difference between boundary layer methods is that friction velocity is used directly, whereas resistance measurements should use the second version of the equation.

Boundary layer measurements are very time consuming and requires expensive and sensitive measurement equipment. But better control of displacement thickness is possible than indirect methods.

1.3.Pipe Friktion Measurements

Pipe friction measurements is probably the most cost effective method along with Couette Cell flow. It is also well suited for tests with for example bio fouling as the test pipes can be transported relatively easy between test site and fouling site.

Measurement method is indirect as measured parameters is average flow velocity and pressure drop over test section. Accuracy is much lower than for instance towed flat plate however for surfaces with high skin friction increase it is deemed sufficient (as for instance barnacle surface). Boundary layer is not free (confined by the pipe radius) and correction to flat plate skin friction must be performed.

1.4.Flow Cell

Mainly mentioned to include types of tests. Flow cell is not well suited skin friction measurements within the maritime sector as Reynolds number is very low and requires too extensive extrapolation to full scale skin friction.

1.5.Couette Cell

Couette cell is relatively simple in construction and build cost. It does however produce results which is difficult to interpret accurately due to mainly the formation Taylor-Couette cells, complex axially non-uniform boundary layer and boundary layer development, but also issues such as increasing water temperature during tests. Therefore, some difficulty exists calculating C_f based on torque measurements, but [Arcapi, 1984] suggested

$$\frac{1}{\sqrt{C_f}} = \frac{1}{\kappa\sqrt{2}}\ln\left[Re_h\sqrt{\frac{C_f}{2}}\right] + 5.5$$

where κ is the von Karman constant and Re_h is the Reynolds number based on the gap length between cylinders.

Advantage with Couette cells is that it is rather easy to apply a new surface, and especially for tests which require measurements over long time (for example to test self polishing) Couette cell is well suited.

1.6.Other shapes

Generally using other shapes than flat plate for towing, seems like an unnecessary complication in model scale. The goal of skin friction measurements is to acquire skin friction lines which can be extrapolated to full scale. Using for example a ship model will introduce much higher residual and wave resistance than for a flat plate, but even more important large variations of skin friction locally due to accelerating flow around the model. This makes it difficult to interpret extracted increase in resistance. It is therefore not a recommended procedure.

2. Test Procedure Recommendations

2.1. Reynolds Number

It must be ensured that the Reynolds number is sufficiently high. The lower the Reynolds number the higher the risk is that the surface becomes hydraulically smooth. This is the case no matter what measurement equipment is being used.

$$y^+ = 5 = \frac{U_\tau y}{\upsilon} \quad C_f = \frac{\tau_w}{\frac{1}{2}\rho U^2} \quad u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

Theoretically, the surface is hydraulically smooth when y^+ is lower than 5. If this is the case the Reynolds number is too low for measuring any effect related to skin friction (exceptions does exist as for example ribblets or active surfaces), and results will be of very questionable value.

There is another reason to keep Reynolds number relatively high which is that the results will require less extrapolation to full scale.
C_f smooth can be taken from any source, for example $C_{f,ITTC}$.

2.2. Flow speed

At least 2m/s above hydraulically smooth must be tested. If not it will be difficult to perform regression analysis and extract parameters such as efficiency for the given surface. Ideally points should be fairly dense for more confidence in regression analysis, but also to identify possible problems with the test equipment/measurement method.

For some test equipment this can present a problem, especially in a towing tank. Therefore it is recommended that it is possible to fulfil this recommendation before tests commences.

2.3. Reference surface

To be able to compare different surfaces skin friction, it is imperative that all measurements are completed with reference to a hydraulically smooth surface. Most measurements are unfortunately reference to another rough surface, for example SPC to silicone. This makes it impossible, or at the very least quite difficult to collect results from many different sources. Therefore at least one measurement must be carried through with a hydraulic smooth surface

$$h < \frac{\upsilon y^+}{u_\tau} = \frac{\upsilon y^+}{U\sqrt{1/2C_f}}$$

where y^+=5 is the limit. This value will for most test setups be in the range 5-50μm, so some polishing of for example a primer will usually be necessary.

