ESTCP
Cost and Performance Report

(PP-9502)

Advanced Non-Toxic Silicone Fouling-Release Coatings

May 1999

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Advanced Non-Toxic Silicone Fouling-Release Coatings**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**35**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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LIST OF ACRONYMS

AF	Air Force
EHS	Environmental, Health, and Safety
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FIT	Florida Institute of Technology
GE	General Electric Company
GE-CRD	General Electric Corporate Research and Development Center
IUCB	Industry/University Center for Biosurfaces
NAWC	Naval Air Warfare Center
NCCOSC	Naval Command, Control and Ocean Surveillance Center
NEPCO	New England Power Company
NRL	Naval Research Laboratory
NSWC	Naval Surface Warfare Center
NSWCCD	Naval Surface Warfare Center, Carderock Division
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Administration
RCB	Range Control Boat
SUNY	State University of New York
USCG	United States Coast Guard
USN	United States Navy
UTB	Utility Training Boat
VOC	Volatile Organic Compound

ACKNOWLEDGMENTS

The General Electric-Corporate Research and Development Center fouling release team would like to acknowledge the support and contributions of:

- Environmental Security Technology Certification Program (ESTCP)
- Naval Research Laboratory (NRL)
- Naval Surface Warfare Center, Carderock Division (NSWCCD)
- Florida Institute of Technology (FIT), Melbourne, Florida
- Bridger Scientific, Inc., Sandwich, Massachusetts
- State University of New York (SUNY), Buffalo, New York-Industry/University Center for Biosurfaces (IUCB)
- Naval Command, Control and Ocean Surveillance Center (NCCOSC)
- Hopkins Marine Station, Stanford University, Pacific Grove, California
- Naval Sea Systems Command (NAVSEA)
- United States Coast Guard (USCG)
- United States Navy (USN), SLICE program
- Consumer Power, Bay City, Michigan
- Ontario Hydro, Nanticoke, Ontario, Canada
- New England Power Company (NEPCO), Brayton Point, Somerset, Massachusetts.

The accomplishments made through this program would not have been possible without the enthusiasm and support from individuals in these organizations. A complete list of program participants and other interested individuals may be found in Appendix A.

Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

This Environmental Security Technology Certification Program (ESTCP) project demonstrated and validated the use of the duplex silicone fouling-release coating system developed by the Naval Research Laboratory (NRL), for use on boat hulls and power plant cooling water intake tunnels as a replacement for toxic copper antifouling paints. The ESTCP program team (which comprised General Electric Company (GE), Naval Surface Warfare Center, Carderock Division (NSWCCD), Florida Institute of Technology, State University of New York (SUNY), and Bridger Scientific) carried out thirteen full-scale field applications of the duplex system to meet specific performance objectives for an acceptable replacement antifouling coating system. The duplex coating system was evaluated in cold, temperate and tropical environments in fresh, brackish and marine waters on static and dynamic platforms. Fouling extent, type, and ease of removal were assessed, as well as the effect of hull cleaning on subsequent boat engine performance.

The duplex coating system was shown to be highly durable and easily cleanable with a water jet. To date, successful service life of over three years has been achieved. While some instances of delamination or abrasion did occur, a coating repair package was developed to easily rectify them. Projected operating and maintenance costs associated with using the new silicone-based coatings are comparable with those for the conventional antifouling paints being replaced. However, overall projected savings to the U.S. Navy are $35-50 million per year through 10-15% reduction in fuel consumption.

The power plant demonstrations were extremely successful, with the coatings remaining in good condition and continuing to be 99% effective against zebra mussels. Consumer Power has saved $10-20,000 annually through avoidance of cleaning costs.

Recommendations for further work include determining the expected service life, optimizing surface aesthetics, and investigating alternatives to the Wacker Silicones Silgan J-501® tie layer technology used in the demonstration.

2.0 TECHNOLOGY DESCRIPTION

Toxic, copper-based antifouling (AF) paints and applications of other chemicals have long been used by shipping companies, shoreline industries, and power plants to combat aquatic biofouling. Concern about the environmental impact of these paints and chemicals such as chlorine and bromine, as well as new federal regulations regarding these substances, has led to the search for environmentally benign methods to control biofouling. Research by the U.S. Navy (USN), GE, and others has shown that silicone-based materials are excellent candidates for fouling-release coatings. These easy-release coatings employ a physical rather than a chemical approach and resist fouling by presenting a surface unsuitable for strong adhesion of the fouling organisms.

