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Biofouling and barnacle adhesion data for fouling-release coatings subjected to static immersion at seven marine sites

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Biofouling and Barnacle Adhesion Data for Fouling-release Coatings Subjected to Static Immersion at Seven Marine Sites

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Little is known about the performance of fouling-release coatings at different geographical locations. An investigation was designed to measure the differences in biofouling and biofouling adhesion strength on three known silicone formulations and an epoxy control at seven static immersion sites located in California, Florida, Hawaii, Hong Kong, India, Italy and Singapore. The study found that whilst the relative performance of the coatings was similar at each site, there were statistically significant differences in the type and intensity of fouling that developed on the coatings and in barnacle adhesion strength among sites. The results emphasize the importance of evaluating potential coatings at more than one static immersion site.

Keywords: fouling-release coatings; barnacle adhesion; silicon elastomers

INTRODUCTION

In December 1985, the US Congress passed the Fiscal Year 1986 Appropriation Bill with a rider that prohibited the Navy from the purchase or application of any organotin antifouling coatings with appropriated funds until certain conditions were met. In 1988 the US Congress passed, and President Reagan signed into law, the Organotin Antifouling Paint Control Act of 1988 (Public Law 100-33) that restricted both the use and release rates of organotin-based formulations. This forced the Navy to return to copper-based paints (Alberte *et al.*, 1992). The commercial paint industry responded to the regulatory pressures

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by developing "tin free" ablative antifouling paints containing only cuprous oxide as the biocide. The early ablative copper formulations did not provide the consistency of performance required by a modern fleet, and the Office of Naval Research (ONR) and the Office of Naval Technology (ONT) initiated a program to develop a non-polluting antifouling coating. The program looked at three main areas, *viz.* the identification of naturally occurring non-toxic antifouling agents, the refinement of controlled-release systems for the antifouling agents in coatings, and the development of fouling-release coatings. It was decided that the most promising of these technologies were the fouling-release coating systems, represented by silicone elastomers.

A series of test and evaluation protocols were established to quantify the performance of the fouling-release coatings (Swain and Schultz, 1996; Swain, 1997). These included short-term laboratory and field tests and longer-term static immersion of panels and ship trials. The static immersion panels were initially exposed at Florida and Hawaii, but it was recognized that these two sites represented only a limited range of the physical, chemical and biological conditions encountered in the oceans of the world. In 1995, ONR identified seven institutions willing to participate in a study, which was designed to investigate the variations in coating performance within and among coating types and individual test sites (Swain *et al.*, 1998a; 1998b). Static immersion of the coatings started in April 1996 and ended in September 1997. This paper reports the changes in biofouling cover the barnacle adhesion strengths.

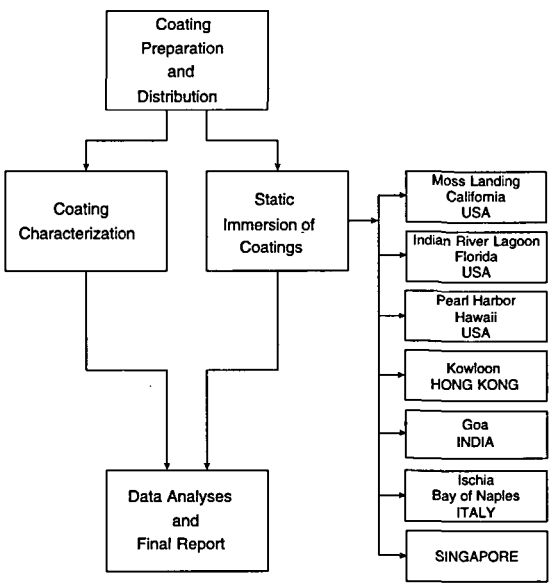

FIGURE 1 Experimental design.

EXPERIMENTAL DESIGN

The experimental protocol (Figure 1) included the selection and preparation of test coatings, characterization of coating surfaces, static immersion of coatings at seven test sites, data collection, and data analyses.

Test Coatings

Four coating types were selected for testing (Table I). The Navy F152 white epoxy (15W) was chosen as a non-toxic control without fouling-release properties. Dow Corning 3140RTV (RTW) and General Electric RTV11 (GE3) were chosen as two commercially available silicones of known composition designed for other purposes but with inherent fouling-release properties. International Paint's Intersleek (IN5) was chosen to represent the state of the art commercially available silicone-based, fouling-release formulation. The coating systems were spray applied, by the Naval Surface Warfare Center, Carderock Division. A total of twenty-one 10″ × 12″ G10 epoxy static immersion panels were identically prepared for each coating type. These were distributed among the test sites providing three panels of each formulation (six sides) for evaluation at each site. In addition, 2″ × 2″ coupons for each formulation were prepared and sent to the Center for Biosurfaces, SUNY Buffalo for surface and wear characterization.

Coating Characterization

Test coupons for each coating were subjected to pre-exposure analyses (Baier *et al.*, 1997; Meyer

TABLE I Coating systems

	Coating type (abbreviation)							
	F152 Epoxy (15W)		3140RTV (RTW)		RTV11 (GE3)		Intersleek (IN5)	
	Paint name	DFT (μm)	Paint name	DFT (μm)	Paint name	DFT (μm)	Paint name	DFT (μm)
Anticorrosive 1	F-150 type IV Epoxy polyamide	100	F-150 type IV Epoxy polyamide	125	F-150 type IV Epoxy polyamide	100	Intergard FPL274/FPA327 Epoxy polyamide	125
Anticorrosive 2	F-152 type IV Epoxy polyamide	150	F-152 type IV Epoxy polyamide	125	F-151 type IV Epoxy polyamide	150	Intergard FPJ034/FPA327 Epoxy polyamide	125
Mist coat					EPON 828 + Versamide 140	12.7		
Tie coat			1200 Coat	12.7	J501 Black	250	Intersleek tie coat	125
Top coat			3140 RTV	150	GE RTV11	460	Intersleek top coat	150