2.4. Reproducability

Reproducability will vary quite a lot between different measurement equipment. Two levels of reproducibility exists, with and without re-rigging. A full ITTC uncertainty analysis would be the best procedure to follow, but at least for some measurement techniques will require too much additional work.
Minimum. Repeat 3 measuring points 3 times without re-rigging
Recommended. Same as test 1, but completed twice between re-rigging. Re-rigging implies that the setup is dismantled to a degree where a new surface can be applied.

Reproducibility is paramount, especially for testing for example coatings, as difference between coatings and hydraulically smooth is quite low (below 20% for most cases and Reynolds numbers), between most commercial coatings below 10%. If reproducibility is only 5% it will have a significant impact on the analysis.
Many factors can produce low reproducibility. This committee is aware of the following error sources.
Towing tank: Poor alignment of plate, too little time between tests, suspension allowing plate to bend or Yaw.
Cavitation tank: Not stiff enough floating element increasing gap size, test section not flush with surroundings, scatter in LDV measurements.
Pipe friction device: Reproducability in measurement of average flow velocity, non-flush pressure tap.
Couette cell: Temperature change between and under tests

2.5. Surface

Two aspects of the surface must be considered

Application

Roughness height (and possibly other parameters)

Application of commercial coatings must be completed in a fashion similar to the procedure at the shipyard. For instance, temperature and humidity range from the supplier must be followed, if high pressure spray system is required the surface topology and roughness height can change significantly from the intended if a low pressure system or roller is used.

The committee agrees that steel/primer surface need not be considered. Even though a real untreated hull surface is not smooth, applying the coating system usually consisting of multiple layers, most of the steel roughness will be masked by the coating. This is off course not the case for welding seems for example, but taking such imperfections into account will be practically impossible. A further (very small) added friction could eventually be proposed.

Roughness height measurement should preferably be completed with a BMT roughness analyser. However, other devices can be used, if they as a minimum produce a measure of R_a. **MA can perhaps add to this.** Other parameters can be added such as average distance between roughness elements for barnacles for instance. This might be usefull at a later stage when a relatively high number measurements are collected.

3. ITTC Rough Skin Friction Database

It is proposed that an international database of skin friction measurements are created. Many different researchers have measured skin friction on a lot of different surfaces seen on a ship hull. This includes coatings, bio-fouling and bio-films.

As no single facility will have the funding available to test every coating, bio-fouling and bio-film surface, the second best option is to analyse results following the same guidelines and procedures.

Tests have been completed with test equipment as described in section 1.1 at varying Reynolds numbers, facilities, surface size, roughness height measurement method (if any) and so forth. Many tests are also referenced to another coating and not a hydraulically smooth surface.

It is therefore at present difficult to collect skin friction lines and present them in the same figure. For experiments which fulfil the test procedure recommendations in chapter 2, it will however be possible to collect and compare the results.

3.1. Procedure

SSPA and **Newcastle University** will jointly be responsible for creation and maintaining the homepage, and evaluate and present new results.

After submission of results hydro dynamist from either SSPA or Newcastle Uni. will evaluate results submitted (see 3.2), and determine if results can be used. After analysis is completed results will be publically available on the homepage.

3.2. Submission of results

Any party can submit results completing the submission form and appending data in electronic form. At a minimum raw measurement data and analysis to skin friction coefficient must be supplied, along with description of analysis method.
Unless requested otherwise all material submitted will be publically available. It is assumed that at a minimum the material can be used to extract necessary data by RSFD and present it together with other results.

RSFD will evaluate the material in accordance to items described in Chapter 2, and decide a confidence level and whether or not results will be added to the database. The submitter will have the option to comment on the results before they are made public on the homepage.

