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Advanced Nontoxic Fouling Release Coatings

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14. ABSTRACT

Historically, marine antifouling paints have used compounds toxic to marine organisms as a means of combating fouling. Foul-release coatings don't use copper or any other metal toxicant to provide effective biofouling control; rather their unique surface chemistry creates a surface to which fouling can not easily adhere. Because they employ a physical rather than a chemical means to reduce fouling, these silicone coatings have been ruled exempt from reporting under FIFRA (Public Law 95-396).

NRL developed and patented an advanced foul-release coating system called the duplex silicone coating system to address the durability issues associated with silicone elastomeric coatings. This system employs a tough, cross-linked thermoplastic elastomeric layer (Silgan J501, Wacker Chemie, Ltd.) to bond the foul-release silicone topcoat to the anticorrosive system for ship hulls or to epoxy paint on concrete walls in power plants. The ESTCP demonstrations/validations included 6 Coast Guard aluminum hull boats, 2 Navy Range Boats, a Navy Transporter, an ONR/Lockheed prototype (SLICE) and power plant cooling water intakes (concrete walls, steel trash racks/ traveling screens/deflecting veins). Barnacle adhesion measurements (ASTM D 5618-94), oyster adhesion measurements and water jet cleaning were developed as part of this project.

15. SUBJECT TERMS

easy release coating, silicone coating, foul-release coating, non-toxic hull coating, barnacle adhesion test, ASTM D 5618-94

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1. Introduction

1.1 Background Information

Toxic antifouling paints and 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, 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 chemical means of reducing fouling.

1.1.1 Why control biofouling? The U.S. Navy has sought an effective antifouling (AF) paint since the 19th century[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. It is estimated that \$34 million to \$50 million of the Navy's approximately \$500 million annual propulsive fuel bill could be saved by the use of an effective AF hull paint[2]. In addition, an estimated \$100 million per year is spent for hull cleaning, paint removal and repainting, toxic water and grit disposal, meeting OSHA requirements during repainting, and labor to remove biofouling.

In the utility industry, macrofouling (large organisms such as barnacles, mussels, and snails) lowers condenser efficiency and requires high maintenance. Macrofouling reduces the flow of cooling water, which decreases the efficiency of heat transfer in the condensers and therefore reduces the gross power generation of the plant. A study by the Electric Power Research Institute[3] estimated that more than 75% of condenser availability losses in fossil-fueled plants rated at greater than 600MW were attributed to biofouling; of these, more than 30% were related to macrofouling of intake structures and circulating water systems. The tube blockage and erosion/ corrosion of condenser tubes caused by macrofouling also incurs capital costs for premature tube replacement. Until the late 1980's macrofouling was a problem primarily for coastal power generation stations. However, the introduction and rapid spread of the freshwater mollusk species *Dreissena polymorpha* (zebra mussels) in the rivers and Great Lakes of the eastern United States has brought the economic issues of macrofouling to freshwater power generation stations as well.

Because the cost of cleaning a power generation unit's cooling water intake system is substantial, many methods for biofouling control have been explored. Utilities historically have relied on mechanical, thermal, or hydraulic methods and seasonal chlorination to control macrofouling. Mechanical methods include the use of trash racks, traveling screens, and filtration; hydraulic methods include pumping water through the systems at velocities greater than seven feet per second. Additional approaches include optimization of chemical treatments (targeted chlorination/bromination and chlorine minimization), alternative chemical treatments (hydrogen peroxide, ozone, non-oxidizing biocides, and polymeric surfactants), and surface protection (toxic paints, barrier coatings).

1.1.2 Previous methods of biofouling control. The Office of Naval Research (ONR) has supported basic research on marine biofouling since 1950. Early studies on the life cycle of biofoulers, their settlement and attachment, and the factors controlling growth gave rise to research and evaluation of AF coatings. Organometallic paints emerged as the primary technology. Initially, copper-based "free association" coatings, such as Navy Formula 121, were used[4]. Free association coatings consist of a water-soluble cuprous oxide pigment dispersed throughout a polymeric matrix; cuprous oxide closest to the surface is dissolved on contact with sea water, and the oxide more deeply embedded in the matrix is dissolved as water travels through pockets created by the dissolved pigment. The release rate of copper ions from this type of AF coating is highest during initial seawater exposure and decreases with exposure time as the deeply embedded cuprous oxide becomes less accessible.

Ablative organotin paints were used on Navy ships in the 1970's but were discontinued in 1986 due to environmental and health concerns. Since 1984 cuprous oxide ablative paint has been used on the majority of Navy ships. "Ablative" coatings consist of a polymeric resin that wears away as a ship moves through the water. Fresh copper oxide dispersed in the polymer matrix is continuously exposed to seawater and releases copper ions as the matrix wears away. The release rate of copper ions is proportional to the rate of ablation. The greatest issue with the use of copper oxide pigment is the release of copper toxicant into harbor waters during underwater cleaning. The environmental issues with organometallic paints has spurred further research for environmentally safe AF coatings.

1.1.3 The role of silicone fouling release coatings in the control of biofouling. An applied research program begun in 1991 at ONR (6.2 Exploratory Development Program, Biomolecular Antifouling Program) focused on materials that would inhibit the attachment of organisms by acting as fouling-release coatings. Also, the Long Island Lighting Company began testing non-fouling coatings in 1982 to address the substantial costs of cleaning the massive macrofouling of their concrete cooling-water intake tunnels and cell blocks. Silicone-based paints were excellent candidates for evaluation in these programs because they provide a physical (rather than chemical), environmentally benign approach to the control of biofouling in marine and freshwater environments.

Silicones in their cured state are crosslinked elastomers of infinite molecular weight and therefore are water insoluble and too large to pass through membranes of living organisms. Because silicone-based coatings use a physical rather than chemical means of biofouling control, the Environmental Protection Agency has ruled that these coatings are not subject to the provisions of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA, Public Law 95-396). The toxicity and general environmental fate of silicones has been studied extensively under funding from the World Silicone Environmental Health and Safety Council; silicones are not considered a threat to aquatic environments. Because of the high-molecular weight structure of cured silicone, any ecological risk would result not from the silicone matrix but from leachates of trace additives or by the breakdown of the matrix into water-soluble species. Tests have been performed to evaluate the leachates' potential to harm both salt- and freshwater species. Fathead minnow, *Ceriodaphnia dubia*, sheepshead minnow, and mysid shrimp all showed no significant levels (>10%) of mortalities or effects at either of two treatment levels (0.1 g/l and 0.5 g/l) after 7 to 30 days exposure[5].

General Electric has developed a silicone-based paint for marine applications and has introduced commercial products EXSIL2200® and RTV11® into this market. This paint is designed for use in systems aimed at controlling biofouling on marine hulls, underwater surfaces, etc. One of the most promising systems, the duplex coating system originally developed at the Naval Research Laboratory (NRL), consists of epoxy anticorrosion (AC) layers, a tough thermoplastic elastomeric tie layer for adhesion and durability, and a silicone-based topcoat[6,7]. Further development and testing of the NRL's duplex coating system was needed for this system to gain acceptance in the commercial and military sectors; this ESTCP contract provided the opportunity for that development. The improvements made to increase the anticipated service life and reduce application costs were derived from data on the duplex coating system durability, longevity, cleanability, and reparability in full-scale marine ship and power plant intake applications. Application of this advanced non-toxic fouling release technology to ship hulls and power plant cooling water intakes provided the opportunity to assess ease of application, physical appearance, adhesion quality, extent and type of fouling coverage, overall service life system characteristics, ease of fouling removal, and reparability on a full scale. Application to U.S. Coast Guard boat hulls provided the opportunity to evaluate the abrasion resistance of the coating system. Experimental coatings were evaluated in the laboratory in an effort to reduce system costs, to develop repair technology, and to improve coating and surface properties.

A benefit of applying the duplex coating system to a power plant cooling water intake is the direct application of the paint to the surface structures of cooling water systems; current chemical treatments involve the release of toxins into the bulk cooling water. The silicone paints are environmentally benign and exhibit no release of toxic components. The frequency of cleaning may be reduced by using silicone paints, and the risk of equipment and plant shutdown can also be reduced. The time and costs for cleaning macrofouling from a ship hull can be reduced by the use of hydrodynamic cleaning or by gentle brushing or a water jet. When a ship is completely repainted with the duplex coating 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 of toxic marine antifouling paints for many freshwater and marine applications.

1.2 Official DoD Requirement Statement(s)

This technology demonstration addresses 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. The technology used, easy-release silicone duplex coating systems, is the basis for fouling-release hull coatings. These coatings do not use copper or any other metal toxicant to provide effective biofouling control. Rather, their unique surface chemistry creates a surface to which fouling cannot easily adhere. This technology is the basis for the next generation of non-fouling coatings, which will be environmentally safe and will meet Navy operational requirements. In addition, these easy-release coatings address the Army's broader requirement to eliminate hazardous paint systems. Easy-release silicone duplex coatings eliminate the toxic metal components of antifouling paints and by their nature also are volatile organic compound- (VOC-) compliant well into the next century. These are high-solids systems with little or no VOC content, depending on the specific system utilized. These systems are also compliant with current and future lead restrictions and contain no carcinogenic compounds. The easy-release silicone duplex coating systems are the building blocks for 21st century coatings that provide effective nonfouling control for Navy hulls, for Army Corps of Engineers structures, and for industrial sites in freshwater and saltwater environments.

1.3 Objectives of the Demonstration

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

- demonstration of easy release of fouling with brush or water jet or by hydrodynamic cleaning
- fouling release capability against a variety of fouling organisms
- easy application to metal and concrete substrates
- adhesion of the system to the substrate
- durability against abrasion and other damage
- ability to repair damage to the duplex coating system
- acceptable aesthetics of the coating
- three to five year service life
- cost effectiveness comparable to that of existing AF technology

The ESTCP program team (NRL, GE, NSWCCD, FIT, SUNY-Buffalo and Bridger Scientific, Inc.) carried out several full-scale field applications of the duplex coating system to demonstrate its fouling release and durability performance in several use environments. The general scope of the demonstration platforms is shown in Table 1-1. In addition to these large-scale demonstrations, warm- and cold-water test sites were utilized for test panel exposure. The analysis of these tests is described in the final reports on this project from Florida Institute of Technology and the State University of New York Industry/University Center for Biosurfaces. The platforms and their locations are described in greater detail in Section 3, Site/Facility Descriptions.

1.4 Regulatory Issues

Environmental regulations impose major constraints on methods for controlling marine biofouling. Among the environmental 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 1-2 enumerates some of the federal and state regulations that pertain to biofouling control.

Table 1-1. Demonstration platforms and the duplex systems applied to them.

