

Development of Corrosion Resistant Energy-Curable Coatings

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Development of energy-curable acrylate coatings for marine paint applications is reported in this article. Submarine ballast tank repair where coatings with six-year life cycles required was the target application. During field trials successful systems that use visible-light photoinitiators were shown to affect deep cure. A recent modification lets these coatings be cured with UV LEDs. UV light emitting diodes (LED) were compared to conventional light sources for curing acrylate formulations. The results indicate that UV LEDs are acceptable alternatives to conventional commercial light sources for various applications.

Introduction

Acrylate-based coating formulations cured with visible light to be used for corrosion protection on steel surfaces have been developed and optimized.^{1,2,3}

The results indicate UV LEDs are acceptable alternatives to conventional commercial light sources for various applications.

The successful coatings consist of an acrylate forming matrix binder, corrosion inhibitors and other fillers, plasticizers, photoinitiators and other additives. The coatings exhibit good adhesion to metal, hydrophobicity and impact resistance. They also perform well under long-term saltwater immersion and salt fog exposure. Improvement in coating adhesion achieved through the use of plasticizers

and silane adhesion promoters results in better corrosion protection.

Field trials were conducted in which these coatings were used as repair paints for submarine ballast tanks. After 10 months of service, the coatings had performed well and provided good rust protection, evidence of little adhesion loss or blistering. This technology was developed under a Phase II Navy⁴ contract as repair paints to replace or augment current two-part epoxy systems. Broader application of the technology to other metal surfaces where corrosion protection is a necessity is anticipated.

Background

Metal paints and coatings that protect from corrosion form a large market and have numerous industrial, commercial and military applications. Generally, coating technologies based on epoxy, alkyd, urethane and other chemistries give the best end performances. However, a problem associated with each is that they are solvent-based and release VOCs (volatile organic compounds). Reducing VOC emission is a widespread target and is particularly so in the military.⁵ Modification of existing coating chemistries and new developments in waterborne, high solids, UV cure and other coating methods have resulted in more “environmentally friendly” coating systems. Energy-cured coatings, in particular, have made a major impact on the field. Formulations that can be dried without emitting VOCs into the

atmosphere are, in large part, responsible for the rapid growth of the industry.⁶

Corrosion is a huge problem for the U.S. Navy. The Government Accounting Office (GAO) estimates that in peacetime the U.S. Navy spends up to 25% of total fleet maintenance budget on corrosion prevention and control.⁷ The U.S. Navy is not unique in this regard as in 2001 GAO estimated corrosion costs for all military systems to be as high as \$20 billion annually.⁸ The service life for most paints and coatings now used at sea is less than five years, but the Navy has aspirations to more than double this time (i.e., an 11-year life cycle).⁹ The submarine ballast tank is continually subjected to harsh conditions. It is exposed to saltwater in an ocean going boat and suffers substantial corrosion stress because of it. A two-part epoxy/amido-amine modified polyamide system (U.S. Navy fleet specification MIL-P-24441)¹⁰ is currently used to paint and repair corrosion as it occurs. The protection afforded by paints of this type is due to a high degree of crosslinking and good adhesion to metal, that significantly delays the onset of corrosion. The paints, however, also have problems:

- They are solvent-based and release unpleasant odors when they are used.
- Take a full day to cure tack-free and up to seven days to achieve full cure.
- Are two-part systems, requiring accurate on location mixing.
- Have a pot life of a few hours after mixing.
- Do not cure well at low temperatures or under high humidity.

Light-cured coatings obviate many of these issues. Energy-cured formulations are typically more than 90% solids formulations; cure completely in a few minutes; require no on site mixing; have a long, though not infinite, pot life; and cure well under a broad range of temperature and humidity conditions.