The U.S. Navy has sought an effective antifouling paint since the 19th century (Ref. 1). Marine biofouling on a ship increases the hull's hydrodynamic drag, which causes greater fuel consumption and compromises the ship's speed and range. The U.S. Navy currently uses copper-based ablative AF paints to control the settlement and attachment of biofouling. An applied research program (6.2 Exploratory Development Program, Biomolecular Antifouling Program) begun in 1991 at the Office of Naval Research (ONR) focused on materials that would inhibit the attachment of organisms by acting as fouling-release coatings. Silicone-based paints were excellent candidates for evaluation because they provide a physical rather than chemical, environmentally benign approach to the control of biofouling in marine and freshwater environments.

Substrates having critical surface tensions in the 25 to 30 mN/m range optimally resist strong macrofouling attachment (Ref. 2). Silicone coatings typically exhibit surface free energies in this range and thus are uniquely suited for fouling release applications. A complete rationale for silicone's unique behavior has not been established, since it has not been proven that surface free energy is solely responsible for the unique ability of silicones to resist fouling.

Silicone fouling-release coatings are crosslinked films that are elastomeric and highly extensible. Due to their elastomeric nature, these coatings are susceptible to mechanical failure caused by shearing, tearing, or abrasion. Also, the inherent nonstick nature of the silicone coatings makes it difficult to establish good adhesion to most substrates.

The duplex coating system was developed at the Naval Research Laboratory (Refs. 3 and 4) to address the durability issues associated with silicone elastomeric coatings, and was the fouling-release technology evaluated in this demonstration. The duplex coating system is illustrated in Figure 1. The duplex coating system provides corrosion protection, excellent bonding of all coating layers, enhanced durability and toughness, and easy release of macrofouling. It is a multi-layered coating made up of the following: (1) one or more layers of epoxy anticorrosive paint; (2) an epoxyamide mistcoat to ensure bonding of the tiecoat to the anticorrosive layer; (3) the toughening tie layer (Wacker Silicones product, Silgan J-501®), which bonds the silicone fouling-release coating to the anticorrosive layers and provides enhanced toughness to the silicone coating; and (4) the elastomeric silicone topcoat. Silgan J-501® is the only commercial material that has been identified as a tiecoat thus far. GE Silicones products RTV11® and EXSIL2200® are suitable as fouling release topcoats with the duplex system.

Application of the entire system usually takes 3-4 days. Application of the duplex system to smaller craft such as the U.S. Coast Guard Utility Training Boats (UTBs) requires one person to spray the layers and at least one person to mix and prepare the paint for spraying, and to help move spray lines as the painter moves around the boat. Other labor is necessary to pull boats or to dewater intake tunnels, and to sandblast the surfaces to be painted. It is possible for one trained person to perform the coating performance inspection and water jet cleaning and brushing. If an underwater cleaning and inspection were desired, trained dive inspectors would be needed.

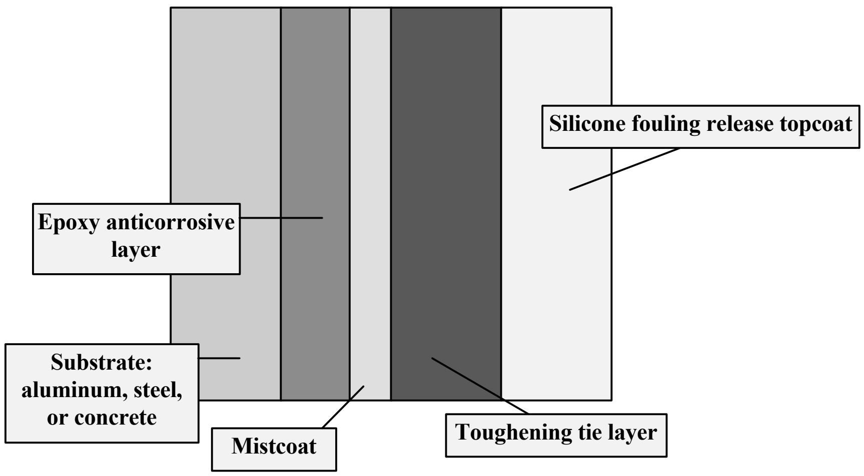

Figure 1. The NRL-GE Duplex Fouling-Release Coating System.