Demonstration Platform	Application Date	Surface Area Coated (ft^2)	Substrate	Topcoat
USCG 41' UTB #41312 USCG 41' UTB #41393 (Yorktown, VA)	June 1995 June 1995	400 400	Aluminum Aluminum	RTV11® gray RTV11® + 20% SF1154® gray
USCG 41' UTB #41345 USCG 41' UTB #41486 (Panama City, FL)	April 1996 April 1996	400 400	Aluminum Aluminum	RTV11® gray RTV11® + 20% SF1154® gray
USN 30' Range Control Boat #1 USN 30' Range Control Boat #3 (Valley Lee, MD)	July 1996 September 1996	300 300	Aluminum Aluminum	EXSIL2200® gray EXSIL2200® clear
USCG 55' Search and Rescue Boat #55103 (Parramore) (Wachapreague, VA)	August 1996	1,000	Aluminum	EXSIL2200® gray
USCG 55' Buoy Boat #55117 (Mobile, AL)	September 1998	1,000	Aluminum	RTV11® + 20% SF1154® gray
ONR/Lockheed SLICE (Honolulu, HI)	November 1996	2,000	Steel	EXSIL2200® gray
NAWC MV Transporter (Patuxent River, MD)	September 1997	3,500	Aluminum	RTV11® + 20% SF1154® gray
Ontario Hydro Nanticoke Generating Station Trash Racks (Nanticoke, Ontario)	March 1995	50-100	Steel	EXSIL2200®, RTV1®
Consumer Power D.E. Karn Units 1 and 2 Cooling Water Intake Bay (Saginaw Bay, MI)	March 1995	500	Concrete, steel	EXSIL2200®, RTV11®
New England Power Company Brayton Point Station Unit 1 Screenwell and Tunnels (Mount Hope Bay, MA)	March 1996	17,000	Concrete, steel	EXSIL2200®, VOC-free topcoat, RTV11® +20% SF1154®

1.5 Stakeholder/End-User Issues

The duplex coating system is a multi-layer system with fairly tight application windows. Its expected useful service life has not been fully determined beyond three years, and its topcoat color and aesthetics are not yet as well controlled as those of traditional marine paints. Also, the availability of Silgan J-501® is a potential issue since this material is supplied by a competing company (Wacker Silicones Corporation) and is not under GE's control. Technology transfer will be most efficient if GE Silicones, the silicone manufacturer, allies with a partner in the marine paint industry for commercialization of this system.

1.6 Previous Testing of the Technology

The Long Island Lighting Company (LILCO) began research on non-fouling coatings in 1982[8]. Three of its power plants use Long Island Sound water for once-through cooling and all are subject to massive macrofouling of the concrete intake tunnels and cell blocks. Cleaning was previously performed once or twice per year, but because the cost of cleaning a single unit's intake system is substantial, numerous methods for controlling macrofouling have been explored. These methods include heat treatments, chlorination, water velocities greater than seven feet per second, and coatings. Regulations controlling water temperature or chlorination prohibit their use or reduce their effectiveness. Even brief periods of reduced water velocity allow mussels to attach firmly, and intake bays usually have velocities below one foot per second. Many coating types, including a copper powder/epoxy resin paint and several silicone paints, were tested at LILCO; the four most promising were considered for application to the intake tunnels. Three of the four effective coatings use toxic components; two of these are banned or were deemed unsuitable for use. The silicone paints varied in their resistance to fouling and abrasion; this indicated that further modifications were required to increase the longevity and effectiveness of the paint. Cost analysis showed that, while relatively expensive to install, silicone paints are far less costly than cumulative cleaning costs or unexpected outages resulting from macrofouling. Fouling release coatings are also being evaluated by the United States, French, Australian, and British Navies.

GE has had two previous contracts to study the duplex silicone fouling release coating system. VOC-free formulations were developed under DOD contract number N61533-93-C0062, and improvements to the duplex coating system were made under contract number N00014-94-C0150.

Table 1-2. 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.	Provides protection of intertidal zones (estuaries, coastal waters). Contains state
(PL 92-583)	programs to protect coastal resources and

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 sources; sets ambient air pollutant and emission standards

2. Technology Description

2.1 Description

Silicone fouling release coatings present a surface unsuitable for strong adhesion of macrofouling organisms. The accumulation of macrofouling organisms on immersed substrates occurs after an initial conditioning film and subsequent layers of the algal or slime films are deposited. In spite of this layering it is evident that the surface properties of the substrate are key in determining macrofouling adhesion strength. Substrates having critical surface tensions in the 25 to 30 mN/m range optimally resist strong macrofouling attachment[9]. Silicone coatings typically exhibit surface free energies in this range and thus are uniquely suited for fouling release applications. Figure 2-1 shows that silicones, while not having the lowest possible critical surface tension, exhibit the least biofilm attachment[9].

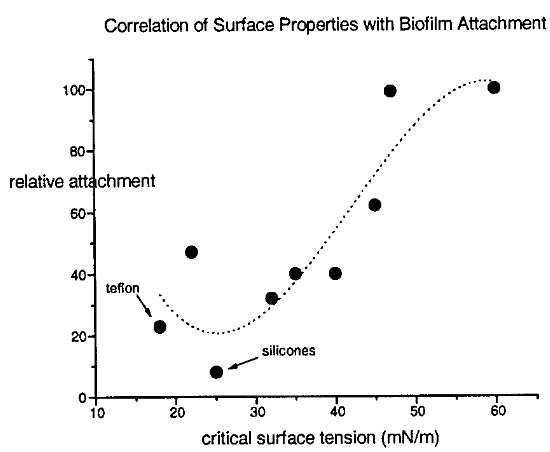

Figure 2-1. Graph illustrating the correlation between surface properties with biofilm attachment to those surfaces (from Baier[9]).

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. Besides acting as a means of biofouling control, the unique surface properties of silicone coatings are being evaluated in a number of industrial applications such as coatings for aircraft and automotive leading edges to minimize drag caused by impacted insect debris, nonmetallic fouling release protection for submerged radar and sonar domes and nonmetallic submarine substrates, and impact-resistant coatings to minimize aircraft damage caused by hail. Silicone foul release coatings are generally formulated as 1 or 2 component systems that cure on exposure to ambient moisture. The resulting crosslinked films are elastomeric and highly extensible; they typically exhibit an elongation of 100 to 400%. Due to their elastomeric nature, these coatings are susceptible to mechanical failure caused by shearing, tearing, or abrasion. The inherent nonstick nature of silicone coatings makes it difficult to establish good adhesion to most substrates, particularly smooth resinous films such as epoxies used as anticorrosive coatings.

The duplex coating system, which is the fouling release technology being evaluated in this demonstration, was developed at the Naval Research Laboratory[6,7] to address the durability issues associated with silicone elastomeric coatings. The concept employs a tough crosslinked thermoplastic elastomeric layer to bond the silicone fouling release coating to the anticorrosive layers and provide enhanced toughness to the silicone coating. Silgan J-501®, which is produced by Wacker Silicones Corporation, is the only commercial material that has been identified for this application thus far.

The duplex coating system was designed for use on ship hulls. It is a multi-layered coating made up of one or more layers of epoxy AC paint, an epoxyamide mistcoat to ensure bonding of the Silgan J-501® tiecoat to the AC layer, the toughening Silgan J-501® tie layer, and the elastomeric silicone topcoat. GE Silicones products RTV11® or EXSIL2200® are suitable as fouling release topcoats with the duplex coating system. This system provides corrosion protection, excellent bonding of all coating layers, enhanced durability and toughness, and easy release of macrofouling. The fouling release properties of the silicone topcoat may be enhanced by the addition of nonbonded polydimethyldiphenylsiloxane oils.

Figure 2-2 illustrates the system as it is applied to metal (steel or aluminum) and concrete substrates. Concrete substrates are coated similarly to metal surfaces except that a concrete sealer (such as Ameron Amercoat 105A) is used to prime the freshly blasted surface instead of a high-solids epoxy paint. The application procedures for each layer are described in Sections 2.1.1 through 2.1.4. Application of the entire system usually takes 3-4 days: 1 day for each layer of anticorrosive paint (usually the system requires two coats); 1 day for the mistcoat, tie layer, and topcoat; and 1 day for application of the coating system to block shift patches for small craft. Application specifications for each layer of the system are shown in Table 2-1.

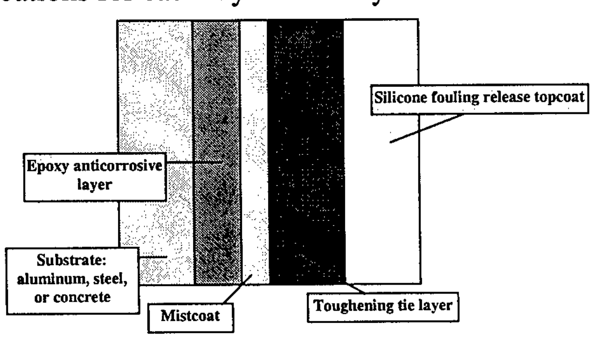

Figure 2-2. The NRL-GE duplex fouling release coating system.

Table 2-1. Application specifications for the NRL-GE duplex fouling release coating system.

	Anticorrosive Epoxy	Mistcoat	Wacker Silgan J-501® Tie Layer	GE Silicone Topcoat
Pot Life	5.0 hr @ 50°F 1.5 hr @ 90°F	2 hr @ 80°F *induction time:* 1 hr @ 45°F, 30 min @ 80°F *reaction time:* 2 hr @ 45°F, 45 min @ 80°F	"skins" over in just a few minutes	2 hr @ 80°F
Application Temp. Range (°F)	40-120	45-80	45-80	50-80
Relative Humidity (%)	40-95	40-95	40-95	40-95
Film Thickness (0.001 inch)	6-9 WFT 4-6 DFT	2-6 WFT 1-3 DFT	10-16 WFT 8-12 DFT	16-20 WFT 12-14 DFT
Time Until Application of Next Layer	10 hr @ 50°F 6 hr @ 90°F	until slightly tacky; 2 hr @ 45°F, 30 min @ 80°F	until slightly tacky; 1 hr @ 45°F, 30 min @ 80°F (but adhesion possible for any time <8 hr)	tack-free in 2 hr, immersion OK after 3 days

2.1.1 Anticorrosive layer. The AC paints for this system are Ameron Corporation's Amerlock 400®, Amerlock 400FD®, or Amercoat 385® high-solids two-part epoxy paints. These paints are high-performance coatings that form a tough, abrasion-resistant, durable barrier coating to prevent corrosion. They are easily sprayed to a wet film thickness of 0.006-0.009 inches over both previously-applied epoxy paints and clean metal.

Surface preparation is critical to good adhesion of the epoxy. Previously-applied paints must be clean, dry, tightly bonded and free from any residue; if the existing paint is in poor condition, the substrate must be grit blasted down to the metal.

The resin and cure of the two-part epoxy are mixed thoroughly in a 1:1 ratio. The resulting paint is filtered using a 60-mesh filter bag and is thinned only when necessary with ½ pint of Amercoat 65® thinner per 1 gallon of epoxy paint. Pot life and application conditions of the epoxy are shown in Table 2-1. The epoxy paints are applied using standard airless equipment (such as the Graco Ultimate 1500®) using a 0.015-inch (615) spray tip at 3000 psi of operating pressure to obtain a 0.015-inch wide flat fan spray. The epoxy may be completely cured before application of the mistcoat. The spraying system may be flushed with Amercoat 65® thinner to remove epoxy residue.

2.1.2 Mistcoat. The mistcoat primer is critical to the adhesion of the toughening tie layer to the epoxy AC layer. The mistcoat enhances adhesion in two ways; the epoxy imparts active functionality to the surface of the AC layer and the butanol softens the AC layer. It is easily sprayed to a 0.002-0.006 inch wet film thickness, but is very sensitive to ambient conditions.

The mistcoat consists of a blend of 55 parts of Shell Epon 828® epoxy resin and 45 parts Henkel Versamid 140® catalyst diluted in a 1:1 ratio with butanol. The resin and catalyst are mixed and allowed to react for 30 to 60 minutes before adding the butanol. When the butanol is added, the epoxy emulsifies and develops a milky appearance. This mixture is stirred occasionally until the emulsion breaks to form a clear solution. This solution is then filtered through a 60-mesh filter bag before spray application with standard airless spraying equipment using a 0.015-inch (615) spray tip at 3000 psi of operating pressure to obtain a 0.015-inch wide flat fan spray. Pot life and application conditions for the mistcoat are shown in Table 2-1. The solution must be stirred occasionally during the application to prevent premature gelation. The tie layer may be applied when the mistcoat is slightly tacky, and extreme caution should be taken to apply the next coat neither too soon, when the mistcoat is still wet, nor too late, when the mistcoat is completely cured. The spraying system may be flushed with naphtha to remove mistcoat residue.