DFT = dry film thickness

TABLE II Static immersion test sites

Site	Abbreviation	Latitude	Longitude	Temperature (°C)		Salinity (‰)	
				Low	High	Low	High
California	CA	36°55′ N	121°46′ W	14	17	5	35
Florida	FL	27°56′ N	080°31′ W	22	34	16	32
Hawaii	HI	21°21′ N	157°58′ W	23	27	33	35
Hong Kong	HK	21°45′ N	115°00′ E	15	30	25	37
India	IN	15°18′ N	073°35′ E	na	na	na	na
Italy	IT	40°37′ N	014°12′ E	15	27	36	36
Singapore	SG	01°22′ N	103°45′ E	28	31	25	32

na = not available

et al., 1997). The coupons were washed lightly with a mild laboratory detergent ["Sparkleen", Fisher Scientific Corporation], rinsed thoroughly with both tap water and distilled water, and dried under ambient laboratory conditions for at least 2 d prior to analysis. This procedure removed any losely adsorbed contaminants from surfaces due to prior handling or shipping. The 2-d post-wash standing time allowed the materials to equilibrate to laboratory conditions and was sufficient time for low-energy coating components (such as oils) to "bloom" to the solid/air interface. Surface properties and coating thickness values were then obtained using the following methods: i) comprehensive contact angle analyses, to determine critical surface tensions and surface energies (outermost 0.5 nm of the coatings); ii) multiple-attenuated internal reflection infrared (MAIR-IR) spectroscopy, to determine the chemical composition (covalently-bound moieties) of the outermost 100 nm of the coatings, and to evaluate the nature and relative mass of loosely bound surface residues [*e.g.* low molecular weight components such as oils or uncrosslinked components]; iii) cross sectioning using a band saw, to measure coating layer thicknesses.

Test Sites

Seven static immersion test sites were established to examine the performance of the test coatings under different environmental conditions (Table II). The temperature and salinity ranged between 14°C to 34°C and 5‰ to 37‰, respectively. Biofouling was represented by a wide diversity of organisms (Table III).

TABLE III Predominant fouling categories observed on test panels at each site

	Abbreviation	CA	FL	HI	HK	IN	IT	SG
Algae	Algae				X		X	X
Cnidaria	Cn	X		X		X		
Encrusting bryozoans	EB	X	X			X	X	X
Arborescent bryozoans	Br						X	X
Barnacles	Barn	X	X	X	X	X	X	X
Calcareous polychaete	TW			X			X	
Sedimentary polychaete	Psed			X				
Molluscs	Mol	X		X	X	X		X
Sponges	Sp			X				
Tunicates	Tun	X		X			X	X

Static Immersion Test Protocol

All test panels were placed at their respective static immersion sites during the first two weeks of April 1996. The panels were fully submerged in a vertical position approximately 0.5 m below the surface. The panels were visually inspected on a monthly basis for physical condition and biofouling cover. Barnacle adhesion data were taken when the organisms were present.

Assessment of Biofouling

The biofouling assessment was based on ASTM D 3623-78a (1978). This reports the percentage cover of the coating by fouling organisms. Only organisms that were attached directly to areas of undamaged coating surface were included in the analyses of coating performance. The biofouling was recorded as follows: i) absorbed organic and inorganic chemicals, trapped silt and detritus, were recorded as "silt"; ii) diatoms, initial algal germination and low form algae were recorded as "slime"; iii) immature foulers were recorded as incipient fouling; and iv) mature forms of foulers were recorded as percentage cover. A fouling rating (*FR*) was determined using the following equation:

$$FR = 100 - A - 5B$$

where A = total % cover, excluding silt and slime and $B = \left\{ \begin{array}{l} 1 \text{ if incipient fouling present} \\ 0 \text{ if no incipient fouling} \end{array} \right\}$.

A fouling rating of 100 represented no mature or incipient fouling and a fouling rating of 0 represented 100% cover by macrofouling.

Barnacle Adhesion Strength

The measurement of barnacle adhesion strength in shear was based on ASTM D 5618-94 (1994). This method uses a hand-held force gauge to dislodge individual barnacles from the coating. Measurements are made only on isolated, live organisms growing on intact portions of the coating. Force is applied to the base of the organism, parallel to the surface, at a rate of approximately $1\,\mathrm{lb\,s^{-1}}$ ($4.5\,\mathrm{N\,s^{-1}}$) until the organism is detached. If more than 10% of the base of the organism is left attached to the coating, the reading is discarded. The organism base is then measured with calipers in four directions (0°, 45°, 90°, 135°) and the basal area, A, is estimated from an average base diameter, d_a, using the formula, $A = \pi d_a^2/4$. The shear adhesion strength is then calculated by dividing the force for removal by the basal area.

Data Analyses

A universal procedure was used on each of the data sets to identify where statistically significant differences existed. In cases where the data were normally distributed with homogeneous variances, One-way, parametric Analyses of Variance (ANOVAs) were used. Tukey's test was used for pairwise comparisons where the ANOVA was significant. In cases where the data were not normally distributed or the variances were not homogeneous, a non-parametric Kruskal-Wallis ANOVA on ranks was used, along with Dunn's method for pairwise comparisons. The significance level, α, was set to 0.05 for all the ANOVAs and pairwise comparisons.

To test for differences among replicate panels of one coating type, a One-way ANOVA with

panel side as the replicate was run for each coating type at an individual site. Subsequently, to test for differences among coating types, an ANOVA with coating type as the main factor was run for the data of each site. To test for differences among coatings at all sites, the data from all the test sites were pooled by coating type, and a One-way ANOVA was run.

It is understood that, in a strictly statistical sense, a factorial ANOVA design would have been more appropriate to analyze the data and would have allowed (site × coating) interaction effects to be addressed. However, due to many factors, gaps in the data exist. The missing data make a more appropriate statistical analysis impractical.

RESULTS AND DISCUSSION

The results are presented with respect to the surface characterization of the coatings, the biofouling of the coatings and barnacle adhesion strength.

Surface Characterization

The visual appearance of the coatings was as follows: IN5 medium gray, glossy topcoat; GE3 mottled white topcoat over black; RTW white, clear glossy topcoat; 15W white, flat-finish topcoat. Dry film thickness values were obtained by sectioning the coatings (Table IV). The coating thickness of the 15W coupons was found to be close to the target values. The thickness of the other coatings, however, was below specification.