2.1 TECHNICAL ADVANTAGES

The primary advantage of using the duplex system is its excellent fouling-release capability. Macrofouling on a ship hull can be removed with a water jet or by gentle brushing to reduce cleaning time and costs. Conventional antifouling paints do not release fouling once it has settled. When a ship is completely repainted with the duplex system, there are no toxic wastes to be disposed of or contained. The duplex coating system is a cost-effective and environmentally benign solution to the problem caused by toxic marine antifouling paints for many freshwater and marine applications. A repair package has also been developed to repair patches of abrasion damage to the coating.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary objective of this project was to demonstrate and validate the effectiveness of the duplex silicone fouling-release coating system applied to a variety of platforms operating in a variety of environments. Within this main objective were included several focused technical objectives, including:

- Fouling release capability against a variety of fouling organisms
- Demonstration of easy release of fouling with brush or water jet or by hydrodynamic cleaning
- Easy application to metal and concrete substrates
- Adhesion of the system to the substrate
- Durability against abrasion and other damage
- Ability to repair any damage to the duplex coating system
- Aesthetics of the coating
- Three to five year service life
- Cost-effectiveness comparable to that of existing AF technology

3.2 PHYSICAL SETUP AND OPERATION

The application of the duplex system requires standard airless or air-assisted paint spray equipment. The Graco Bulldog® and Graco Premier® spray pumps used by the GE CRD team run on standard grounded 220-volt lines. Standard 110-volt power is needed to operate hand-held electric mixers.

The time for the application of the duplex system to a boat or power plant is about four days. Figure 2 illustrates the timeline of the procedure. Spray application of the initial coat of anticorrosive epoxy paint to a clean surface takes place on the first application day. A second coat of anticorrosive paint is applied on the second day and allowed to cure overnight. On the third day, the duplex system itself is applied. The cured epoxy surface is wiped with solvent to remove any residual moisture and dust, and the mistcoat is applied to the epoxy. When the mistcoat is slightly tacky, Silgan J-501® is applied. The silicone topcoat (either RTV11® or EXSIL2200®) is sprayed after the Silgan J-501® is tack-free. Preparation of each of these layers is described in the full report for this program submitted to ESTCP on 30 November 1998. A minimum of three days is recommended before re-immersion of the boat once the system application is complete but seven days are required for complete cure of the system. The inspection and cleaning timeline for the duplex system depends on the platform and timing around the local fouling season.

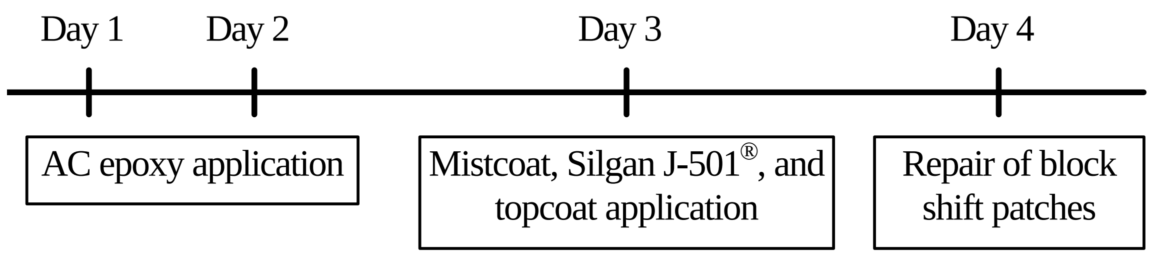

Figure 2. Timeline for Duplex Silicone Coating System Application.

3.3 MEASUREMENT OF PERFORMANCE

Methods used to evaluate the duplex system performance are listed in Table 1. These are described in more detail in the operating procedure for boat hull inspections in Appendix B of the Integrated Inspection Plan submitted to the ESTCP by GE CRD in January 1997. The procedure describes haulout and inspection scheduling, general inspection protocol, methods of assessing the physical condition of the coating, methods for visual assessment of biofouling, the water jet test method, the barnacle adhesion test method, and power trials. The significant properties of the fouling release coating system that were tested included: (1) the extent of fouling on the coating and (2) physical properties such as tear strength, abrasion resistance, adhesion, and cleanability. These parameters were tested both on-site and in laboratory studies. These test methods are summarized in Table 2.