2.1.3 Toughening Tie Layer. The tie layer consists of Wacker Silicones Silgan J-501®, a one-part moisture-curing blend of a silicone and a styrene/butylacrylate copolymer. This material imparts mechanical toughness to the duplex foul release coating system and provides excellent adhesion to the silicone topcoat. It is easily sprayed to a 0.010-0.016 inch wet film thickness at which it achieves a coverage of 90 ft^2/gal. Because it is a moisture-curing material, Silgan J-501® will cure on contact with atmospheric moisture; all containers are tightly sealed when not in use.

Wacker Silgan J-501® is diluted by 10% with a proprietary additive to improve spray quality and to decrease sensitivity to ambient application conditions. Because Silgan J-501® is sensitive to atmospheric moisture, hand-mixing is recommended. After the additive is mixed quickly and thoroughly into Silgan J-501®, the mixture is filtered through doubled 60-mesh filter bags. A small amount of naphtha is poured on top of the mixture to prevent the formation of a "skin" of cured Silgan J-501® at the air interface. Silgan J-501® is sprayed using standard high-power airless spraying systems (such as the Graco Bulldog®) with a 45:1 air pressure ratio; a 617-619 spray tip is used at a 3000-4500 psi operating pressure to obtain a 0.017-0.019 inch wide flat fan spray. It is recommended that the silicone topcoat be applied when the Silgan J-501® is slightly tacky, but laboratory experiments have shown that a recoat window exists for up to eight hours after Silgan J-501® application. The spraying system may be flushed with naphtha to remove Silgan J-501® residue.

Silicone fouling-release topcoat. The topcoat is the surface to which fouling is exposed and therefore is the most critical to the fouling release characteristics of the entire system. GE Silicones RTV11® (alone and with silicone oil additives) and EXSIL2200® were demonstrated/validated in this program. These formulations have state-of-the-art fouling release properties, and exhibit excellent adhesion to the Silgan J-501® tie layer. The topcoat is easily sprayed to a 0.016-0.020 inch wet film thickness at which it can obtain a coverage of 90 ft^2/gal;

it cures to solidity overnight but requires seven days for complete cure. Three days of cure time is the minimum recommended before water immersion of the coating system.
RTV11® is cured with dibutyltin dilaurate catalyst, and EXSIL2200® is cured with the GE EXSIL2205® catalyst package. Once the polymer and catalyst are mixed thoroughly with a mechanical mixer, the resulting mixture is filtered through doubled 60-mesh filter bags. Both RTV11® and EXSIL2200® are sprayed using standard airless spraying equipment (such as the Graco Premier®) with a 45:1 air pressure ratio; a 617-619 spray tip is used at a 3000-4500 psi operating pressure to obtain a 0.017-0.019 inch wide flat fan spray. Two thin coats of the topcoat may be applied twenty minutes apart to achieve the required wet film thickness without sagging. The spraying system may be flushed with lacquer thinner or naphtha.

2.2 Strengths, Advantages, and Weaknesses of the Technology

Advantages of silicone-based fouling release coatings include:

- *No toxicity:* The duplex system does not contain added toxicants such as heavy metals or biocides and therefore exhibits no toxicity to marine organisms. Conventional antifouling paints are toxic to marine life and their use must be reported to the Environmental Protection Agency under FIFRA (see Table 1-2).
- *Environmental safety:* The duplex coating system is VOC compliant and its waste may be disposed of as non-hazardous waste in sanitary landfills after removal from the hull or intake bay. Copper ablative paint waste must be contained because of its toxicity.
- *Excellent fouling release capabilities:* The duplex system allows fouling to be removed easily by water jet or self-cleaning mechanisms; this ability also prevents large macro-fouling buildups. AF paints do not have fouling-release ability once macrofouling has settled.
- *Low maintenance:* Any macrofouling or slime adhering to the Duplex system is easily removable by scrubbing with a brush or by simple water hose pressure; a rotating brush for underwater cleaning is being developed by the Naval Sea Systems Command. AF paints cannot be easily cleaned once macrofouling settles.
- *Ease of Use:* The duplex coating system is applied with conventional airless spray equipment provided that there are no conditions of high or low temperature beyond that recommended in the product data sheets. Application requires trained personnel and a spray line dedicated to the application of silicones only.
- *Repairability:* Practical maintenance and repair technology for the duplex system was developed as part of this demonstration; to our knowledge no other fouling release coating system has this capability.
- *Performance in a variety of environments:* Fouling release capability in freshwater, brackish, and marine waters ranging from cold and temperate to tropical climates has been demonstrated in this program.
- *Variety of applications:* Fouling release coatings have many industrial applications besides power plant cooling water intakes and military ships. Commercial and pleasure craft would benefit from the fouling release characteristics of this technology. Other marine applications include ocean oil drilling platforms and submarine periscopes. Several spin-off applications have been developed as well to take advantage of the release properties;

these applications include radar domes for spacecraft, cowlings for aircraft engines, auto grilles and mirror housings to prevent impacted insect adhesion, and NASCAR to reduce drag.

- *Versatility*: The duplex coating system was designed primarily for application over aluminum or other metal substrates. However, with suitable variation of the primer and anticorrosion coatings, this system has been applied to concrete, plastic, and reinforced plastic composite substrates as well.
- *Reliability*: These coatings have been in service at a number of marine and freshwater facilities for three to four years with minimal coating failure. Test panels coated with this system have been exposed at various test facilities for periods of up to five years with little or no failure.
- *Off-the-shelf procurement*: All of the materials used in the duplex coating system are commercially available and may be purchased directly from the manufacturers or their designated distributors. Table 2-2 shows a few of the products and the company from which they may be obtained, and Material Safety Data Sheets are available for each of the coating system components from the GE CR&D principal investigator (Dr. James Cella).

Table 2-2. Procurement agents for silicone fouling release coating system components

Material	*Distributor*
Amercoat 385®, Amerlock 400®	Ameron Corporation (Edison, New Jersey)
Silgan J-501®	Wacker Silicones Corporation (Adrian, Michigan)
RTV11®, EXSIL2200®	General Electric Silicones Products Division (Waterford, New York)
SF1154®	General Electric Silicones Products Division (Waterford, New York)

Some improvements that must be made to the duplex coating technology before commercial acceptance may be achieved include:

- Determination of the effective service life of these coatings by extending exposure time
- Simplification of the application characteristics
- Elimination of the mistcoat
- Development of a sprayable repair package
- Development of alternatives to the Silgan J-501® tie layer

2.3 Factors Influencing Cost and Performance

Factors influencing the cost to apply the duplex fouling release coating system include:

- Size of the application
- Contractor costs for application
- Special environmental regulatory requirements (such as venting and hot air flow)
- Special equipment necessary for access to the application site

- Weather (may prolong or postpone application)

Factors influencing the performance of the duplex fouling release coating system include:
- Adequate surface preparation
- Proper application procedures (timing of each layer, thickness, age of materials, etc.)
- Atmospheric conditions
- Adequate drying time before re-immersion
- Ratio of dockside time to operational time for boat applications
- Severity of operational conditions
- Type and intensity of the biofouling population
- Proper and timely maintenance and cleaning

3. Site/Facility Descriptions

3.1 Background

The size and operational speeds of U.S. Coast Guard 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. Coast Guard utility training boats, Navy range control boats, a Navy Transporter and an experimental vessel (the ONR/Lockheed SLICE) 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 a better demonstration of the application methods and cleaning procedures than patch tests do on 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. Dewatering activities for inspection of the bays, screenwells, and tunnels were scheduled during the spring prior to or during the mussel pre-attachment larval stage.

A complete description of the sites chosen for this demonstration is below.

3.1.1 Ontario Hydro, Nanticoke Generating Station. The first demonstration site was the 4000-megawatt Nanticoke Generating Station of Ontario Hydro located on the north shore of Lake Erie. Two eight-foot by twelve-foot carbon steel TGS intake trash racks (having a surface area of 300 ft^2) from the Condenser Cooling Water Pumpset #1 of Unit No. 6 were coated with the duplex coating system using EXSIL2200® and RTV11® topcoats at the Blastco Corporation facility in Brantford, Ontario on 21 March 1995 and reinstalled at the Nanticoke site on 24 April

1995. Painting these trash racks served as an introduction to large-scale application at a power plant and demonstrated the utility and sprayability of silicone coatings for a large-scale freshwater application. Buy-in with the station was ensured by scheduling annual inspections to be performed by an Ontario Hydro dive team.

The Nanticoke Generating Station has two intake bays that draw water from Lake Erie and one outlet bay that discharges water back to the lake. The trash racks that were coated for this demonstration were installed in the No. 1 condenser cooling water intake, which has a maximum water flow of 12.5 m^3/sec (165,000 gallons per minute). Zebra mussels (*Dreissena polymorpha*) first appeared at the Nanticoke site in 1989, but infestations at the time of application were almost entirely quagga mussels (*D. bugensis*). Both species are capable of clogging condenser tubes. Before the application of the fouling release coatings, pump wells were cleaned with a fire hose during scheduled dewatering (every 18 to 24 months); mussels that were blown off the wall by the hose were sucked up into a vacuum truck. Chlorine injection systems were installed in 1990. The advantage of applying silicone fouling release coatings to the pump wells is that the macrofouling adhesion strength would decrease and thus far less force would be required for macrofouling removal. Also, the silicone coatings do not release toxins into the lake with the discharge water like chlorination does.

3.1.2 Consumer Power, D.E. Karn Units 1 and 2, Saginaw Bay, Michigan. The second power plant demonstration/validation site was at the 515-megawatt D.E. Karn Plants 1 and 2 of Consumer Power in Essexville, Michigan. Test patches on the tunnel walls and steel deflecting vanes of the intake bay that serves both units of the Consumer Power plant were coated during the week of 18-24 March 1995. This application expanded on the work done at the Nanticoke Generating Station to evaluate the duplex coating fouling release performance in fresh water with a larger application.

The D.E. Karn plant has a single intake bay that draws water from Saginaw Bay to serve four units through two tunnels. Water is pumped through each tunnel at 150,000 gallons per minute. The water flow velocity varies between 1.4 ft/sec and 3.7 ft/sec. Zebra mussels first appeared at the Consumer Power site in 1988. Prior to this infestation the intake tunnels did not require cleaning. The extensive fouling that has occurred every year since the zebra mussel infestation requires that the plant plan annual outages to dewater the intake tunnels and sandblast the fouling from the tunnel surfaces. No anti-fouling approaches were tried before the application of the silicone fouling release coatings in March of 1995.

3.1.3 Two 41' U.S. Coast Guard Utility Training Boats, Yorktown, Virginia. The first boat platform demonstration involved coating the aluminum hulls of U.S. Coast Guard Utility Training Boats (UTB's) 41312 and 41393 with systems containing 2 slightly different topcoats at a private marina in Gloucester Point, VA during the week of 19 June 1995. UTB 41312 was coated with the standard RTV11® topcoat, and UTB 41393 was coated using RTV11® with 20% SF1154®. These applications covered approximately 400 square feet of each boat.