Critical surface tensions [γ^c] and surface polarities for IN5, GE3, and RTW were typical for silicone elastomers, indicating the presence of closely-packed methyl groups at the outermost sample surface for each of these coatings (Table IV). The critical surface tension of the GE3 coating (23.9 mN m^{-1}) was slightly greater than that for the IN5 and RTW coatings (21.7 and 22.4 mN m^{-1}, respectively). Some instabilities of nonpolar diagnostic fluids were noted on the RTW topcoat, indicating surface-active components within the RTW surface zone. Diagnostic

TABLE IV Coating dry film thickness and surface properties for test coupons

	15W	RTW	GE3	IN5
Layer descriptions	top: F152	top: 3140RTV tie: 1200 coat	top: RTV11 tie: J501 black	top: Intersleek tie: Intersleek tie
	AC: F150	AC: F150/152	AC: F150/151	AC: Intergard
Target DFT* (μm)	top: 150	top: 150 tie: < 25	top: 460 tie: 250	top: 150 tie: 125
	AC: 100	AC: 250	AC: 250	AC: 250
Measured DFT (μm)	top: 150	top: 100 tie: < 25	top: 125 tie: 180	top: 75 tie: 25
	AC: 75	AC: 75	AC: 180	AC: 100
Surface Properties				
γ^c	28.2	22.4	23.9	21.7
γ^d	25.9	22.0	22.3	20.7
γ^p	3.9	3.9	4.5	4.5
γ^s	29.8	25.9	26.8	25.2
γ^{LW}	29.6	23.9	27.1	27.7
γ^a	< 0.1	[1.1]	[1.4]	[1.5]
γ^b	7.1	2.3	2.0	2.8
γ^{AB}	0.9	−3.2	−3.3	−4.1
γ^{tot}	30.5	20.7	23.8	23.6

Note: all values are in mN m^{-1}; γ^c = critical surface tension; γ^d = dispersion component of γ^s; γ^p = polar component of γ^s; γ^s = estimated composite surface free energy [$\gamma^d + \gamma^p$]; γ^{LW} = London forces component of γ^{tot}; γ^{AB} = combined acid/base component of γ^{tot}; γ^a = acid component of γ^{AB}; γ^b = base component of γ^{AB}; γ^{tot} = total surface energy [$\gamma^{LW} + \gamma^{AB}$]

fluids showed little or no instability on the IN5 or GE3 topcoats, with the exception of coating swelling when in contact with straight-chain alkane fluids (a frequent observation for silicone elastomers).

ASTM Fouling Rating

Changes in the average ASTM fouling rating with increasing days exposure for each coating type is presented in Figures 2–8. The individual data points are the average of six observations for each coating (3 replicate panels, 2 sides) at approximately 2 month intervals. This rating provides an overall assessment of the percentage surface cover by fouling. A fouling rating of 100 represents no macrofouling and a fouling rating of 0 represents 100% cover by macrofouling. The fouling rating of the panels showed variations both among coatings and among test sites. The fouling rating of the 15W panels decreased to less than 50 at all sites by day 200, and did not exceed 50 for the remainder of the study. As expected, this epoxy coating, which is both non-toxic and exhibits no fouling-release properties, consistently had the lowest fouling rating of the four test coatings. The fouling ratings of the GE3 and RTW coatings were relatively higher than the 15W panels and also fluctuated during the exposure period. The fluctuations may represent seasonal changes in the fouling communities. However, they may also be caused by loss of organisms from the surface due to lower adhesion strengths to these surfaces. Previous studies (Swain *et al.*, 1998) have shown that disturbance due to predation and grazing may significantly reduce and remove the fouling communities that become established on fouling-release surfaces at the Florida site. The fouling rating of the IN5 panels remained above 40 at all sites for the duration of the study and was the best performing coating. An exception to this occurred in Singapore and

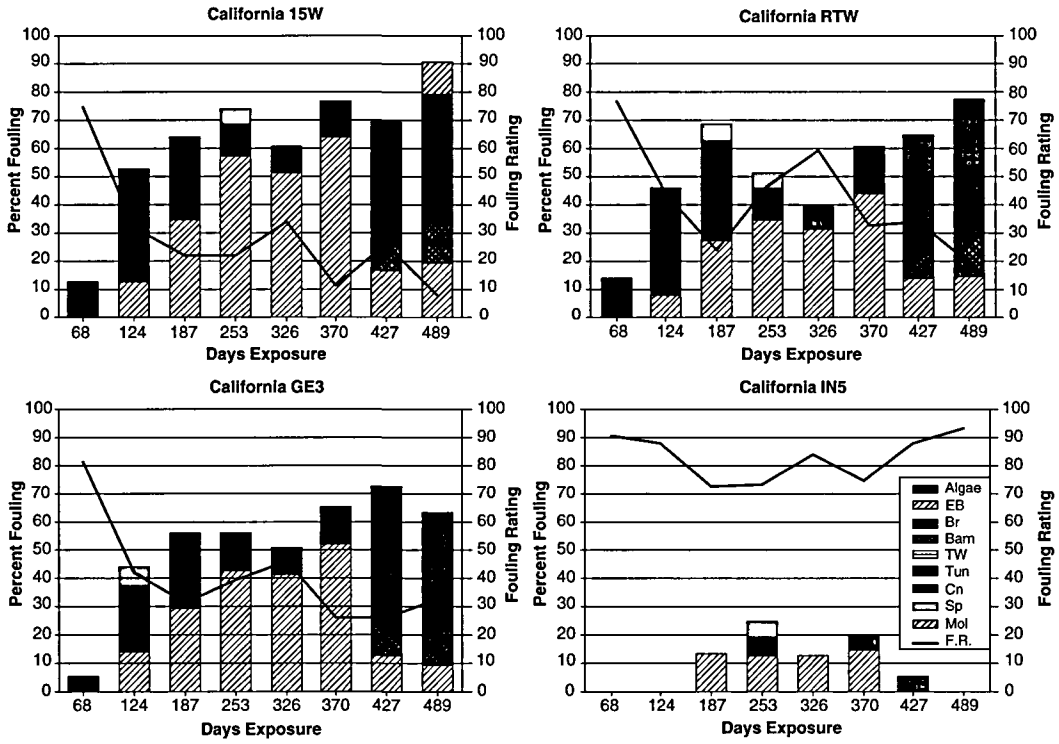

FIGURE 2 ASTM fouling rating and average percentage fouling cover for California.