Table 1. Methods Used to Evaluate the Duplex Silicone Coating System.

Criterion	Method
Physical condition of coating	Qualitative visual inspection Still photography Video recording
Type and extent of fouling	Qualitative visual inspection Species identification and enumeration Extent of fouling measurement (ASTM D3623)
In-situ coating quality	Visual inspection by dive team
Self-cleaning capability	Power trials Extent of fouling before and after running at high speed
Effect of hull cleaning on boat performance	Power trials repeated after complete hull cleaning

Table 2. Methods Used to Test the Duplex Silicone Coating System.

Criterion	Method
Fouling release capability	Barnacle adhesion force gauge measurement (ASTM D5618-94)
Cleanability	Water jet fouling adhesion test
Silicone surface characterization	Laboratory surface characterization techniques
Topcoat abrasion resistance	Rotating brush test
Adhesion of coating to substrate	Adhesion testing (ASTM D4541) Scrape adhesion (ASTM D2197)

3.4 DEMONSTRATION SITE/FACILITY BACKGROUND AND CHARACTERISTICS

The thirteen demonstration sites and general scope of the demonstration platforms in this program are summarized in Table 3. A complete description of the sites chosen for this demonstration is included in the final report for this program submitted to ESTCP on 30 November 1998.

The size and operational speeds of U.S. Coast Guard (USCG) boats and U.S. Navy Range Control boats and transporters provide excellent platforms for the assessment of fouling-release paint technology in terms of fouling-release performance, durability, and serviceability. U.S. Coast Guard Utility Training Boats (UTBs), U.S. Navy Range Control Boats (RCBs), a U.S. Navy Transporter, and the ONR/Lockheed SLICE experimental vessel were chosen to demonstrate and validate the durability and performance of the duplex system on active vessels. Full-hull applications were performed because they provide better demonstration than patch tests of the application methods and cleaning procedures required for larger ships.

Power plants are excellent sites for demonstration and validation of the fouling-release coating technology in both fresh- and saltwater environments because of the extensive seasonal fouling and the potential for major damage to occur. In shoreline plants, for example, more than six inches of mussels can build up in one season. Mussels that slough off can plug small-diameter cooling system tubes. Blockages decrease heat exchange capabilities and have the potential to cause failure of a condenser or a heat exchanger. The power plants selected for this demonstration were chosen because they have large intake structures that have shown severe zebra mussel fouling (in fresh water) or marine macrofouling in salt or brackish water.

In addition to these large-scale demonstrations, warm- and cold-water test sites were utilized for test panel exposure.

The primary regulatory driver for the development of the duplex fouling-release coating system was the need for non-toxic paints in marine applications. This technology demonstration addressed U.S. Navy requirement N 3.I.4.b, Nonhazardous Antifouling/Fouling Release Hull Coatings, and U.S. Army requirement A.3.12, Hazardous Paint Elimination. Environmental regulations impose major constraints on methods for controlling marine biofouling. Among the environmental

Table 3. Demonstration Platforms and the Duplex Silicone Coating Systems Applied to Them.

Demonstration Platform	*Application Date*	*Surface Area Coated (ft^2)*	*Substrate*	*Topcoat*
USCG 41' UTB #41312	June 1995	400	Aluminum	RTV11® gray
USCG 41' UTB #41393	June 1995	400	Aluminum	RTV11® + 20% SF1154® gray
USCG 41' UTB #41345	April 1996	400	Aluminum	RTV11® gray
USCG 41' UTB #41486	April 1996	400	Aluminum	RTV11® + 20% SF1154® gray
USN 30' Range Control Boat #1	July 1996	300	Aluminum	EXSIL2200® gray
USN 30' Range Control Boat #3	September 1996	300	Aluminum	EXSIL2200® clear
USCG 55' Search and Rescue Boat #55103 (Parramore)	August 1996	1,000	Aluminum	EXSIL2200® gray
USCG 55' Buoy Boat #55117	September 1998	1,000	Aluminum	RTV11® + 20% SF1154® gray
ONR/Lockheed SLICE	November 1996	2,000	Steel	EXSIL2200® gray
NAWC MV Transporter	September 1997	3,500	Aluminum	RTV11® + 20% SF1154® gray
Ontario Hydro Nanticoke Generating Station Trash Racks	March 1995	50-100	Steel	EXSIL2200®, RTV11®
Consumer Power D.E. Karn Units 1 and 2 Cooling Water Intake Bay	March 1995	500	Concrete, steel	EXSIL2200®, RTV11®
New England Power Company Brayton Point Station Unit 1 Screenwell and Tunnels	March 1996	17,000	Concrete, steel	EXSIL2200®, VOC-free topcoat, RTV11® +20% SF1154®