The UTB's 41312 and 41393 are used for routine training exercises at the UTB Systems Center located at the U.S. Coast Guard Training Center in Yorktown. The UTB's are designed for training use on inland waters and limited offshore use in moderate weather and seas. These UTB's operate in icy conditions and scrape bottom on sand bars, so durability against damage is paramount for these applications. The UTB's experience seasonal fouling by macrofouling species such as barnacles, tubeworms, and oysters. To control macrofouling in the past, US Coast Guard vessels were painted with organotin paints, but the EPA has banned the use of this toxic antifouling paint and the USCG wants a more environmentally safe coating. Copper paint cannot be used on the aluminum hulls of these vessels because it causes galvanic corrosion. UTB's coated with organotin paints were pulled every two years for sand sweep cleaning and fresh paint. UTB's painted with only anticorrosive epoxy paint require a water blast and scraping every two weeks, and a complete repainting every two years. An advantage of the duplex coating system for these boats is that the hull may be easily cleaned with only a water spray, and, unlike the toxic organotin paints, all waste generated from removal of the hull coating may be placed in a non-hazardous landfill.

3.1.4 New England Power Company, Brayton Point Station, Brayton Point, Massachusetts. The final power plant demonstration/validation site was the New England Power Company's 1600-megawatt Brayton Point Station in Somerset, Massachusetts located on Mount Hope Bay at the confluence of the Lee's and Taunton Rivers. During the weeks of 1-16 March 1996, the duplex fouling release coating system was applied to approximately 17,000 square feet of the intake bay of Unit No. 1. The surfaces coated include concrete tunnels, cast iron sections, screenwells, steel trash racks, and traveling screen frames. Steel test panels were also prepared and submerged for regular performance monitoring. This application provided information on duplex coating fouling release performance in a brackish marine environment, against a variety of fouling organisms. The application also demonstrated the ability to apply the system on a very large scale.

The Brayton Point Station Unit No. 1 has a single intake bay that draws brackish water from the Mount Hope Bay through concrete intake structures and circulating water tunnels to cool the main condensers. Water flows through the six-foot diameter tunnels at 181,000 gallons per minute with a linear velocity of 7 ft/sec. Dominant macrofouling species include the blue mussel (*Mytilis edulis*), barnacle (*Balanus balanus*), and two species of *Crepidula* (gastopods and slipper shells). Other fouling species include algae, sponges, hydroids, bryozoans, polychetes (*Polydora sp.*), and oysters (*Crassostrea virginica*). Hydroids are not considered "hard" foulers because they lack a calcified shell, but can form thick mats that restrict cooling water flow and block condenser tubes. Because of colder seasonal water temperatures at Brayton Point, macrofouling is seasonal; maximum fouling of the intake system occurs between May and October. Because much of the fouling dies off each season, biological debris regularly settles in waterboxes, plugs condenser tubes and otherwise restricts cooling water flow.

NEPCO has explored a number of options for the control of macrofouling including mechanical and screening methods, static chemical treatments, and chlorination. Chlorination has been used at the traveling screens but was replaced by targeted bromination at the condenser inlet. Silicone fouling release coatings are an improvement over these methods because mechanical and screening methods impose flow restrictions and bromination (or chlorination) causes eventual bromine (chlorine) release into Mount Hope Bay.

3.1.5 Two 41' U.S. Coast Guard Search and Rescue Utility Training Boats, Panama City, Florida. The next demonstration consisted of coating the aluminum hulls of U.S. Coast Guard UTB's 41345 and 41486 with systems containing two slightly different topcoats at Tibbett's Marina in Panama City, Florida during the week of 15 April 1996. UTB 41345 was coated using the standard RTV11® topcoat, and UTB 41486 was coated using RTV11® with 20% SF1154®. These applications covered approximately 400 square feet of each boat.

UTB's 41345 and 41486 are used for search and rescue missions in the Gulf of Mexico; UTB 41345 operates between Lake Powell and Rock Island, Florida and is based in Panama City, Florida, while UTB 41486 operates between Neva Beach, Florida and Alabama Highway 59 and is based in Pensacola, Florida. These boats are a good dynamic platform to study fouling release performance in warm waters. The UTB's experience seasonal fouling, but the season is much longer than that experienced in northern U.S. waters. The macrofouling species in the warm Florida waters include barnacles, tubeworms, oysters, encrusting bryozoans, hydroids, tunicates, and algae.

3.1.6 Two 32' U.S. Navy Range Control Boats, Valley Lee, Maryland. This demonstration/validation involved coating the aluminum hulls of U.S. Navy Range Control Boats RCB-1 and RCB-3 with systems containing two different topcoats at Cedar Cove Marina in Valley Lee, Maryland. RCB-1 was coated with EXSIL2200® gray during the week of 29 July 1996, and RCB-3 was coated with EXSIL2200® clear during the week of 24 September 1996. This application covered approximately 300 square feet of each boat.

Range control boats are used to keep pleasure craft and unauthorized vessels out of target areas used for Navy guns in the Chesapeake Bay. The boats are stationed at the Naval Surface Warfare Center/Dahlgren Division in Dahlgren, Virginia and are manned by the Patuxent Naval Air Station (Lexington Park, Maryland). Range control boats are not as active as UTB's and so provide the opportunity to evaluate fouling release performance on a hull that spends more time pierside each week[10]. They run at higher speeds than the UTB's, which makes them an excellent platform for testing and demonstrating the self-cleaning capabilities of the duplex coating system. The fouling community consists of barnacles, tubeworms, and oysters. Previous macrofouling control methods included organotin paints; copper ablative paints could not be used because they would cause galvanic corrosion with the aluminum hull. The self-cleaning capabilities of the duplex silicone fouling release coatings make it a viable option for a long-lasting means of macrofouling control for range control boats.

3.1.7 U.S. Coast Guard 55' Search and Rescue Boat #55103 (Parramore), Wachapreague, VA. In this demonstration, the aluminum hull of USCG 55103 (Parramore) was coated with EXSIL2200® at the Coast Guard Support Center in Portsmouth, Virginia during the week of 19 August 1996. This application covered approximately 1,000 square feet.

The Parramore serves the Coast Guard Station for search and rescue, maritime law enforcement, and support of federal and state agencies. She is based in Wachapreague, Virginia and has a normal range of operations up to thirty miles offshore between Metompkin Island and Cobb

Island. The Parramore rarely operates in icy conditions and its pierside time varies greatly. Seasonal macrofouling consists mostly of barnacles and green sea grass. In the past the hull was coated with organotin or copper ablative paints to control fouling, but recently the hull was painted with a rapidly-fouling "boat bottom paint." Coating this boat with the duplex fouling release coating system was an opportunity to carry out a larger-scale application to demonstrate the coating's self-cleaning capability.

3.1.8 ONR/Lockheed SLICE, Honolulu, Hawaii. In this demonstration, the two port side aluminum pontoon hulls of the reconfigurable ONR/Lockheed SLICE were topcoated with EXSIL2200® (gray) at the Honolulu Shipyard in Honolulu, Hawaii in November 1996. This application covered approximately 2,000 square feet of the pontoons.

The SLICE is an experimental vessel developed under a cooperative agreement with the Office of Naval Research and Lockheed; the hull consists of four pontoons designed to produce low drag, reduce wavemaking, and maximize speed. The streamlined design gives the SLICE improved ship control, seakeeping abilities, and maneuverability, and its lightweight construction improves forward propulsion and aft payload. The application of the duplex coating system to two of the pontoons provided a chance to study fouling release performance in the tropical waters of the Pacific Ocean (which has a different fouling community than the Atlantic Ocean, where most of our applications have taken place), as well as a chance to compare duplex coating performance with that of a competitor's fouling release coating, which had been applied to the two starboard pontoons.

3.1.9 NAWC MV Transporter, Patuxent River, Maryland. This demonstration/validation involved coating the aluminum hull of the 100' MV Transporter with RTV11® + 20% SF1154® at Yacht Maintenance in Cambridge, Maryland during the week of 15 September 1997. This application covered approximately 3,500 square feet.

The Transporter is used for a variety of missions such as transporting supplies and cargo for the Navy in the Chesapeake Bay. The transporter experiences seasonal fouling by macrofouling species such as barnacles, tubeworms, and oysters. Previous methods used to control fouling on the Transporter hull include copper ablative paints; these have proven effective, but concerns about the toxicity of these coatings has been raised. Silicone fouling release coatings such as the duplex coating system are non-toxic. This demonstration provided GE with a large platform to evaluate duplex coating performance, durability, and patch repair on a ship in regular use.

3.1.10 U.S. Coast Guard 55' Buoy Boat #55117, Mobile, Alabama. In this demonstration, the aluminum hull of the 55' USCG 55117 was coated with RTV11® + 20% SF1154® at Master Marine, Inc. in Bayou La Batre, Alabama during the week of 9 September 1998. This application covered 1,000 square feet.

USCG 55117 is used for servicing aids to navigation such as buoys, fixed structures, lights, and day markers. It is based in Panama City, Florida where it experiences a long warm-water fouling season with exposure to organisms such as barnacles, tubeworms, oysters, hydroids, encrusting bryozoans, and algae. This demonstration provided GE with a large platform to evaluate duplex coating system performance in a warm water environment.

4. Demonstration/Validation Approach

4.1 Performance Objectives

The primary objective of this project was to demonstrate and validate the effectiveness of the duplex silicone fouling release coating as it was applied to a variety of platforms and exposed to a variety of environments. Effectiveness was determined by the ease of fouling removal (fouling release capability), the type and extent of fouling on the system under various use conditions, and the ease of application. Fouling release capability and the extent and type of fouling coverage capable of control by the duplex coating system were to be demonstrated by the normal use on stationary platforms (power plant cooling water intakes) and dynamic platforms (U.S. Coast Guard and U.S. Navy ships) in cold, temperate, and tropical waters by measuring fouling coverage before and after water jet cleaning or brushing. The percent coverage of hard fouling and the comparison of duplex-coated surfaces with control surfaces were also used to measure the fouling coverage performance. Effectiveness of the duplex coating system in both freshwater and marine environments was to be demonstrated and validated.

Performance objectives for the demonstration also included assessment of physical appearance, adhesion quality, and cost effectiveness. The adhesion quality and durability of the duplex system (and thus the quality of the application itself) was evaluated in this demonstration.
Quality was judged by the extent of delamination, propagation of delamination when it occurred, and the occurrence of adhesive or cohesive failure and its subsequent propagation after abrasion damage from large waterborne objects, sand, docks, and macrofoulers such as snails. Physical attributes of the coating system that are believed to effect fouling release performance were evaluated; these attributes include appearance characteristics such as a smooth surface, uniform color (to verify thorough mixing of the topcoat), good wetting ability, and complete coverage. Cost effectiveness was analyzed by comparing the application costs and maintenance and operation costs of the duplex fouling release coating system versus those of copper ablative paint systems.

The purpose of this demonstration/validation was to further improve the duplex fouling release coating system to gain commercial and DOD acceptance. The performance improvements that have been addressed by testing the system in various marine environments include:

- Five to seven years of sustained fouling release performance
- Improved abrasion resistance
- Development of practical maintenance and repair technology
- Lower system costs (materials, application, disposal)

Over the past four years, ten boats or ships were painted and portions of three power plant cooling water intake bays were painted for this demonstration. Power plant applications ranged from coating trash racks to complete coating of the bay and tunnels of the cooling water intake. The application of the duplex coatings system to large surface areas of ships and intakes highlighted the technical issues associated with the spray application process, since the silicone materials were not designed to be sprayed; recommendations for improvements in future applications were made as a result of this demonstration. Many substrates, such as aluminum, steel, concrete, and plastic surfaces, were coated with the duplex coating system using standard spray application. GE's inspections will cease after completion of this contract, but contact will be maintained with the parties responsible for the various application sites in order to track the long-term fate and performance of the duplex coating system.