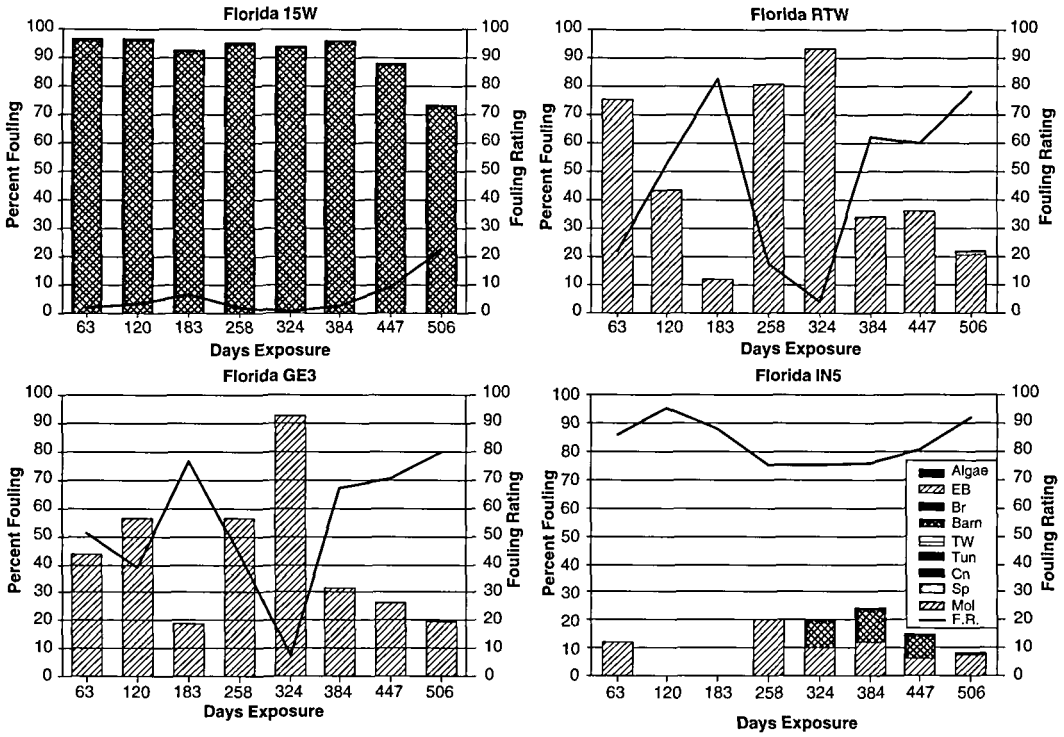

FIGURE 3 ASTM fouling rating and average percentage fouling cover for Florida.

India where all the panels became completely covered by macrofouling at some time during the study. All three fouling-release coatings performed exceptionally well at Hong Kong where the ASTM fouling rating did not drop below 90.

Statistical analyses of the fouling rating data were run for four inspection dates, where complete data sets were available (August 1996, December 1996, April 1997, and August 1997 inspections, Table V). The analyses indicated that no significant differences existed among replicate panels of a coating type at any of the sites. This result was important as it demonstrated consistency in the extent of fouling at the individual test sites.

When the fouling rating data from all sites were pooled, pairwise comparisons indicated significant differences between the performance of 15W and IN5 and the other coatings. No statistical differences were found between the GE3 and RTW. This analysis indicates that IN5 had the best fouling resistance, followed by GE3 and RTW, and that the worst performer was the 15W. These results were not consistent across sites. However, IN5 was the best performer at all sites (Table V).

Structure of Biofouling

The structure of the biofouling communities showed variation both among sites and among coatings (Figures 2–8). The variation among sites was expected and reflected differences in biofouling communities that were present at the seven test locations (Table III). The variation among coatings at individual sites, however, was due to the influence of coating type. For example, in Florida the epoxy panels were dominated by barnacles, whilst the silicone based coatings were dominated by encrusting bryozoans with only few barnacles present. In Hawaii, the epoxy panels

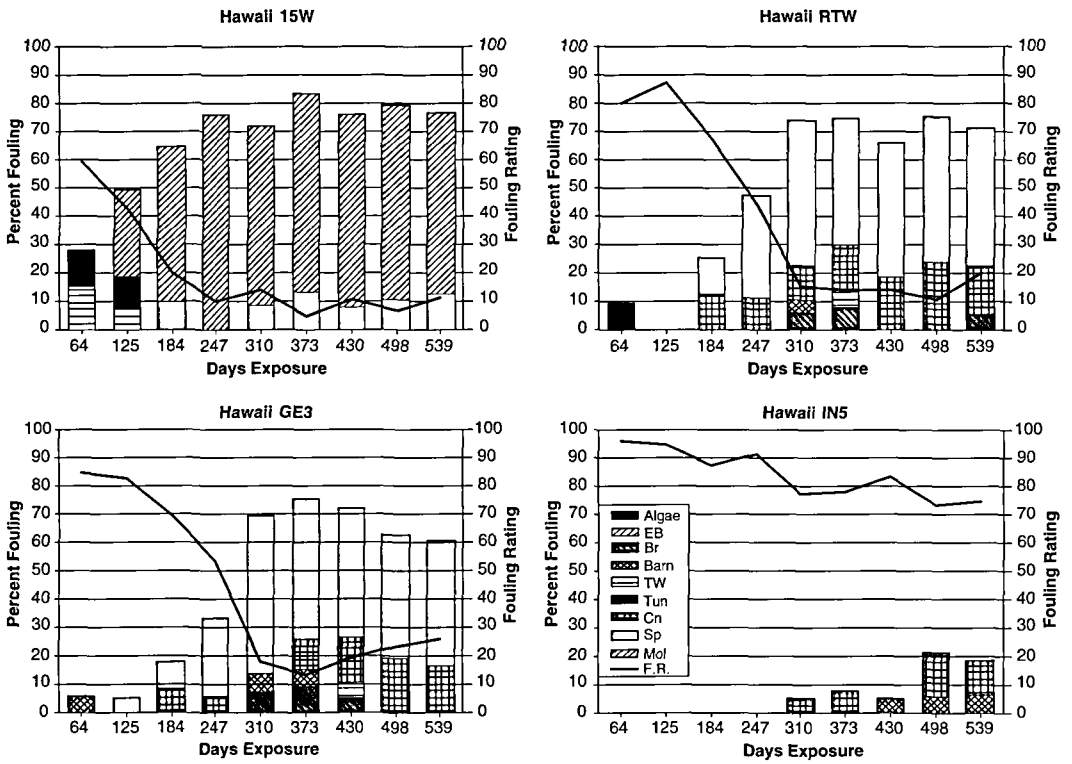

FIGURE 4 ASTM fouling rating and average percentage fouling cover for Hawaii.