concerns about fouling control methods is the toxicity of metals (tin, copper) and chemicals (chlorine, bromine) to aquatic organisms. The trash rack coating and subsequent cleanup that took place in Ontario, Canada was carried out by a contractor familiar with Canadian Federal and Provincial Ministries of the Environment. Table 4 enumerates some of the federal and state regulations that pertain to biofouling control.

Only the application at the NEPCO Brayton Point cooling water intake required specific approval from a government agency. For approval, an Architectural and Industrial Maintenance Coating Registration and Certification Form was submitted to the Massachusetts Department of Environmental Protection Division of Air Quality Control describing the amounts of Volatile Organic Compounds (VOCs) emitted during application of the duplex system.

Table 4. Regulations Pertaining to Biofouling Control Measures.

Legislation	Description
Federal Water Pollution Control Act, 1972, and amendments (Clean Water Act, 1977); 33 USC 1251 et seq.	Goal is to restore and maintain chemical, physical, and biological integrity of U.S. waters. Includes control of toxic pollutants (copper) and thermal effluent.
National Pollution Discharge Elimination System (NPDES), Oct 1972; 40 CFR 122 (PL 92-500)	Sets discharge limits on chlorine, bromine, and other pollutants.
Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); 7 USC 136 et seq. (PL 95-396)	Regulation of chemicals designed to be toxic and introduced into the environment.
Organotin Antifouling Paint Control Act (OAPCA), June 1988; 33 USC 2401	Restricts the use of tributyl tin to non-Aluminum vessels greater than 82 feet long.
Coastal Zone Management Act (CZMA), October 1972; 16 USC 1451 et seq. (PL 92-583)	Provides protection of intertidal zones (estuaries, coastal waters). Contains state programs to protect coastal resources and manage development.
Toxic Use Reduction Act (TURA), MA General Law, Chapter 21, 310 CMR 50	Goal is the reduction in the use of toxic materials over time.
Water Quality Standards (MA 314 CMR 4.0)	Establishes criteria for water temperature, pH, dissolved oxygen, and aesthetics. Prevents discharge of pollutants.
Clean Air Act, 42 USC 1857 et seq.	Enacted to protect and enhance the quality of the nation's air resources; sets ambient air pollutant and emission standards.

4.0 PERFORMANCE ASSESSMENT

The primary objective of demonstrating the effectiveness of the duplex silicone fouling release coating system over a variety of platforms and environments was accomplished. The duplex system was evaluated in cold, temperate and tropical environments in fresh, brackish and marine waters, and on static and dynamic platforms. Fouling extent and type were assessed, and the effect of hull cleaning on boat engine performance was evaluated.

Tables 5, 6, and 7 summarize the results of inspections performed on the U.S. Coast Guard, U.S. Navy, and power plant cooling water intake demonstrations/validations. Details of the applications and inspections are available in the original application and inspection reports, which are included in Appendix B of the final report submitted to ESTCP on 30 November 1998.

Duplex coating systems successfully applied to boats showed good fouling-release and durability performance. The power plant demonstrations were also extremely successful, with the coatings remaining in good condition and continuing to be 99% effective against zebra mussels.

The data presented in the inspection reports and summarized in Tables 5, 6, and 7 are a realistic assessment of the objectives set forth in this demonstration. There are no known conditions that effect the validity of the findings; only the ability of the inspector would effect the data because of the subjective nature of the fouling and coating quality assessments. The individuals who carried out the inspections for these demonstrations were well versed in the determination of fouling release coating quality and performance.

A repair package was developed to repair patches of abrasion damage to the coating. In addition, test panels have been exposed at various facilities for periods of up to five years with little or no failure.

Table 5. Summary of Inspection Results for U.S. Coast Guard Boat Platform.