4.2 Physical Setup and Operation

The application of the duplex coating 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-V power is needed to operate hand-held electric mixers. A clean, dry, flat space approximately eight feet long by eight feet wide and covered with a plastic sheet is sufficient as a paint preparation area; this area should be at least twenty feet away from the boat being painted to allow mixing and spraying to occur concurrently. The spray pumps should be equipped with wheels to allow free motion around the boat.

The time for the application of the duplex coating system to a boat or power plant is about four days. Figure 4-1 illustrates the timeline of the procedure. Assuming that the hull or concrete surface has already been cleaned and grit-blasted to the desired surface profile, the clean surface is wiped with naphtha to remove any residual moisture and dust; subsequent spray application of the initial coat of AC epoxy paint takes place on the first application day. The epoxy is allowed to cure overnight. A second coat of anticorrosive paint is applied on the second day and allowed to cure overnight.

On the third day, the duplex coating system itself is applied. The cured epoxy surface is wiped once again with solvent to remove any residual moisture and dust; once the mistcoat is prepared as described in Section 2.1.2 of this report, it is applied to the epoxy AC layer to a 0.002-0.003 inch wet-film thickness. When the mistcoat is slightly tacky, Silgan J-501® is applied to a 0.017-0.019 inch wet-film thickness. The silicone topcoat (either RTV11® or EXSIL2200®) is sprayed after the Silgan J-501® is tack-free. Seven days is required for complete cure of the system, but a minimum of three days is recommended before re-immersion of the boat once the system application is complete.

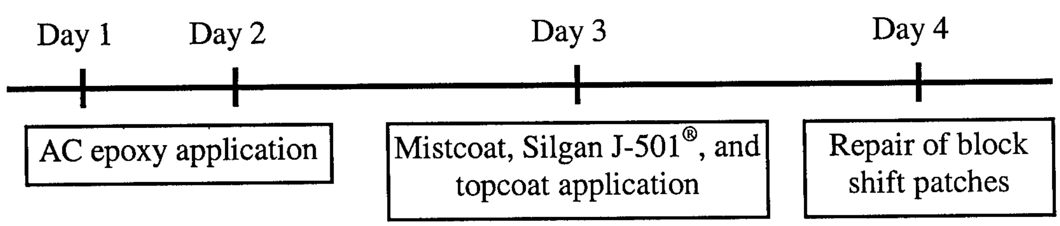

Figure 4-1. Timeline of duplex coating system application.

The inspection and cleaning timeline for the duplex coating system depends on the platform and timing around the local fouling season. The only time the duplex coating system is available for cleaning in power plant cooling water intakes is during the annual maintenance shutdown of the plant.

Application of the duplex coating system to smaller craft such as the U.S. Coast Guard UTB's 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. For larger boats, two painters should be used for a more efficient application. Each painter would require at least one person to assist. Other labor is necessary to pull the boats, dewater the 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 barnacle adhesion measurements (if desired). If an underwater cleaning and inspection is desired, trained dive inspectors would be needed.

Table 4-1 lists the physical properties of the materials used in the duplex fouling release coating system. The AC epoxy is a two-part bisphenol A/epichlorohydrin-polyamide-based high-solids epoxy paint manufactured by Henkel Corporation. The mistcoat consists of Shell Epon 828® bisphenol A/epichlorohydrin-based epoxy resin, Henkel Versamid 140® polyamide resin (which also contains a triethylenetetramine catalyst), and reagent-grade butanol. Silgan J-501® is a blend of a silicone with a styrene/butylacrylate copolymer manufactured by Wacker Silicones. RTV11® and EXSIL2200® are silicone rubber compounds catalyzed with dibutyltindilaurate.

Table 4-1. Physical properties of the components of the duplex fouling release coating system.

	Solids Content (Volume %)	Flash Point (°F)	Weight (lb/gal)	Dry Film Thickness (lb./ft^2/mil DFT)
Epoxy	83	85	11.7	0.090
Mistcoat	50	84	7.9	0.0056
Silgan J-501	80	78	7.24	0.0046
GE Topcoats	98	570	10	0.062

All unused cured materials used in the duplex fouling release coating system are suitable for disposal in a non-hazardous landfill; this includes the AC epoxy paint, the mistcoat, Silgan J-501®, and the silicone topcoat. All uncured material not applied to the boat must be disposed of as hazardous flammable waste. Disposal of these materials must follow guidelines specified by OSHA and EPA.

4.3 Testing Procedures

The significant properties of the fouling release coating system that are being tested and evaluated under this contract include (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 in the field and in laboratory studies. The test methods used in this program are summarized in Table 4-1.

Table 4-1. Methods used to test the duplex coating system.

Criterion	*Method*
Fouling release capability; cleanability	Barnacle adhesion force gauge measurement (ASTM D5618-94) 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)

Fouling release capability is evaluated using two different test methods. The water jet test assesses biofouling adhesion by applying a jet of water to the organisms at incrementally increasing pressures and monitoring the removal of organisms and slime films at each pressure. The details of the method, the testing apparatus, and the associated calibration curve are described in the Second Inspection Report for the intake tunnel of Consumers Energy D.E. Karn Plants 1 and 2 (Kavanagh, Schultz, and Swain, March 1997). The water jet test was carried out at various test sites by either Bridger Scientific or by FIT. Barnacle adhesion strength is measured by using a hand-held force gauge to apply a parallel force to the base of a hard fouling organism until the organism detaches[11,12,13]. The force to remove the organism and the contact area of the organism's base plate is used to calculate the shear strength required for removal. This test was developed at FIT and is registered as ASTM method D5618.

Laboratory characterization and analysis of the surface physical properties of the silicone coatings was conducted by the Industry/University Center for Biosurfaces at SUNY-Buffalo and NSWCCD using concrete and steel panels prepared at GE CRD. The IUCB has developed standard protocols for measuring and quantifying the performance of fouling release coatings[14].

Abrasion resistance was measured using a rotating brush method developed by SUNY-Buffalo IUCB that is similar to methods used to determine tooth enamel hardness. Adhesion of the coating to the substrate was tested using standard ASTM methods and the Hydraulic Adhesion Testing Equipment (HATE), which was used to estimate the force necessary to delaminate the coating system by ASTM method D4541. These test methods are described in detail in the Technology Demonstration Plan for the US Coast Guard 55103 ("Parramore"), submitted to ESTCP by GE CRD in August 1996.

4.4 Evaluation Procedures

The operating procedure for boat hull inspections is described in detail 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, and the water jet test method, barnacle adhesion test method, and power trials. Other methods used to evaluate the duplex coating system performance are listed in Table 4-2.

Hydrodynamic self-cleaning evaluations were run in conjunction with power trials on boat demonstrations. The purpose of the trials was to investigate the potential for self-cleaning of the coatings by the boat's movement through the water. Self-cleaning is assessed by evaluating the extent of fouling on the hull before and after the power trials. Power trials measure the coating's self-cleaning capability by assessing maximum ground speed and engine RPM's; direct reading of shaft power is desired but not always available.

Coating quality may be assessed both above water and *in situ* by a dive team. Visual inspection includes the evaluation of physical integrity (appearance, delamination, and blisters) and extent of fouling coverage. To assess the coating quality and extent of fouling on a coating, the Navy maintains quantitative fouling ratings and paint deterioration ratings in Chapter 081 of the Naval Ships' Technical Manual.

Table 4-2. Methods used to evaluate the duplex 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

5. Performance Assessment

5.1 Performance Data

Tables 5-1, 5-2, and 5-3 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, as are the quarterly progress reports, from GE Corporate Research & Development (Dr. James Cella; see Appendix A). The analytical methods used to perform the inspections are outlined in Table 4-2 of Section 4.4, Evaluation Procedures. There are no known conditions that effect the validity of the findings; because of the subjective nature of the fouling and coating quality assessments, only the ability of the inspector would effect the data. The individuals who carried out the inspections for these demonstrations were well versed in the determination of fouling release coating quality and performance.

Figure 5-1 shows the UTB 41312 after application of the duplex coating system. The appearance of this UTB is representative of all of the USCG demonstrations. The 41312 and 41393 U.S. Coast Guard UTB's did not show similar fouling release performance over time. Comparison of the extent of fouling on the two boats over one and a half years illustrates the importance of oil addition for enhancing fouling release performance. After only two months, UTB 41393 (RTV11® + 20% SF1154®) had less fouling than UTB 41312. The boats were equally fouled after nine months, but the 18-month inspection showed that the coating on UTB 41393 had half the barnacle adhesion strength and showed evidence of self-cleaning while the coating on UTB 41312 did not; these results may indicate that the oil's performance enhancement improves with time. The 25% increase in boat speed after cleaning of the duplex coatings illustrated the silicone coating's drag reduction benefit. The demonstration on these UTB's also showed that addition of silicone oil to the topcoat does not sacrifice the durability of the duplex coating system, since both coatings sustained only minor abrasion damage. In September 1997, minor ice damage to UTB 41312 was repaired, and no subsequent damage or delamination has been reported. In April 1997, UTB 41393 was sold to the Louisville, Kentucky Fire Department for use on the Ohio River, which is infested with zebra mussels. After one year, the coating on that boat continues to be 100% effective against zebra mussels, and, while slight damage has been repaired, no delamination has been reported.

UTB 41486 proved to be the first instance of delamination on a boat platform that required extensive repair. The duplex coating system had been rolled on prior to the development of spraying expertise. A dive inspection in the summer of 1996 reported that the coating was "peeling off" and the hull was severely fouled. When the boat was pulled from the water for repairs in September 1996, the damage was found to be much less extensive than reported; only 10 ft^2 of the original 400 ft^2 had delaminated, and no hard fouling was observed (except on exposed epoxy paint).

Table 5-1. Summary of U.S. Coast Guard boat platform inspection results.

Site Description	Topcoat	Water Condition	Fouling and Damage
USCG 41' UTB #41312	RTV11®	Temperate Marine	Aug 95: 2 months service. More encrusting Bryozoans & barnacles than UTB #41393; minor damage. Mar 96: 9 months service. 18 psi barnacle adhesion; minor ice abrasion damage. Oct 96: 1 ½ yrs service. 18 psi barncle adhesion, much more fouled than UTB #41393, cleans easily. Sept. 97: 29 months service. Repair the ice damage from 1995.
USCG 41' UTB #41393	RTV11® + 20% SF1154®	Temperate marine	Aug 95: 2 months service. Fewer encrusting byrozoans & barnacles than UTB #41312; minor damage. Mar 96: 9 months service. 18 psi barnacle adhesion; minor ice abrasion damage. Oct. 96: 1 ½ yrs. Service. 9 psi barnacle adhesion, much less fouled than UTB #41312, evidence of self-cleaning, cleaned easily.

USCG 41' UTB #41393 (cont.)			May 98: 3 yr. Service. Decommissioned to Louisville, KY Fire Department in Apr 97; completely effective against zebra mussels.
USCG 41' UTB #41345	Exsil 2200® gray	Temperate marine	No inspection report available.
USCG 41' UTB #41486	RTV11® + 20% SF1154®	Temperate marine	Sept 96: 5 months service. Algae, slime, no hard fouling; evidence of self cleaning; 10 ft^2 delamination at epoxy/J501 interface on rudder-keel area. Repaired in Sept 96.
USCG 55' Search and Rescue Boat #55103 (Parramore)	Esxil 2200® Gray	Temperate marine	Dec. 96: 4 months service. Bottom of hull fouled with encrusting bryozoans, clams and 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.

Figure 5-1. The duplex coating system as applied to UTB 41312.