A corrosion protective repair paint that is cured using broad-spectrum

near-UV and visible light has been developed. This corrosion protective repair paint has undergone successful field-testing in ballast tanks of nuclear submarines.^{1,2,3}

Results and Discussion

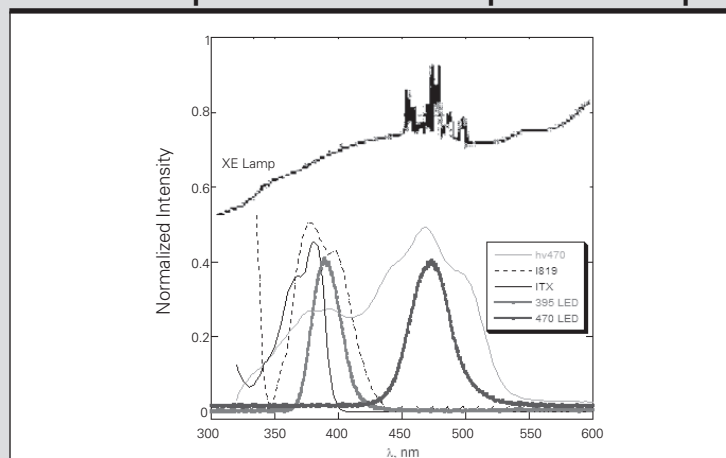
There is no tolerance for mercury on board of Navy ships, so mercury vapor additive lamps are forbidden. Because visible light achieves greater depth of cure in thick, pigmented coatings, near UV/visible light sources were used to harden the acrylate-based anti-corrosion paints. Because curing is an on-site process, it requires a light source that can be held physically close to a repair patch area, often in a confined space. Xenon Corporation RC-740 and RC-500B light sources were used successfully in laboratory paint development and field trial settings and each gave a good depth of cure in the highly pigmented acrylate coatings. But both require a heavy, awkward power supply and large light curing heads, so except for demonstration purposes, neither was

useful in the field. Essentially this became a showstopper for the target application.

LED sources can be made energy efficient and cool with power requirements only slightly higher than the average flashlight. Recently available narrow-band near-visible UV LEDs¹¹ have been used to establish the practicality of acrylate-based anti-corrosion coatings in Navy applications. LED devices are also solid-state sources and contain no mercury. Some have recently come on the experimental market with outputs centered at 365 and 395 nm having total emission ranges of only 30-40 nm. In contrast, conventional gas plasma light sources emit over a relatively wide spectral range. Since most photoinitiators do not absorb over the entire range of a lamp's emission, much of the energy output of the lamp is wasted. In theory since LEDs emit over a narrow wavelength range, one can pick an emission source whose spectrum fits the absorption

FIGURE 1

Schematic representation of the spectral overlap



Schematic representation of the spectral overlap between the absorbance spectra of commercial photoinitiators—*isopropylthioxanthone (ITX, Albemarle Corp.), Irgacure 819 (Ciba Specialty Chemicals), H-Nu 470 (5,7-diiodo-3-butoxy-6-fluorone, Spectra Group Limited Inc.)*—and selected LED emissions. The selectivity of LED emissions is contrasted to the broad-spectrum emission of the RC-500B lamp,¹⁴ shown above other spectra.

TABLE 1

Typical formulations

Formulation Component	Amount, weight %
Acrylate resin blend (includes film forming oligomer, oligomer modifier and diluent monomer)	30-75
Filler (corrosion inhibitors, extenders, plasticizers)	25-70
Additives	1-5
Photoinitiators	2-4
Amine coinitiator	3-10

profile of the photoinitiator used for the photopolymerization process (Figure 1). LED sources are also small. In theory, they could be used easily in cramped quarters and they are competitive in price.

In this paper, the development of formulations for visible-light curable corrosion resistant paints and performance in field trials will be discussed. The paints will also be shown to acceptably cure with LED sources.¹²

Visible-Light Curable Anti-Corrosion Paint

Originally, visible-light corrosion protection repair paint was developed under the auspices of the U.S. Navy SBIR (N00167-96-C-0046). It was based on acrylate formulations that are cured using visible light.^{1,2,3} To our knowledge, this is the first energy-cured solution for an in-field curable metal protection coating.

Such a coating has to exhibit excellent adhesion to a substrate of choice and, in the case of metal coatings, vigorously resist corrosion. The properties are interconnected since resistance to corrosion cannot be maintained following adhesive failure. If corrosion begins under a seemingly adhered coating, adhesion will be compromised at its site.