were dominated by molluscs, but the silicone based coatings had few molluscs and became dominated by sponges, tubeworms and barnacles. The exact causes of these differences are as yet undetermined. However, it may be speculated that the fouling-release properties of the silicone based coatings influenced the settlement, growth and permanence of the fouling communities.

Barnacle Adhesion Strength

Barnacle adhesion strength values were obtained using the ASTM standard test method for measurement of barnacle adhesion strength in shear (ASTM D 5618-94, 1994). These measurements are considered to provide a good indication of coating fouling-release performance. The present study provided an opportunity to measure the adhesion strength of four different species of barnacle to the same coatings under different environmental conditions (Table VI). The adhesion data were analyzed using a Kruskal-Wallis one way ANOVA on ranks applied to data pooled from all sites, comparison of the mean barnacle adhesion strength between coatings at each site, and an analysis of the mean barnacle adhesion strength for the same coating between sites. The first analysis pooled the barnacle adhesion data for each coating from all the sites (Table VII, Figure 9). A Kruskal-Wallis one way ANOVA on ranks was applied to these data, and showed that the adhesion strength on each of the coatings was significantly different from one another ($\alpha = 0.05$). The order of mean adhesion was 15W > RTW > GE3 > IN5.

The second analysis compared the mean barnacle adhesion strength of the four test coatings at each site (Table VII, Figure 9). Hong Kong and India were not included in the analyses due to insufficient data from these sites. The mean

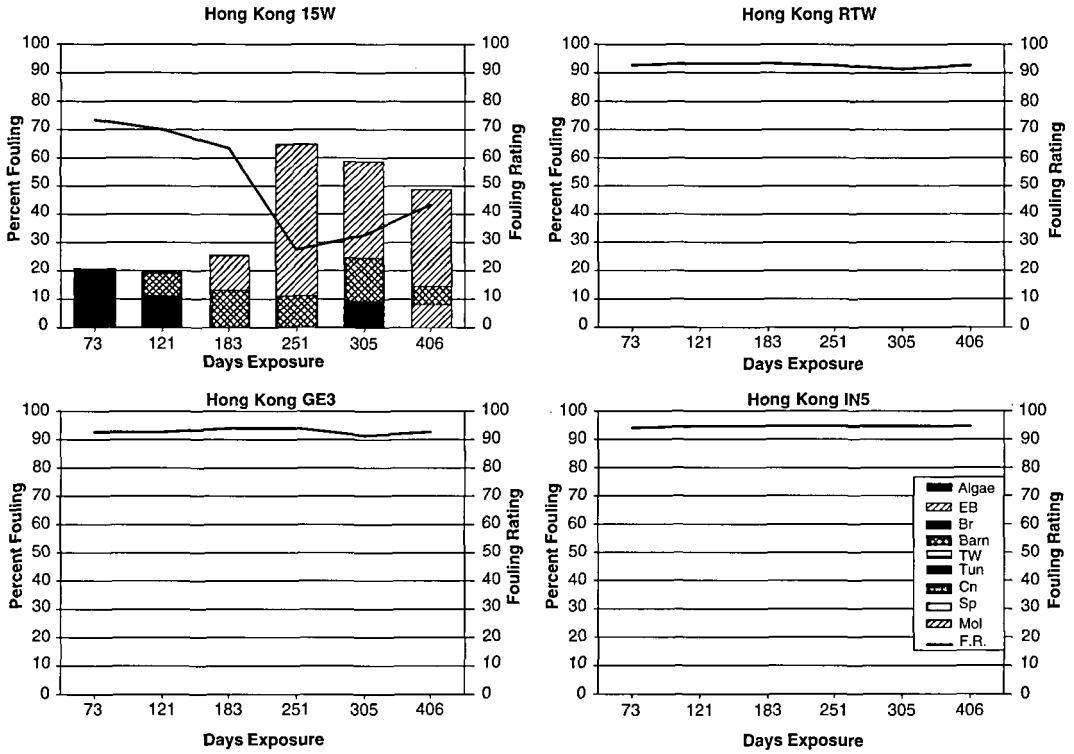

FIGURE 5 ASTM fouling rating and average percentage fouling cover for Hong Kong.

adhesion value was obtained by pooling all the data obtained during the exposure period. Several trends were observed. In California, Florida, Hawaii and Italy it was found that the barnacle adhesion strength followed the same pattern, *i.e.* 15W > RTW > GE3 > IN5. A statistical analysis demonstrated that the differences were significant for most of the comparisons. However, the power of the analysis was reduced by the low number of adhesion measurements.

Barnacle adhesion strength measured on the epoxy coatings (15W) showed high variability both among and within sites. This is because it is extremely difficult to obtain values when the adhesion strength is high. When the adhesion strength of the barnacle to the coating is greater than the strength of the shell, failure occurs at the shell and there is incomplete removal of the base plate from the surface. Shear force measurements on surfaces where the adhesion strength exceeds the shell strength tend to underestimate the actual adhesion strength of the organism.

The third analysis tested for differences in barnacle adhesion strength on the same coating among sites (Table VIII, Figure 9). This included four different species of barnacle (Table VI). The analysis consisted of running several Kruskal-Wallis one-way ANOVAs. Hong Kong and India were not included in the analyses due to insufficient data and the 15W panels were not included due to problems of shell breakage.