A photograph of the duplex system on the UTB 41486 after one year of service is shown in Figure 5-2. The damage was repaired with RTV11® catalyzed with SCM501C®, which contains a high percentage of adhesion promoter to adhere to many types of surfaces. Unfortunately, the repair to UTB 41486 was unsuccessful, mostly likely due to poor surface preparation of the repaired area, and the Duplex system was removed and replaced with a conventional marine paint. The EXSIL2200® coating system on UTB 41345 was also removed at the same time and replaced with a competitor's easy release coating.

Figure 5-2. Duplex system applied to UTB 41486 after one year of service.

The duplex coating on the USCG 55103 (Parramore) is shown in Figure 5-3. An inspection after four months of service showed very good performance; a gradient of increasing fouling toward the keel indicated self-cleaning ability, and minor sand abrasion damage at the rudders and keel showed the coating's durability and good adhesion. The coating on the Parramore was removed without warning in 1997. Personnel at Yacht Maintenance in Cambridge, MD, where the boat was pulled for recoating, reported that the coating was in excellent condition when the boat was pulled and that the little macrofouling that existed was easily cleaned from the hull.

Figure 5-3. Duplex coating as applied to USCG 55103 (Parramore).

The application of the duplex fouling release coating system to the U.S. Navy ships described in Table 5-2 provided opportunities for larger-scale application experience, as well as the chance to test the duplex coating system against the fouling indigenous to tropical Pacific waters. Minor repairs to the U.S. Navy range control boats took place in May 1998; abrasion damage along the waterline and delamination at the block shift patches were repaired with the GE SEA210A®/GE SCM501C® repair package with an EXSIL2200® topcoat. There have been no further complaints of delamination or repairs needed. The users of the RCB's are happy with the fouling release performance and durability of the duplex coating system. A photograph of the EXSIL2200® coating's appearance on RCB-1 is shown in Figure 5-4.

Table 5-2. Summary of U.S. Navy boat platform inspection results.

Site Description	Topcoat	Water Condition	Fouling and Damage
USN 30' RCB #1	EXSIL 2200® gray	Temperate marine	Apr 97: 9 months service. Light slime layer, no hard fouling; abrasion at boot top and bow; delamination at block shift patches. Repaired in May 98.
USN 30' RCB #3	EXSIL 2200® clear	Temperate marine	Apr 97: 7 months service. Light slime layer, no hard fouling; ice abrasion damage at boot top and bow, delamination at block shift patches. Repaired in May 98.
ONR/Lockheed SLICE	EXSIL 2200® gray	Tropical marine	Feb. 97: Gearbox installation problem required coating repair. May 97: 6 months service. Dive inspection. Many algae and soft foulers, sea grass, no hard foulers; easily wiped clean. June 97: 8 months service. Mostly slime film, some oysters (30 psi adhesion), encrusting bryozoans; minor abrasion damage.
NAWC MV Transporter	RTV11® + 20% SF1154®	Temperate marine	Repaired in Apr 98 (6 months service) and June 98.

A problem with the initial gearbox installation on the SLICE required the removal of 200 ft^2 of the duplex coating system applied to the port forward pontoon and to the competitor's coating on the starboard forward pontoon. The repair was done with the GE SEA210A®/GE SCM501 C® repair package with an EXSIL2200® topcoat. No issues have emerged from the SLICE application.

The NAWC MV Transporter, which, at 3,500 ft^2, was the largest of the boat demonstrations, required a repair to 30-40 ft^2 of the front of the hull due to delamination of the coating between the epoxy AC paint and the Silgan J-501® tie layer. In April 1998, the first repair, in which the edges were brushed with the GE SEA210A®/GE SCM501C® repair package and the center was coated with the entire duplex coating system including mistcoat, remained intact only along the edges. A second repair was then carried out in June 1998 using the GE SEA210A®/GE SCM501C® repair package over the entire damaged area.

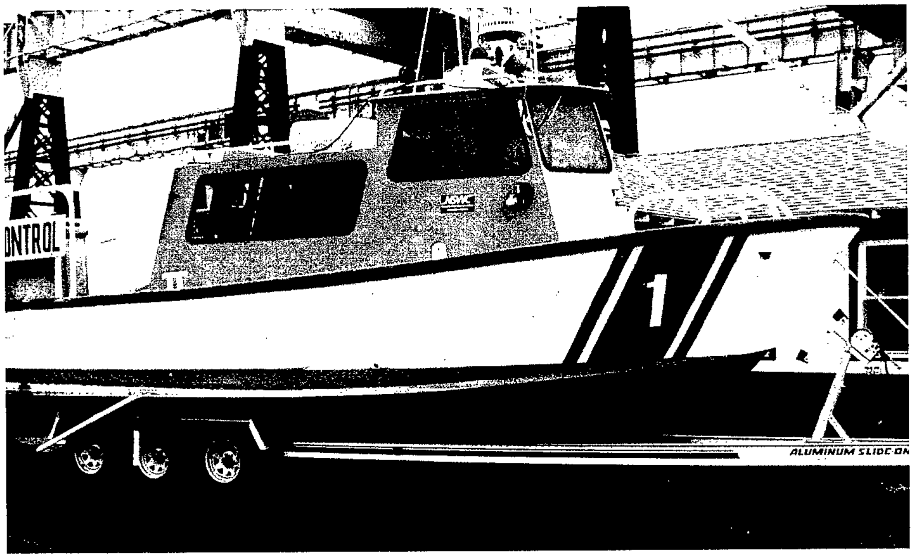

Figure 5-4. U.S. Navy RCB-1 coated with the duplex fouling release coating system using the EXSIL2200® gray topcoat; this boat was coated in September 1996 in Valleelee, Virginia.

Application of the duplex fouling release coating system to power plants in the Great Lakes and New England provided excellent experience with coating applications and fouling release data in cold water and freshwater applications. Although no inspections were carried out on the Ontario Hydro Nanticoke trash racks by the GE fouling release coatings team, discussion with contacts at the site in July 1998 revealed that the coating is in very good condition and exhibits minimal fouling after three and a half years of service. The coatings applied to the Consumer Power D.E. Karn cooling water intake bay continue to be 99% effective against zebra mussels and show no signs of delamination after three and a half years of service. Personnel at the Consumer Power site estimated the annual savings from the patches of duplex coating to be $20,000 and are extremely happy with the performance of the easy release coating systems. Figure 5-5 illustrates the performance of the duplex coating system against fouling on the intake walls and deflecting vanes in the Consumer Power cooling water intake tunnel. The right-hand vanes were not coated with the duplex system and are completely fouled with zebra and quagga mussels.

The application at the New England Power Company's Brayton Point Station brought a new fouling organism to light: the C*repidula* snail. This snail, which digs its shell into the topcoat as it filter-feeds, damages the fouling release topcoat of the system since it exposes Silgan J-501®, which does not have fouling release properties. Even though the snail does not cause delamination problems, the damaged areas showed some macrofouling attachment in the March 1997 inspection. Most of the C*repidula* snails and other fouling organisms observed during the September 1996 dive inspection fell off the walls as the intake bay was dewatered; this showed that the coating's fouling release capability was not completely destroyed by the snail damage. Other than damage from the C*repidula* snails, the tunnels of Unit 1 were in excellent condition. The screenwells exhibited about 20% delamination at the epoxy-Silgan J-501® interface; the extent of damage was attributed to excessively damp application conditions in the intake bays and an insufficient topcoat thickness. The delamination was repaired in February 1998 using the GE SEA210A®/GE SCM501C® repair package on the edges and reapplying the entire duplex coating system to the centers of the damaged areas.

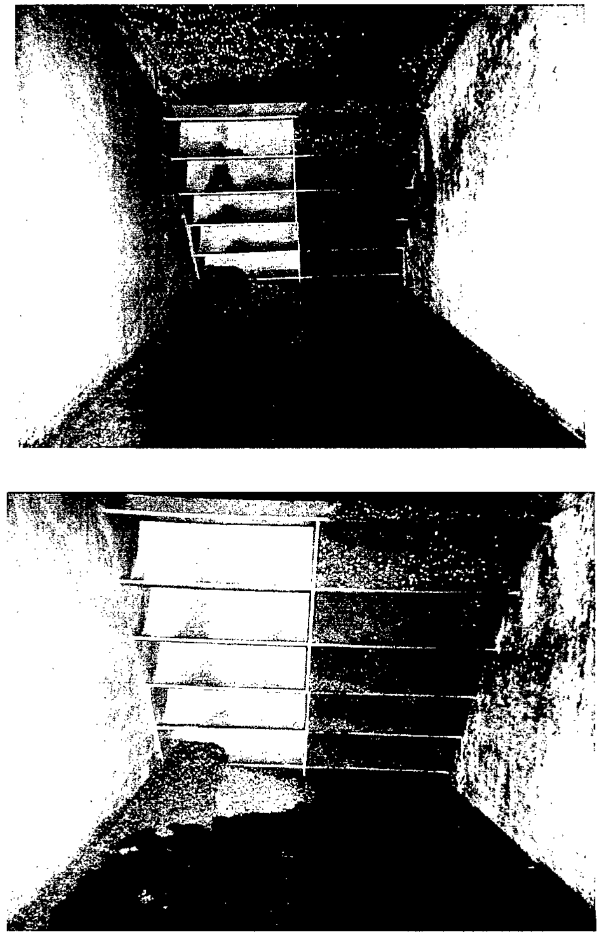

Figure 5-5. Effectiveness of the duplex coating system on intake walls and deflecting vanes in the Consumer Power D.E. Karn Unit #1 cooling water intake, Essexville, Michigan. The right-hand baffles are untreated steel fouled with zebra mussels and quagga mussels.

Table 5-3. Summary of power plant platform inspection results.

Site Description	Topcoat(s)	Water Condition	Fouling and Damage
Ontario Hydro Nanticoke Generating Station Trash Racks	EXSIL 2200® and RTV11®	Cold freshwater	Nov 95: 11 months service. Underwater inspection showed no mussels (quagga or zebra) on either coating. Panels put out in 1996 and 1997. An inspection took place in Nov 96, a diver inspection Apr 97 and inspection in Oct 97: all the coatings held up very well with no mussel attachment.
Consumer Power D.E. Karn Units 1 & 2 Intake Bay	EXSIL 2200® and RTV11®	Cold freshwater	Feb 96: 11 months service. Slime layer, minimal hard fouling; easy removal except in small cavitities in the concrete walls; no abrasion damage. Mar 97: 2 years service. Slime layer, virtually no hard fouling; excellent coating integrity. Mar 98: 3 years service. Slime layer, virtually no hard fouling; excellent coating integrity.

New England Power Company Brayton Point Station Unit 1 Intake Tunnel, Screenwell and Trash Racks	EXSIL 2200® and VOC-free and RTV11® + 20% SF1154®	Cold brackish	Sept 96: dive inspection, some soft foulers, hydroids and blue mussels. Mar 97: 1 yr service. EXSIL 2200® and VOC-free topcoats 10% fouled with *Crepidula* (snails) and hydroids; easily removed; some coating delamination in corners of screenwells. RTV11® +20% SF1154® showed gouging of topcoat by *Crepidula* but good adhesion to J501 tiecoat; 20% delamination of coating in screenwells; tunnels in excellent condition. Patch repair done in screenwells. Feb 98: Inspection by Bridger Scientific (report available); repair additional damaged areas in screenwells.

5.2 Data Assessment

The data presented in the inspection reports and summarized in Section 5.1 are a realistic assessment of the objectives set forth in this demonstration. The primary objective of demonstrating the effectiveness of the duplex silicone foul release coating system over a variety of platforms and environments was accomplished. 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 and type were assessed, and the effect of hull cleaning on boat engine performance was evaluated. Missing information that would have been useful at all locations would have been thorough documentation of ambient conditions (air temperature, relative humidity) during coating application to evaluate the effect of these variables on application quality. The mistcoat layer is particularly sensitive to ambient conditions during application, and the delamination at that point in the coating system might have been prevented with a thorough understanding of the conditions necessary to obtain good adhesion.