Site Description	Topcoat	Water Condition	Fouling and Damage
USCG 41' Utility Training Boat #41312	RTV11®	Temperate marine	*Aug 95*: 2 mos. service. More encrusting bryozoans, barnacles than 41393; minor damage *Mar 96*: 9 mos. service. 18 psi barnacle adhesion; minor ice abrasion damage *Oct 96*: 1½ yr. service. 18 psi barnacle adhesion, much more fouled than 41393, cleans easily *Sept 97*: 2 yr, 5 mos. service. Repair to ice damage
USCG 41' Utility Training Boat #41393	RTV11® + 20% SF1154®	Temperate marine	*Aug 95*: 2 mos. service. Fewer encrusting bryozoans, barnacles than 41312; minor damage *Mar 96*: 9 mos. service. 18 psi barnacle adhesion; minor ice abrasion damage *Oct 96*: 1½ yr. service. 9 psi barnacle adhesion, much less fouled than 41312, evidence of self-cleaning, cleans easily *May 98*: 3 yr. service. Decommissioned to Louisville, KY Fire Department in Apr 97; completely effective against zebra mussels
USCG 41' Utility Training Boat #41345	EXSIL2200® gray	Temperate marine	No inspection report available
USCG 41' Utility Training Boat #41486	RTV11® + 20% SF1154®	Temperate marine	*Sept 96*: 5 mos. service. Algae, slime, no hard fouling; evidence of self-cleaning; 10 ft^2 delamination at epoxy/J-501 interface at rudders, keel. Repaired in Sept 96
USCG 55' Search and Rescue Boat #55103 (Parramore)	EXSIL2200® gray	Temperate marine	*Dec 96*: 4 mos. service. Bottom of hull fouled with encrusting bryozoans, clams, barnacles; evidence of self-cleaning; minor sand abrasion damage at rudders and keel
USCG 55' Buoy Boat #55117	RTV11® + 20% SF1154®	Warm marine	No inspection to date

Table 6. Summary of Inspection Results for U.S. Navy Boat Platform.

Site Description	Topcoat	Water Condition	Fouling and Damage
USN 30’ Range Control Boat #1	EXSIL2200® gray	Temperate marine	*Apr 97*: 9 mos. service. Light slime layer, no hard fouling; abrasion at boottop and bow, delamination at block shift patches. Repaired in May 98.
USN 30’ RCB #3	EXSIL2200® clear	Temperate marine	*Apr 97:* 7 mos. service. Light slime layer, no hard fouling; ice abrasion damage at boottop and bow, delamination at block shift patches. Repaired in May 98.
ONR/Lockheed SLICE	EXSIL2200® gray	Tropical marine	*Feb97:* Gear box installation repaired. *May 97:* 6 mos. service. Dive inspection. Many algae and soft foulers, sea grass, no hard foulers; easily wiped clean; no abrasion damage. *June 97:* 8 mos. service. Mostly slime films, some oysters (30 psi), encrusting bryozoans; minor abrasion damage.
NAWC MV Transporter	RTV11® + 20% SF1154®	Temperate marine	No inspection report available. Repaired in Apr 98 and June 98.

Table 7. Summary of Inspection Results for Power Plant Platform.

Site Description	Topcoat	Water Condition	Fouling and Damage
Ontario Hydro Nanticoke Generating Station Trash Racks	EXSIL2200®, RTV11®	Cold fresh	No inspection report available
Consumer Power D.E. Karn Units 1 and 2 Intake Bay	EXSIL2200®, RTV11®	Cold fresh	*Feb 96*: 11 mos. service. Slimes, minimal hard fouling; easy removal except in small cavities; no abrasion damage. *Mar 97*: 2 yrs. service. Slimes, virtually no hard fouling; excellent coating integrity. *Mar 98*: No inspection report available.
New England Power Company Brayton Point Station Unit 1 Screenwell and Tunnels	EXSIL2200®, VOC-free, RTV11® + 20% SF1154®	Cold brackish	*Sept 96*: dive inspection: no report available. *Mar 97*: 1 yr. service. EXSIL2200®, VOC-free 10% fouled with crepidula and hydroids in corners; easily removed; some delamination in corners of screenwells. RTV11 + 20% SF1154 more crepidula; damage from crepidula and 20% delamination in screenwells. Tunnels in excellent condition. Repairs done on patches. *Feb 98*: Inspection by Bridger Scientific (see Ref. 5 for report), repair additional damaged areas.