Pairwise comparisons indicated that barnacle adhesion strengths were most consistent on the GE3 coatings. The only significant difference was found between Italy and Singapore (Italy mean adhesion strength 0.18 MPa ± 0.032, Singapore mean adhesion strength 0.118 MPa ± 0.069). For the IN5 panels there were significant differences in adhesion strength between the three sites, California, Florida and Hawaii, and the remaining

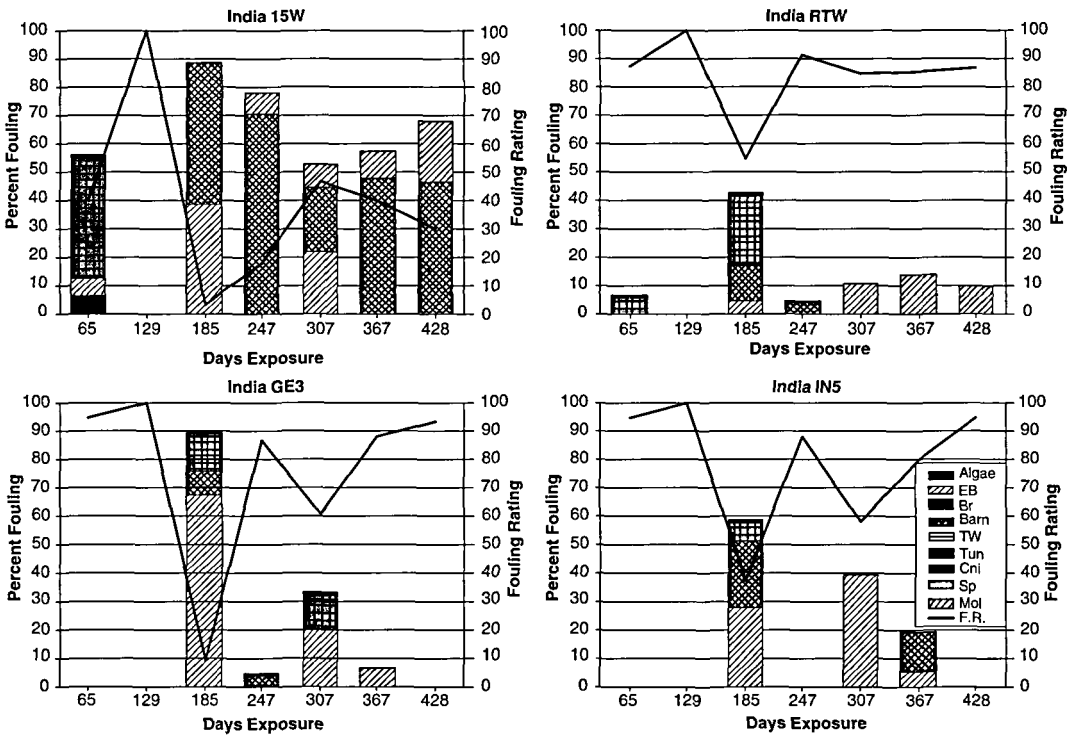

FIGURE 6 ASTM fouling rating and average percentage fouling cover for India.

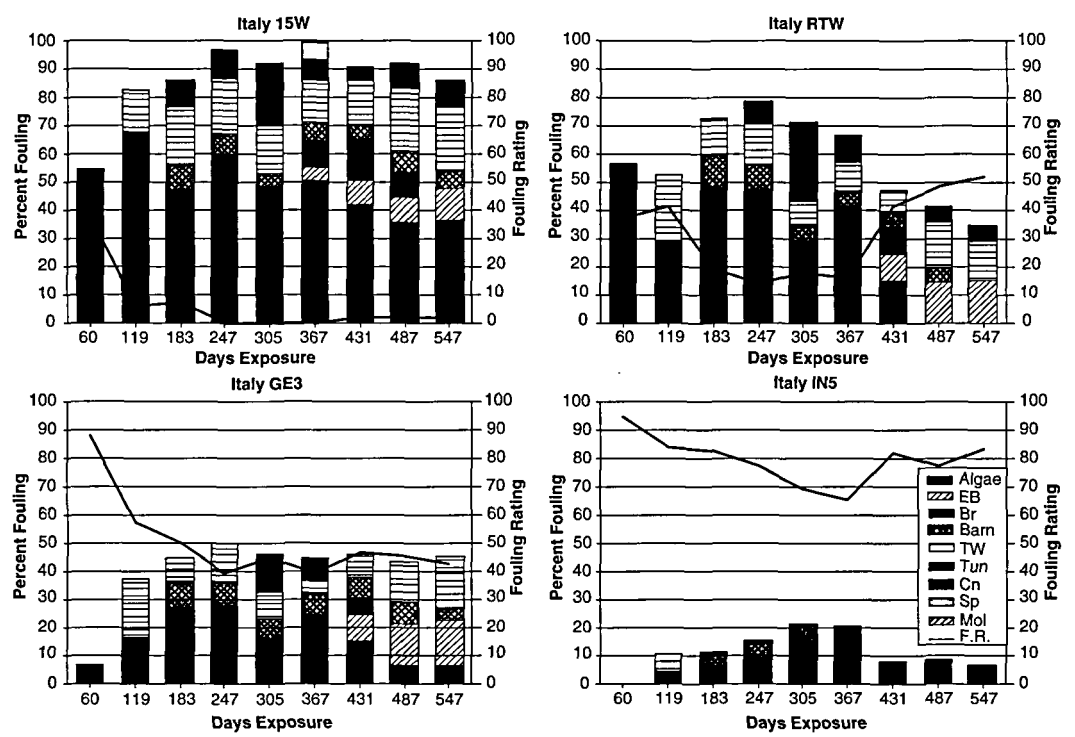

FIGURE 7 ASTM fouling rating and average percentage fouling cover for Italy.