5.3 Technology Comparison

GE has developed a repair package for the duplex coating system. The steps used to carry out the repair are illustrated in Figures 5-6 through 5-10. To our knowledge, competing fouling release coating systems do not have packages with which patches of abrasion damage may be repaired.

One advantage of the NRL-GE duplex coating system is its durability and toughness relative to that of existing commercial silicone fouling release coatings. Ice abrasion damage on the U.S. Coast Guard UTB's 41312 and 41393 occurred to a much lesser extent than abrasion damage to a competitor's coating on a nearby 41' UTB. A comparison of the damage to these UTB's is shown in Figure 5-11.

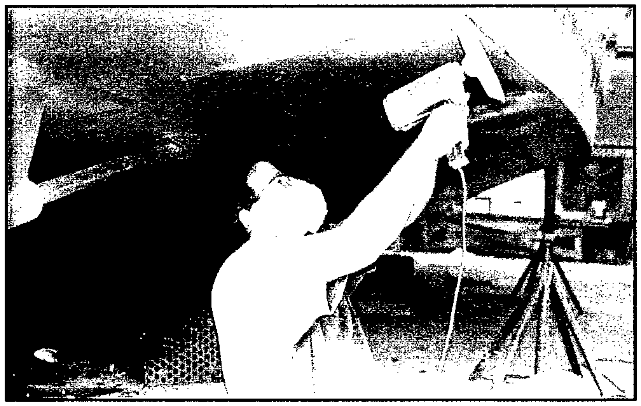

Figure 5-6. Surface preparation of the patches to be repaired on the NRL-GE duplex coating system.

Figure 5-7. Application of fresh AC epoxy to exposed aluminum for repair of the NRL-GE duplex coating system.

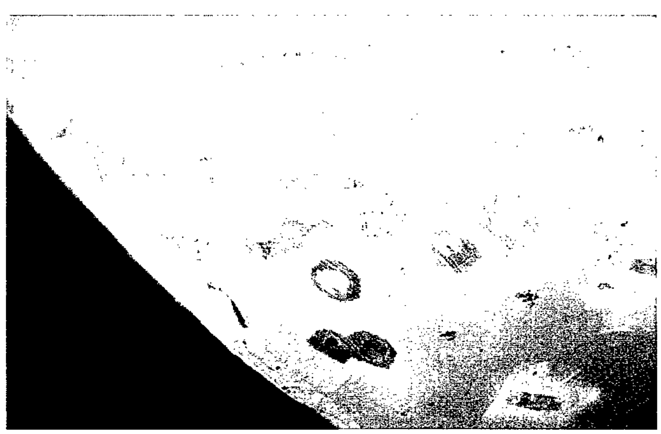

Figure 5-8. Application of adhesive repair package to damaged area of the NRL-GE duplex coating system.

Figure 5-9. Application of toughening tie layer to deficient patches for repair of the NRL-GE duplex coating system.

Figure 5-10. Topcoat applied over patch to complete repair of the NRL-GE duplex coating system.

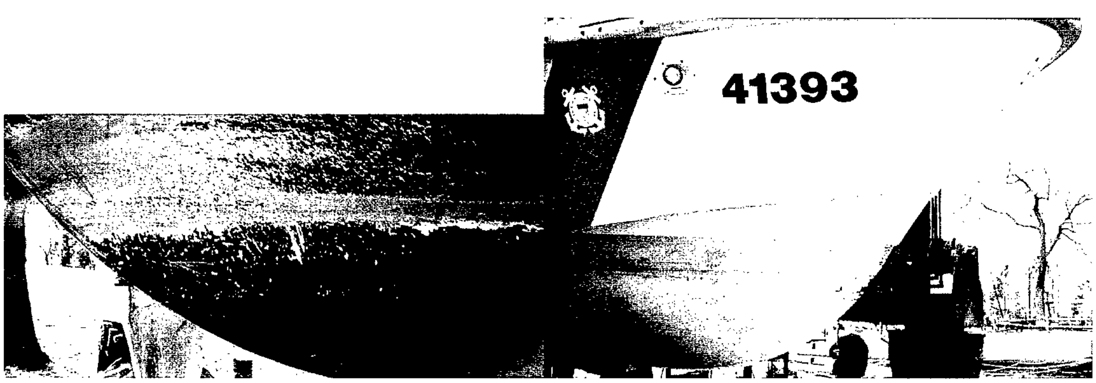

Figure 5-11. Comparison of ice damage to a competitor's fouling release coating (left) and the NRL-GE duplex fouling release coating system (right) on two 41' USCG UTB's.

Figure 5-12 shows the NRL-GE duplex coating system (Exsil2200® topcoat) applied to the ONR/Lockheed prototype (SLICE). Dive inspections of the SLICE compared the performance of the NRL-GE duplex coating on the port pontoons with the competitor's coating (Figure 5-13), but because the SLICE was docked with the starboard side to the dock and macrofouling was reported by SLICE personnel to be less against the dock, the fouling pressure on the starboard (competitor's) side of the boat might have been less than that on the port (duplex coating system) side.

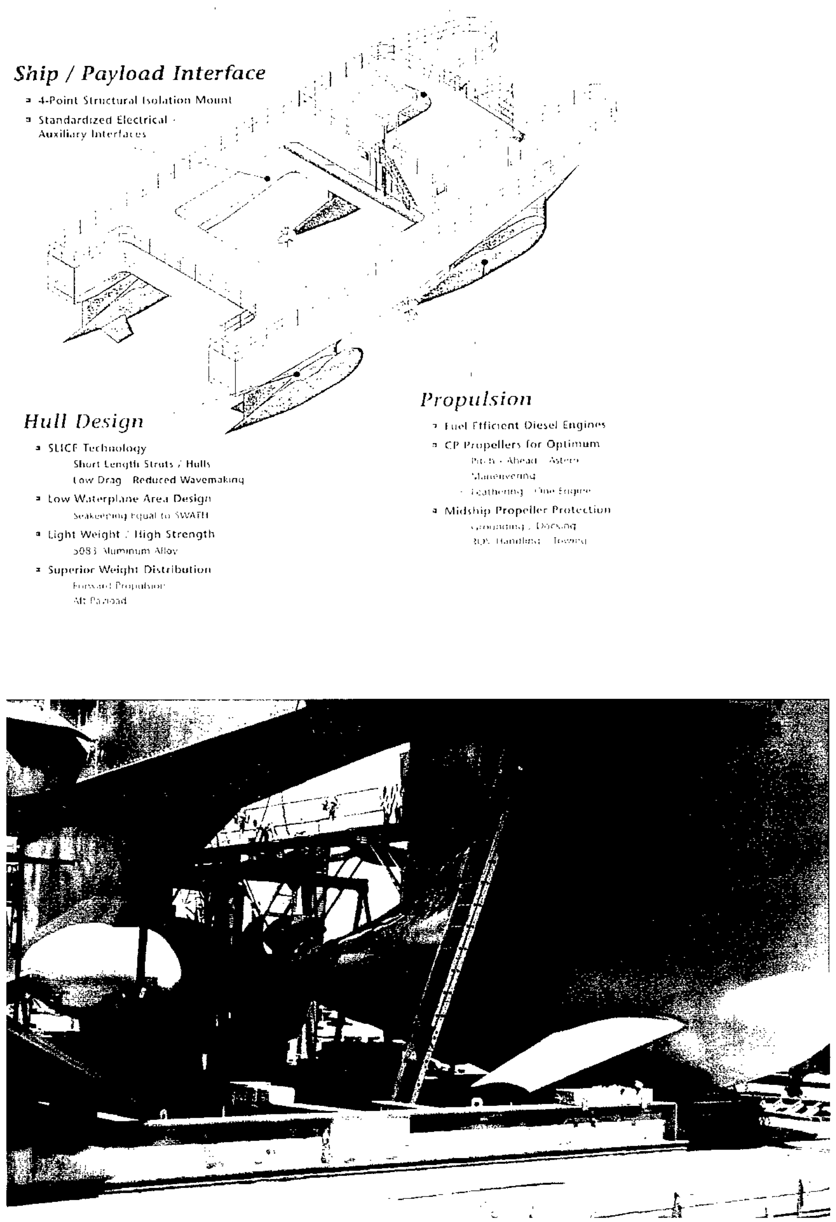

Figure 5-12. Duplex coating (EXSIL 2200® topcoat) was applied in November 1996 to the port hull (pontoon-like supports called pods) of the ONR-Lockheed prototype SLICE.

The vertical biofouling profile in Figure 5-13 showed the following for both the duplex coating system with Exsil2200® topcoat (port pontoons) and Intersleek (starboard pontoons): slime layer of bacteria, algae and diatoms at 2 ft. depth; slime layer, oysters and encrusting bryozoans at 5 ft. depth; and encrusting byrozoans, ascidians and oysters at 12 ft. depth.

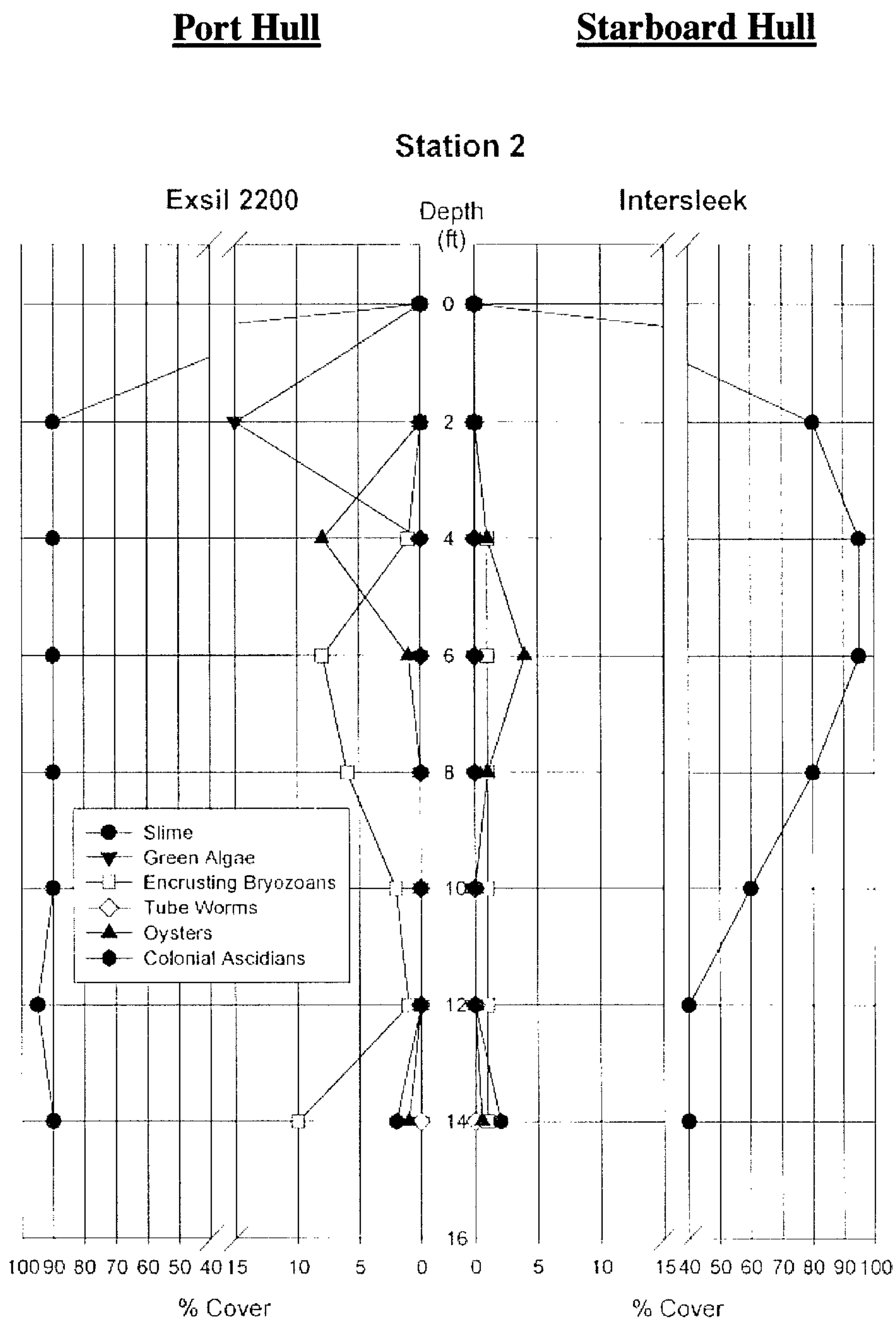

Figure 5-13. Vertical biofouling profile observed on SLICE hulls at Station 2 (forward location).