5.0 COST ASSESSMENT

Table 8 illustrates the assessment of the expected operational costs for the implementation of the duplex fouling-release coating technology. Because the majority of the demonstrations took place on 41' USCG UTBs, the cost assessment is based on the application of the duplex system to a similar aluminum-hulled boat. Calculations were made assuming a hull area of approximately 400 ft^2. The cost per square foot would decrease as the hull size increases. This cost assessment includes consideration of haul-out costs, surface preparation, application of the duplex system, and the disposal of blasting grit and waste generated during application of the system

Because these demonstrations/validations were carried out in full-scale applications to U.S. Coast Guard boats, U.S. Navy ships, and operating power plants, no scale-up issues exist. The larger the application, the greater the potential cost savings.

For purposes of this report, life cycle costs for silicone fouling release coatings are compared to those for typical copper ablative coatings. Since the most likely commercial outlet for this technology at present is in the small boat (30-100 ft) arena, comparisons are based on typical costs incurred during installation, maintenance and removal of coatings from this type of vessel.

In general, installation costs will be slightly greater for silicone fouling-release coatings than for copper ablative coatings due to the higher cost of the topcoat and tiecoat components and the extra labor required to apply the five-coat system compared to the three or four coats required for copper ablative systems.

It is anticipated that the maintenance costs for these coatings are expected to be comparable in that each system will require periodic cleaning to remove slime films and any accumulated fouling. The frequency of cleaning will depend on the vessel's deployment and may be done in conjunction with other maintenance schedules or, less desirably, when the hull becomes so fouled that operational parameters (speed, energy consumption) are compromised. An advantage of silicone coatings in this regard is that cleaning of slime coated or partially fouled hulls can be accomplished by means of a power wash (water jet spray), rather than by the use of brushes. High savings on cleaning costs are expected when power wash cleaning is used for large vessels, such as submarines.

A cost breakdown for materials, labor, maintenance and removal for these two systems is presented in Table 9. This breakdown is only an estimate and will vary significantly depending upon (a) the size of the application (b) the type of vessel coated (c) the operating environment of the vessel and (d) local regulations pertaining to waste disposal. Based on these rough figures, the life-cycle costs for silicone coatings and copper ablative paints may be comparable, and if the actual use life of silicones exceeds five years, these coatings may actually be less expensive than copper ablative paints on a life-cycle basis.

The anticipated Life Cycle cost savings hinge on an as yet not exactly determined service life. If 5 years comparable to conventional antifouling paints can be achieved, then the major savings associated with the new technology due to reduced hazardous waste disposal charges will be realized. If the service life that can be expected for the replacement system is even longer than conventional, then greater savings will be realized through avoidance of costs associated with reapplication of the coating.

Overall projected savings to the U.S. Navy are $35-50 million per year through 10-15% reduction in fuel consumption. Consumer Power has saved $10-20,000 annually through avoidance of cleaning costs. There is also a non-quantifiable environmental benefit associated with the elimination of the use of copper-based antifouling paints.

Table 8. Expected Operational Costs for the Duplex Silicone Coating System as Applied to a 41-Foot USCG Utility Training Boat.

Direct Process Costs				Environmental Activity Costs		Other Costs	
Start-Up		Operation and Maintenance					
Activity	Cost ($)	Activity	Cost ($)	Activity	Cost ($)	Activity	Cost ($)
Site preparation: Boat haulout and storage	260	Labor to operate equipment (contractor application fees)	2,450	Compliance audits	None	Overhead associated with process	None
Site preparation: Surface grit blasting	850	Labor to manage hazardous waste	incl. Above	Document maintenance	None	Productivity/ cycle time	None
Hazardous waste disposal fees/ waste management	400	Consumables and supplies (paint, solvents)	2,185	Environmental management plan development and maintenance	None	Worker injury claims and health costs	None
Project management	3,550	Equipment maintenance	None	Reporting requirements	None		
Operator training	None	Utilities	None	Test/analyze waste streams	None		
Equipment purchase	None	Management/ treatment of byproducts	None	Medical exams (including loss of productive labor)	None		
Equipment design	None			Waste transportation (on- and off-site)	None		
Equipment installation	None			OSHA/EHS training	None		
Life of equipment	None						

Table 9. Approximate Life Cycle Costs of Duplex Silicone Coatings vs. Copper Ablative Paints[a]