Skin friction line, velocity shift function parameters and roughness height will be the main publicised results compared to $C_{F,ITTC}$. All supplied material will be made available on ftp server (or links to for example papers) unless otherwise requested by the submitter in the submission form.

3.3. Analysis Procedure.

3.3.1. Velocity shift function

If results are accepted the analysis procedure will be as follows. Velocity shift function

$$\Delta U^+ = f(h^+) = \frac{1}{\kappa}\ln(\mathrm{h}^+ + 1)$$
$$= \frac{1}{\kappa}\ln\left(\sqrt{\frac{C_{f_r}}{2}}\frac{\mathrm{hU}}{\nu} + 1\right)$$
$$= \left(\sqrt{\frac{2}{C_f}}\right)_s - \left(\sqrt{\frac{2}{C_f}}\right)_r$$

will be used regressively on each skin friction line, however using only one parameter (h) will not be sufficient. Part of the ultimate outcome of SFRD will be to specify the efficiency parameter for various types of surfaces. Bowden added resistance main shortfall is that it is based on a one parameter description of the surface topology which is not sufficient as can be seen in several articles.

Many different two (and more) parameter function have been investigated, but it is this committees conviction that using an additional parameter which is not directly measurable by analysing the surface topology is the most viable method. This additional parameter is the efficiency parameter.

In stead of using

$$\Delta U^+ = \frac{1}{\kappa}\ln(\mathrm{h}^+ + 1)$$

for description of the velocity shift as a function of roughness height, the efficiency parameter C will be introduced as

$$\Delta U^+ = \frac{1}{\kappa}\ln\left(\frac{\mathrm{h}^+}{\mathrm{C}} + 1\right)$$

For each measurement added to the database either the velocity shift (boundary layer measurements) or C_f rough and smooth and roughness height will be known and C can be calculated (by least squares method along the Reynolds number range measured).

It is the hope that collecting many measurements of different types of surfaces, for example silicone surfaces, will reveal a fairly constant value of C, even with varying roughness heights. This will produce a method of calculating the full scale skin friction using the roughness height and a type specific efficiency parameter, rendering a much more reliable method than the Bowden added resistance used today.

Velocity shift function also have the advantage that it can be used locally with for example thin boundary layer methods or Elog method for RANS solvers.

3.3.2. Comparison of results

The only reliable way to compare results from different institutions/measurement methods is to reference the measurements to a surface with known skin friction line. This can in principle be any type of surface for example a specific SPC coating applied exactly the same way each time. However, the only practical procedure is to always use hydraulically smooth surface.

As residual resistance (and wave resistance for some methods) is different for each measurement equipment and design, skin friction lines cannot be compared directly. Therefore, raw results will be re-evaluated using the smooth skin friction measurements under the assumption that the only resistance component that changes between tests of different surfaces is the skin friction. Thus only added skin friction resistance will be used

$$\Delta C_F(Re) = C_F(Re)_{rough} - C_F(Re)_{smooth}$$

The velocity shift function will then be evaluated using a know smooth skin friction line such as $C_{F,ITTC}$ or other lines if deemed more warranted.

$$\frac{1}{\kappa}\ln\left(\sqrt{\frac{C_{f_{ITTC}}+\Delta C_F}{2}}\frac{\text{hU}}{\nu\text{C}}+1\right)=\sqrt{\frac{2}{C_{f_{ITTC}}}}-\sqrt{\frac{2}{C_{f_{ITTC}}+\Delta C_F}}$$

This procedure will to a large degree remove problems with comparing results between measurement techniques at different facilities. It does require measurements of hydraulically smooth surface, which unfortunately is not available in many measurements.

It is conceivable that measurements eventually can be added to the database using other reference surface, but several surface with the correct reference line is necessary before such measurements can be added with confidence.