The barnacle adhesion test (ASTM D 5618-94) was developed by FIT during this project to enable rapid and multiple measurements of barnacle adhesion strength in shear to a coating under field conditions. A hand-held force measuring device is used to apply a force to the base of a barnacle at a rate of about 4.5 N/s (1 lb/s) until the barnacle becomes detached. The force should be applied parallel to the surface, and only live barnacles growing on intact portions of the coating and not settled on weld seams or in direct contact with other barnacles should be tested. If more than 10% of the barnacle base plate is left attached to the substrate, the test is deemed void. The barnacle base is measured in four directions (0, 45, 90 and 135 degrees) and the base plate area, A, is estimated from an average base diameter, d_a using the formula $A = \pi d_a^2/4$. The shear strength is then calculated by dividing the force for removal by the base plate area. Figure 5-14 shows barnacle adhesion measurements using ASTM D-5618-94.

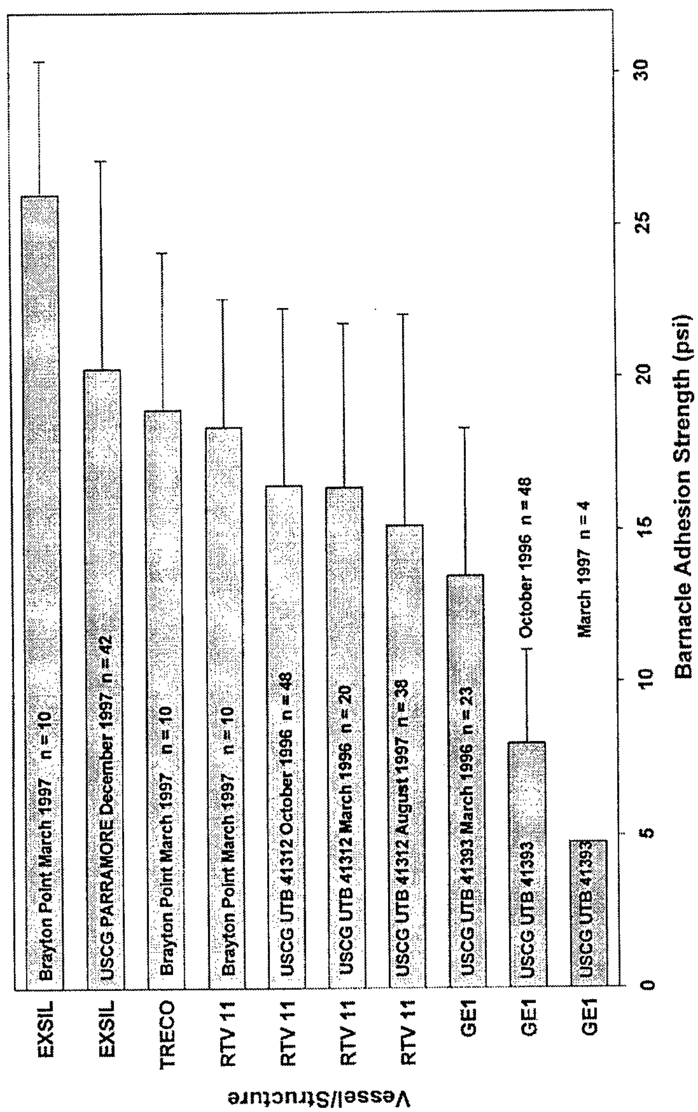

Figure 5-14. Barnacle adhesion data measured using ASTM D 5618-94.

6. Cost Assessment

6.1 Cost Performance

Table 6-1 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 UTB's, the cost assessment is based on the application of the duplex coating 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 haulout costs, surface preparation, application of the duplex coating system, and the disposal of blasting grit and waste generated during application of the system.

Table 6-1. Expected operational costs for the duplex coating system as applied to a 41' USCG UTBs

Direct Process Cost				**Environmental Activity Costs**		**Other Costs**	
Start-Up		Operation and Maintenance					
Activity	Cost ($)	Activity	Cost ($)	Activity	Costs ($)	Activity	Cost ($)
Site preparation: Boat haulout and storage	260	Labor to operate equipment (contractor application fee)	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 (paints, solvents, etc.)	2,185	Environmental management plan; development and maintenance	None	Worker injury claims and health costs	None
Project manage-ment	3,550	Equipment main-tenance	None	Reporting require-ments	None		
Operator training	None	Utilities	None	Test/analyze waste streams	None		
Equipment purchase	None	Management/treat-ment 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						

6.2 Cost Comparisons to Conventional and Other Technologies

Silicone fouling release paints provide a unique, non-toxic solution to the biofouling problem. The use of copper paints is under severe environmental pressure in many parts of the world. However, commercial acceptance of the fouling release approach to biofouling control demands not only comparable performance but competitive life-cycle costs for installation, maintenance and disposal compared to existing technologies.

For purposes of this report, life cycle costs for silicone fouling release coatings will be 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 tie layer and topcoat components and the extra labor required to apply the five-coat system (2 AC's, mist-coat, tiecoat, topcoat) compared to the three or four coats required for copper ablative systems (1 or 2 AC's, 2 or 3 topcoats). Maintenance costs for these coatings are expected to be comparable in that each system will require periodic cleaning to remove slime films and accumulated macrofouling. 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 (SCAMP). For larger vessels, power wash cleaning is expected to be less costly.

The effective life of a typical copper ablative coating system is generally considered to be three to five years. The silicone coatings evaluated in this program, when successfully installed, have experienced up to four years of service with no sign of deterioration in performance. A service life of five to seven years is well within the realm of possibility for these coatings, which typically withstand outdoor weathering for up to 20 years.

Another cost advantage of silicone coatings over copper ablative systems is with regard to the disposal costs associated with spent blasting media when the coating is removed. Silicone contaminated grit can be disposed of in a non-hazardous landfill, while in some areas of the world, copper contaminated grit must be disposed of as contaminated waste at a premium cost.

A cost breakdown for materials, labor, maintenance and removal for these two systems is presented in Table 6-2. 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 and copper ablative paints may be comparable and if the actual service life of silicones exceeds five years, these easy-release coatings may actually be less expensive than copper ablative paints on a life-cycle basis.

Table 6-2. Approximate Life Cycle Costs of Silicone vs. Copper Ablative Paints[a]

Item	Frequency (Life Cycle)		Cost/ft² (Life Cycle)	
	Cu- Ablative	Silicone	Cu - 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 contract.

7. Regulatory Issues

7.1 Approach to Regulatory and End-User Acceptance

Pursuit of regulatory acceptance was carried out at each demonstration site; a complete list of state and federal regulations pertaining to biofouling control measures is shown in Table 1-2. GE has applied for and obtained an exemption from the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA, Public Law 95-396). The duplex coating system has been applied in several states and has 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 coating system has not been exempted from application in any state in which a demonstration was carried out for this program.

The U.S. Coast Guard has certified the duplex fouling release coating system with the RTV11® + 20% SF1154® topcoat for use on boat hulls, and GE is currently pursuing qualification of the system by the U.S. Navy.

8. Stakeholder/End-User Issues

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 trained personnel; the repair package is very effective if applied properly.

The duplex coating system was developed primarily for U.S. Coast Guard boat hulls and U.S. Navy boats. The topcoats used in the system are thus available in limited colors (white, gray, blue, and clear). Improvements in surface aesthetics compared to traditional marine paints have not been addressed in this demonstration project. Technology to remediate these deficiencies would be a benefit of an alliance with a marine paint company.

The components of the duplex system are not currently available in quantities less than five gallons. Once catalyzed, these materials cannot be reused. For some applications, packaging of smaller quantities would be desirable.

The availability of Wacker's Silgan J-501® tiecoat is an issue because this material is no longer being manufactured due to the extremely low demand for the product. Without it or an equivalent material, the duplex coating system cannot be applied. The possibility of licensing from or a special agreement with Wacker Silicones is being investigated, as well as alternate technologies for a toughening tiecoat.

9. Technology Implementation

9.1 DoD Need

The Department of Defense utilizes marine vessels in every branch of service; it is estimated that the U.S. Coast Guard has 1,445 vessels in 62 classes, the U.S. Navy has 4,760 ships in 158 classes, and the Army uses 334 vessels in 23 classes[15]. Leachate from the ablative copper AF paints currently used on these ships is responsible for 62% of the estimated annual copper mass loading within twelve nautical miles of those vessels[15]. The use of the non-toxic duplex silicone fouling release coatings demonstrated in this ESTCP program would eliminate the environmental impact of the toxic copper released from DoD vessel hulls.

9.2 Transition

No formal plan of technology transition has been developed, but the first commercial transition will likely be to the U.S. Coast Guard, for which the duplex coating system has been certified for use. GE is developing next-generation silicone topcoats under DARPA contract N00014-96-C0145 and is seeking qualification of duplex coating system for use by the U.S. Navy. The duplex technology is available now for use on small aluminum-hulled vessels and is ready for transfer to an OEM; in fact, duplex coating system application to OEM vessels would provide a more controlled application environment and guarantee optimum performance of the coating.

The most significant issues for implementation are the establishment of a market channel for the duplex coating system and the resolution of Silgan J-501® supply problems. These issues could be resolved within a year if market demand for a silicone foul-release product were strong enough. The duplex fouling release coating demonstration was carried out by NRL, GE-CRD, NSWCCD, FIT, SUNY-Buffalo IUCB, and Bridger Scientific and has had support from GE Silicones. Commercialization of the duplex coating system will 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 license discussion for technology transfer of the duplex coating system.

10. 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.)
- Understanding of the importance of project management
- Ability to repair abrasion damage and delamination of the coating
- Necessity of careful surface preparation for good adhesion
- Pigmentation of RTV11® and EXSIL2200® to gray

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Appendix B: Acronyms

EHS	Environmental, Health, and Safety
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
NAWC	Naval Air Warfare Center
NCCOSC	Naval Command, Control and Ocean Surveillance Center
NEPCO	New England Power Company
NRL	Naval Research Laboratory
NSWCCD	Naval Surface Warfare Center, Carderock Division
OSHA	Occupational Safety and Health Administration
SUNY	State University of New York
USCG	United States Coast Guard
USN	United States Navy
UTB	Utility Training Boats
VOC	Volatile Organic Compounds