Item	Frequency (life cycle)		cost/ft^2 (life cycle)	
	Copper-Ablative	Silicone	Copper - Ablative	Silicone
Materials	once (installation)	once (installation)	$1.20	$3.76
Labor	once (installation)	once (installation)	$4.00	$5.00
Maintenance	Twice	Twice	$2.00	$2.00
Disposal	once (removal)	once (removal)	$2.00-$5.00	$1.00

Totals			$9.20-$12.20	$11.76

[a] Estimates based on (1) prices at current sales volumes, (2) experience from USCG vessels coated in this project.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Unexpected costs arose from underestimating the amount of project management time needed to coordinate large-scale applications (such as that for NEPCO Brayton Point), in waiting for proper weather conditions for application, and in dealing with other unforeseen circumstances not under the team's control (such as contractors quitting before project completion). The valuable time spent waiting for the weather to clear and new contractors to complete work can become expensive. Costs were reduced with increased large-scale project management experience, which allowed projects to run more smoothly in less time.

6.2 PERFORMANCE OBSERVATIONS

Because these demonstrations/validations were carried out in full-scale applications to U.S. Coast Guard boats, U.S. Navy ships, and operating power plants, no performance-related scale-up issues exist.

Application of the duplex fouling-release coating system is a multi-step process with fairly tight application windows. These narrow windows are sensitive to atmospheric conditions. Because of this sensitivity, it is imperative that the coating system be applied by qualified personnel and that projects be overseen by someone familiar with the technology.

The expected useful service life of the coating system has not been determined. Based on field experience gained during this and similar development projects, a three-to-five-year service life is almost a certainty. This question will be answered as the coatings applied to these demonstration platforms experience real-world usage over time. If the existing coating is damaged, the repair of the coating requires the oversight of trained personnel; the repair package is very effective if applied properly.

6.3 OTHER SIGNIFICANT OBSERVATIONS

The two most significant issues for implementation are the establishment of a market channel and the resolution of material supply problems, which could detrimentally affect material prices. The overall cost of the replacement technology is sensitive to the price of the silicone top-coat material is a major cost component compared to the conventional technology. These issues could be resolved within a year if market demand for such a product were strong enough. For example, Wacker Silicones has discontinued the manufacture of Silgan J-501® but GE is examining alternatives and investigating licensing opportunities. Commercialization of the duplex system will likely require a partnership between GE Silicones and a marine paint company. Such an alliance with a partner interested in marketing marine paints is the best way to implement this technology. NRL is currently in the process of discussing technology transfer of the duplex coating system.

6.4 LESSONS LEARNED

Most of the lessons learned from these demonstrations/validations were gained from full-scale field application experience. The practical nature of the demonstration was of great benefit in learning skills from situations that we could not have anticipated in the laboratory. Accomplishments achieved in under this program include:

- Ability to spray Silgan J-501® tiecoat
- Ability to spray the silicone topcoats; formulations were not designed to be sprayed
- Optimization of the application parameters (recoat windows, coating cure times, spray tip sizes, dilution, proper cleaning solvents, coating thickness, etc.)
- Appreciation of the importance of project management for large-scale applications
- Ability to repair abrasion damage and delamination of the coating
- Necessity of careful surface preparation for good adhesion
- Ability to pigment RTV11® and EXSIL2200® to gray

6.5 END-USER/OEM ISSUES

The duplex fouling release coating demonstration was carried out by GE CRD, NRL, NSWCCD, FIT, SUNY Buffalo IUCB, and Bridger Scientific and had support from GE Silicones. This consortium represented broad involvement across end-users, academia, and coatings material developers/manufacturers. The NRL is currently in discussions to license the technology to commercial companies.

6.6 REGULATORY AND OTHER ISSUES

For most of the boat applications, the project manager and marina officials discussed environmental, health, and safety (EHS) requirements before the application. Usually compliance was not an issue. The NEPCO Brayton Point plant EHS officer was more involved in the cooling water intake application because of the approval required by the Massachusetts Environmental Protection Agency (EPA). There was no discussion of regulatory acceptance at the conclusion of the demonstrations. The duplex coatings have been applied in several states and have met all local environmental regulations regarding volatile organic compound (VOC) content, toxicity, OSHA requirements, etc. Regulations with regard to VOC content vary from state to state, but the duplex system has not been exempted from application in any state in which a demonstration was carried out for this program.

GE has obtained an exemption from the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA).

7.0 REFERENCES

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APPENDIX A

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