Arpaci V.S., Larsen P.S., Convection Heat Transfer, Prentice-Hall, Englewood Cliffs, NJ, USA, 1984

Leer-Andersen M., Larsson L., Andreasson H., *Skin Friction Measurements on Rough Surfaces and Full Scale evaluation*, 2nd International Symposium on Seawater Drag Reduction, Busan, Korea, 2005

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

Conclusion and Recommendations

1 Extrapolation Methods

1.1 Conclusions

At this time no evidence suggests that the recommendation of the 25'th Specialist Committee on Powering Performance Prediction regarding the use of the Townsin roughness allowance should be revoked. This does not imply that the committee believes that Townsin/Bowden roughness allowance is an accurate and universal roughness allowance, but that at this point nothing better seems to be available.

Based on a skin friction model test measurement database a new or modified roughness allowance should be suggested. Considering the variety of surface roughness on a ship (coating, damage, slime, fouling) it is likely that this new formulation will either be several formulations or at least one formulation but with roughness type dependent parameters.

A most likely candidate for an improved roughness allowance is the velocity shift function (Roughness Function), used to generate Bowden or Townsin type formulation for the full scale ship using CFD analysis supported by experimental and full-scale data.

All antifoulings suffer from micro-slime (slime) even in newly applied condition. Foul release coating particularly suffers from slime effect due to their non-biocidal defence mechanism which requires shear stress to keep slime free.

There is a lack of data on the drag-roughness correlation of AF-coatings as well as of a new generation of self-polishing types to improve the performance extrapolations not only for the "as newly applied" (trial) condition but also for the "after some time" (in-service) condition. Limited drag-roughness correlation studies indicate that the skin friction of "newly applied" foul release coated surfaces does not correlate with single hull roughness parameters.

1.2 *Recommendations*

It will not be possible to generate a new formulation without an extensive database of skin friction measurements. A relatively small number of existing datasets which is the basis for all formulations today does not lend credibility to a new formulation which can be used with higher confidence.

There is a need for investigation to establish a relationship between the drag-roughness characteristics of surfaces coated either with foul release coatings or with the new generation of self-polishing coatings to improve the performance extrapolations. These investigations should be extended for coated surfaces "in-service" as the surface characteristics of coatings change progressively in service, particularly in case of self-polishing coated surfaces. Although this is a challenging task it is the reality in predicting power in-service.

There is need for data concerning the roughness-drag correlations of flat plat plates coated with foul release as well as with the modern day self-polishing type coatings. Investigations to collect appropriate data are required.

The effect of micro scale biofouling (slime) on the paint performance should be included in the performance predictions and hence investigations should be widened to cover this effect which is a hot issue in foul release coatings.

2 Model Test Procedures

2.1 *Conclusions*

The most accurate method for skin friction measurements probably is the flat plate in the towing tank, but several other methods, including boundary layer measurements, can produce valid results.

Tests should be carried out at Reynolds numbers which produce a flow above the "hydraulically smooth surface" to have any meaningful results. For comparison with other experiments it is of high importance that a reference surface is tested which is hydraulically over the Reynolds range. If this is not the case it is impossible to compare tests coming from different facilities.

Reproducibility should be tested especially for equipment which needs to be re-installed when changing the surface, e.g. in case of a flat plate in towing tank. Reproducibility with and without re-installing should be checked.

Roughness measurement should as a minimum include Ra. Including more surface parameters such as Rt, profile measurements and so forth adds value to the measurements.
Foul release coated surfaces suffer from inaccurate measurements in full-scale (as well as in model-scale with relatively large surfaces) with stylus type mechanical surface measurement devices.

2.2 *Recommendation*

Regarding future work one issue which this committee feels can progress the confidence and accuracy greatly for roughness allowance and its application range is to establish a comparative database for skin friction measurements.

Initially as much data as possible following the recommendation for test procedure at least to an extent should be collected and compared after which alternative roughness allowance

3 Propeller Coatings

3.1 *Conclusions*

Propeller coating has always been of interest to ship owners by multiple reasons amongst which the prevention and/or reduction of galvanic corrosion and that of biofouling control are well recognized. Recent developments in foul release coating technology and an increasing number of coated propellers indicates that this paint technology has most of the desired properties of propeller coating and is currently the most suitable system for development of a propeller coating.