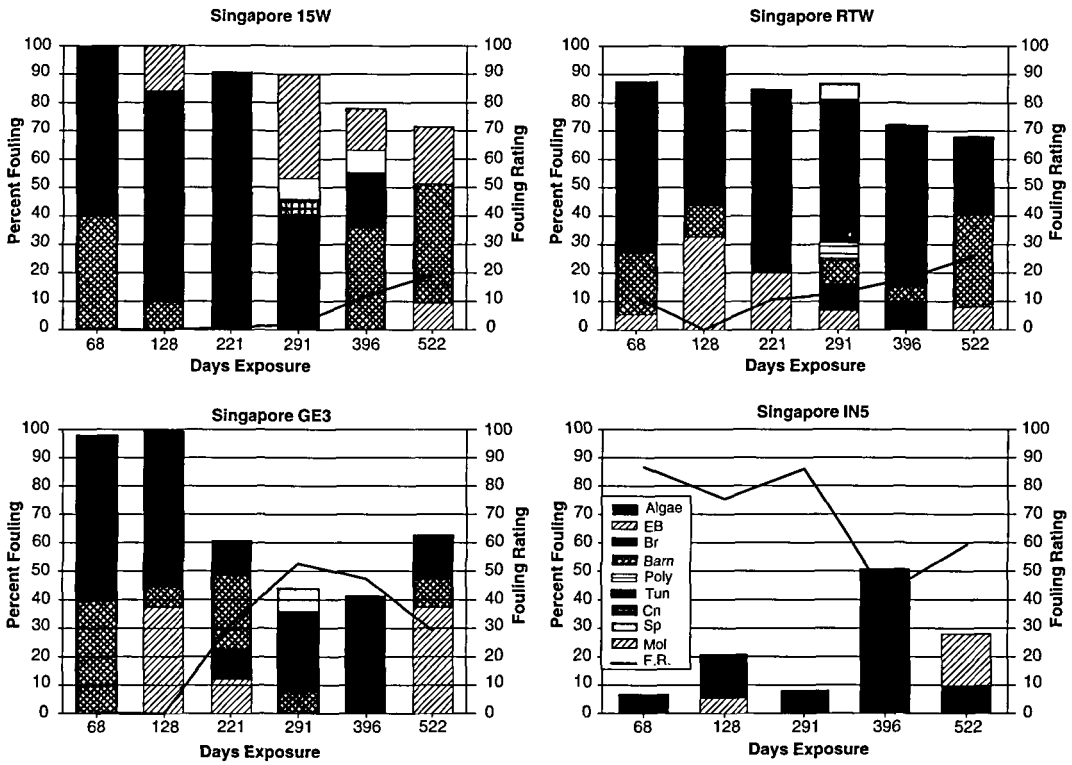

FIGURE 8 ASTM fouling rating and average percentage fouling cover for Singapore.

TABLE V *Summary of ANOVA results for ASTM fouling rating among coatings for four dates*

Coating	Date	CA	FL	HI	HK	IN	IT	SG	All
IN5-GE3	8/96	*	NS	NS	NS	NS	NS	*	*
	12/96	*	*	NS	NS	NS	NS	NS	*
	4/97	*	NS	NS	MD	NS	NS	NS	*
	8/97	NS	NS	*	NS$^+$	NS$^+$	NS	NS	*
IN5-15W	8/96	*	*	*	*	NS	*	*	*
	12/96	*	*	*	*	*	*	*	*
	4/97	*	*	*	MD	*	*	NS	*
	8/97	*	*	*	*$^+$	*$^+$	NS	*	*
IN5-RTW	8/96	*	NS	NS	NS	NS	NS	*	*
	12/96	*	*	NS	NS	NS	NS	*	*
	4/97	*	NS	NS	MD	NS	NS	NS	*
	8/97	*	NS	*	NS$^+$	NS$^+$	NS	NS	*
GE3-15W	8/96	NS	NS	*	NS	NS	*	NS	*
	12/96	NS	*	NS	*	*	NS	*	*
	4/97	NS	*	NS	MD	NS	*	NS	*
	8/97	*	NS	NS	NS$^+$	NS$^+$	NS	NS	*
GE3-RTW	8/96	NS	NS	NS	NS	NS	NS	NS	NS
	12/96	NS	NS	NS	NS	NS	NS	NS	NS
	4/97	NS	NS	NS	MD	NS	NS	NS	NS
	8/97	NS	NS	NS	NS$^+$	NS$^+$	NS	NS	NS
RTW-15W	8/96	NS	NS	*	*	NS	NS	NS	*
	12/96	NS	NS	NS	NS	*	NS	NS	*
	4/97	NS	NS	NS	MD	NS	NS	NS	*
	8/97	NS	NS	NS	NS$^+$	NS$^+$	NS	NS	*

* = $p < 0.05$; NS = $p > 0.05$; MD = missing data; $^+$ = reading taken on 6/97

TABLE VI Barnacle species used to obtain adhesion data

Site	Species
California	*B. glandula*
Florida	*B. eburneus*
Hawaii	*B. amphitrite*
Hong Kong	*B. amphitrite*
India	*B. amphitrite*
Italy	*B. amphitrite*
Singapore	*B. variegatus*

TABLE VII Summary of ANOVA results for barnacle adhesion among the four test coatings

Coating comparison	CA	FL	HI	IT	SG	All sites
IN5-GE3	*	NS	*	*	NS	*
IN5-15W	*	*	MD	*	NS	*
IN5-RTW	*	*	*	*	NS	*
GE3-15W	*	*	MD	*	*	*
GE3-RTW	NS	*	NS	NS	*	*
15W-RTW	*	NS	MD	NS	NS	*

Hong Kong and India are not included due to insufficient data; * = $p < 0.05$; NS = $p > 0.05$; MD = missing or insufficient data