In spite of various anecdotal claims there has been no credible evidence from full-scale measurements to prove any gain or loss from a vessel fitted with a coated propeller compared to a newly polished uncoated propeller. However there is limited evidence that the foul release based coatings can provide the propeller surfaces with roughness and texture levels similar to newly polished uncoated surfaces and even better for a long time after its applications. There is also evidence that these coatings can maintain the blade surface free from major fouling for long time without any maintenance. This suggests potential savings in propeller efficiency and maintenance cost relative to the efficiency and cost of unpolished propellers in-service.

There is no published report of dedicated trials or model tests on the comparative efficiency, cavitation and noise emission characteristics of a propeller uncoated and coated with foul release coatings apart from a single source. Limited amount of tests conducted with model propellers with coated and uncoated blades have not revealed any remarkable difference in open water efficiency, cavitation inception and extent as well as the measured noise levels despite some small variations in these characteristics due to the effect of coating.

Propeller model tests with coated blades suffer from appropriate paint thickness in model scale due to application methods with commercial coatings.
Although this conclusion applies to any coating, as a generic problem of the foul release type coatings, any validation and verification investigation involving the model and full-scale performance of foul release coated propeller will require a standard measurement procedure and reliable measurement tools for the surface measurements.

3.2 Recommendations

There is growing number of full-scale applications and an increasing interest on propeller coatings. Investigations therefore should continue in this field.

There is a need for dedicated model tests, full-scale trials and progressive docking observations to accurately assess the effect of coatings on the propeller efficiency, cavitation and noise performance. At least limited amount round robin tests for open water performances amongst the ITTC community may resolve some current model test related issues.

As a generic problem of the foul release type coatings, investigations on the application and measurement of coatings on model propellers (and full-scale) should continue with the objective of devising standard procedures and resolving the scale effect issue involving paint thickness.

Semi-empirical expressions used for the frictional drag coefficient and perhaps the lift coefficient of uncoated blade profiles need to be modified to take into account the coating effect.

As a generic problem of any coating applied surface the technology investigation of coatings should be extended for the effect of biofouling, at least for the effect of slime which is the natural conditioner of any coating but particularly affecting the performance of foul release coatings.

4 State of the Art Coatings

4.1 Conclusions

Anti fouling technology is under further scrutiny due to environmental concerns. As a result, although currently in small proportion, the applications of foul releasing (non-biocidal) type antifoulings are increasing worldwide requiring further attention and hence further investigation.

Solid evidence comparing the skin friction characteristics between majorities of coatings is non-existing. Different model evaluation, application and measuring techniques make it very difficult to compare measurements for which reason most of the measurements are only able to state that this coating is xx% better than another coating.

4.2 Recommendation

Measurements of hull surfaces coated with foul release surfaces in dry docks suffer from “contact” problems of stylus in mechanical devices. Furthermore, a single hull roughness parameter is not sufficient to characterize the measured surfaces. There is a need for the development of “non-contact” based measurement devices providing options for more parameters and hence investigations in this areas should continue

Appendix:

ITTC Skin Friction Data Submission Form

Company/institution		**Phone**	
Contact person		**Adress**	
e-mail		**Submission date**	

Appended material (raw data, analysed data, reports, papers)	
File name (description)	**Public (Yes/no)**
1.	
2.	
3.	

Test description	
1. Equipment (see document XXX, section 1.1, 1-8). If other please specify	
2. Reynolds number range	
3. Flow speed range	
4. Roughness height measurement type (device and parameter)	
Short description of test equipment if not standard	

Surfaces tested		
Deliverables Description	**Roughness height**	**Other parameters**
1. (name or description)		
2.		
3.		
Additional information		