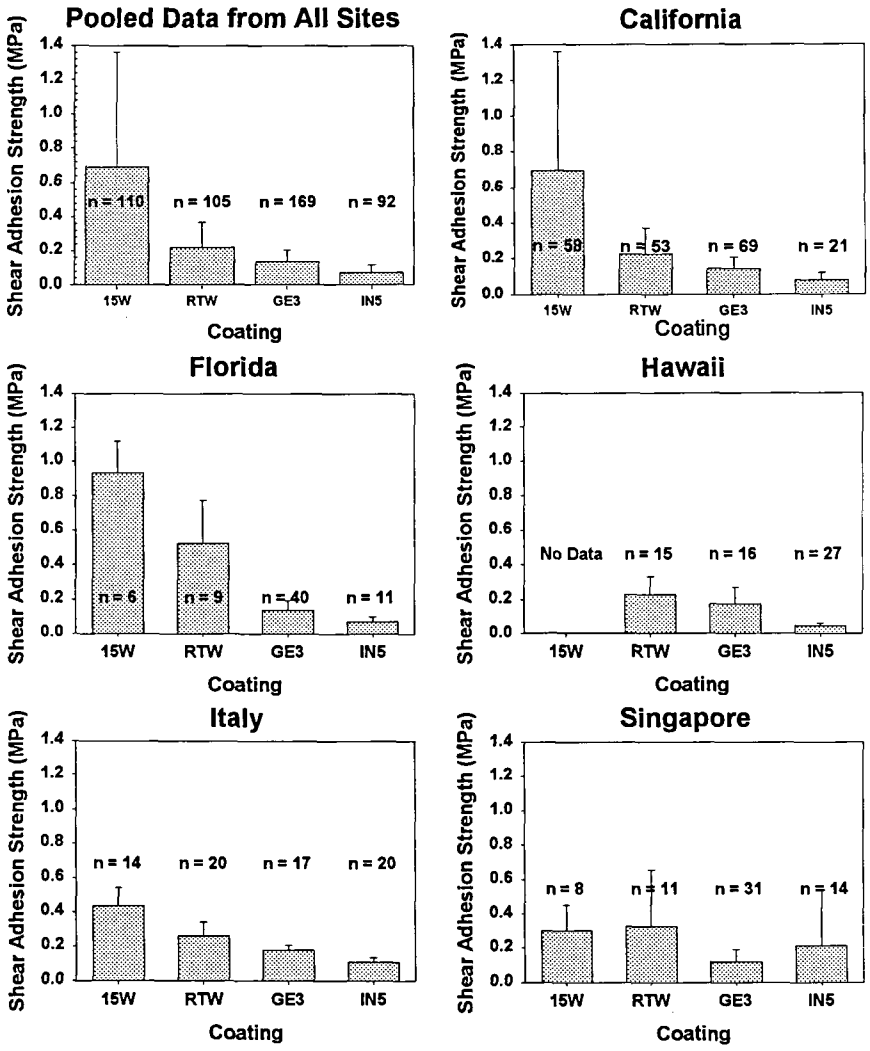

FIGURE 9 Mean barnacle adhesion strength and standard deviation for the four test coatings; n = number of readings. (Data pooled from all sites, California, Florida, Hawaii, Italy and Singapore.)

TABLE VIII Summary of ANOVA results for barnacle adhesion among sites

Comparison	RTW	GE3	IN5
CA (*B. glandula*)–FL (*B. eburneus*)	*	NS	NS
CA (*B. glandula*)–HI (*B. amphitrite*)	NS	NS	NS
CA (*B. glandula*)–IT (*B. amphitrite*)	*	NS	*
CA (*B. glandula*)–SG (*B. variegatus*)	NS	NS	*
FL (*B. eburneus*)–HI (*B. amphitrite*)	*	NS	NS
FL (*B. eburneus*)–IT (*B. amphitrite*)	*	NS	*
FL (*B. eburneus*)–SG (*B. variegatus*)	*	NS	*
HI (*B. amphitrite*)–IT (*B. amphitrite*)	NS	NS	*
HI (*B. amphitrite*)–SG (*B. variegatus*)	NS	NS	*
SG (*B. variagatus*)–IT (*B. amphitrite*)	NS	*	NS

Hong Kong and India are not included due to insufficient data; $* = p < 0.05$; $NS = p > 0.05$

two sites, Italy and Singapore. Hawaii had the lowest adhesion values (0.046 MPa ± 0.015) and Singapore the highest (0.125 MPa ± 0.059). Differences in barnacle adhesion strength to the RTW coating were found between Florida and all other sites and between California and Italy. Barnacle adhesion strengths at Florida (0.526 MPa ± 0.250) were found to be between two to three times higher than the other test sites with a relatively high SD. The most probable explanation is that the barnacle adhesion measurements were taken late in the exposure period (477 d), and the coating had suffered some mechanical damage, mainly from fish bites. This enabled barnacles to become established on areas where the coating was compromised from the original condition. Therefore the readings were higher than from an intact coating.

The barnacle adhesion strength data provide information that helps in the understanding of how fouling-release formulations perform under different conditions. The data obtained in this study demonstrate that barnacle adhesion values can be used to differentiate between the fouling-release performance of different formulations. They also demonstrate that adhesion strength values are not reliable on surfaces where the adhesion strengths are high (15W), and affirm that adhesion strength values will be modified by underlying fouling or coating damage.

CONCLUSIONS

This study provided an insight into the variability in the performance of fouling release coatings at a global level and identified some of the parameters that may affect the development of fouling communities and influence adhesion strengths.

It was found that the structure and permanence of biofouling communities that develop on non-toxic fouling-release coatings vary both geographically and with respect to the fouling-release properties of the coating. The order of performance from highest (least fouling) to lowest (most fouling) ASTM fouling rating number pooled from all sites was IN5 > GE3 = RTW > 15W. The ASTM fouling rating number could statistically differentiate between the performance of 15W (worst) and IN5 (best) for most of the time at individual sites. However, it was insufficiently sensitive to always differentiate between the performance of all four coatings tested. It is therefore unlikely that observations of percentage cover by biofouling alone provide sufficient information to differentiate the performance of fouling-release formulations.

Barnacle adhesion measurements provided a more accurate method to quantify the performance of the coatings at most of the sites. When barnacle adhesion data were pooled from all sites, a significant difference was found among the four coating types (from lowest to highest IN5 < GE3 < RTW < 15W). These differences, however, were not always evident at individual sites. This was partly due to small sample sizes, and differences in the exposure time and coating condition. At two of the sites (Hong Kong and India) there were insufficient or no data. The relatively high adhesion values measured on the RTW at Florida were thought to be due to coating damage mainly from fish bites incurred after 477 d exposure.

Results from this study emphasize the importance of using more than one static immersion test site to quantify fouling-release performance. They also demonstrate that hard fouling adhesion measurements provide a more sensitive method

of evaluating fouling release performance compared to the measurement of percentage biofouling cover. However, it is important that the sample size be sufficiently large for statistical analyses, and that the measurements be made after similar exposure periods on intact coating surfaces.

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