The selection process for the components of the acrylate-resin blend are described elsewhere. Upon cure,

this blend must stick to metal and exhibit good mechanical properties. Acrylates always shrink (become more dense) when polymerized inducing a reduction in volume laced by a stronger, shorter bond.¹³ Accordingly, some degree of stress is unavoidable despite the most careful resin selection. Minimization of shrinkage of the resin leads to less stress residing in the coating. When the coated plate is immersed in salt water, this results in electrolyte uptake. If the coating does not inherently have mechanisms of stress relaxation and the resin strain increases become high, the coating will delaminate in order to relieve that strain. Several different routes minimize the shrinkage:

- Balance the resin/pigment (maximizing pigment volume concentration, PVC, where possible).

- Vary cure parameters to avoid over cure.
- Utilize fillers/resins capable of coating plasticization.
- Utilize dark pigments (both anti-corrosion fillers and/or dark colorants of various nature), thus reducing light penetration and degree of crosslinking.
- Utilize various adhesion promoters.

Formulations

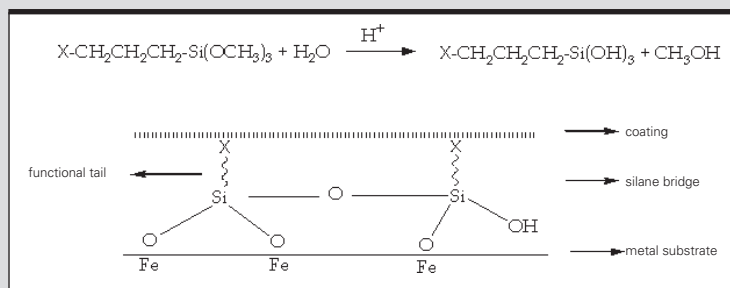
The makeup of the typical formulation for an acrylate-based corrosion resistant coating is shown in Table 1.

Resins

Acrylate-resin blends consist of several oligomers (film forming oligomers and oligomer modifiers) as well as reactive diluents. Epoxy-acrylate oligomers are the best film forming oligomers because they form hard, strong films with good adhesion to metal having excellent hydrolytic stability and chemical resistance. Acrylic acrylates were the modifier oligomers of choice since they offer a low level of stress coupled with improved adhesion to metal. 2-phenoxyethyl acrylate is one of the preferred monomeric diluents because it is a good solvent and it offers good adhesion to metal likely because of the polar nature of the phenoxy group.

FIGURE 2

Chemical structure of a functional silane, its hydrolysis and covalent bond formation with the substrate



Fillers

The corrosion resistance of any clear (unfilled) acrylate coating is poor. Fillers provide most of the protection. Corrosion protection can be provided through various mechanisms. These include barrier fillers that force a circuitous pathway through the binder as water is on its way to the substrate (micaceous iron oxide, glass and aluminum flake, etc.), sacrificial cathodes—a less noble metal dissolves in place of metal under protection (Zn dust) when water penetrates, or metal surface passivation-reinforcement, repair and formation of metal oxide film (Zn, Ca, Fe, Sr phosphates, molybdates, chromates, leads, silicates, borates, etc.).

Some fillers can act simply as extenders helping to achieve an optimum pigment volume concentration/critical pigment volume concentration (PVC/CPVC) balance. At times, a synergy can result between specific extenders and anti-corrosive pigments.

Additives

Besides ensuring defoaming, pigment wetting, dispersion, film flow and leveling during application, specific additives such as adhesion promoters can significantly improve coating adhesion to steel.

Photoinitiators

In energy cure context, the photoinitiator is where the action starts. A photoinitiator blend was used to achieve depth of cure in relatively thick, highly filled coatings and tack-free surface cure when exposed to an intense visible-light source.

Light Source

The sources selected for the trials had spectral outputs of >370 nm.¹⁴ An extremely powerful (1,500W) pancake design Xenon RC-740 “A” proved to be an excellent choice under laboratory conditions. This affords single exposure cure of highly filled thick coatings (4-7 mil) in 40 sec for a 4x6 inch area

when the light source is positioned 1.5" away from the substrate. However, this lamp requires a bulky external power supply and cooling apparatus and is highly impractical for use inside a ballast tank. A more portable and less powerful (500W) linear design Xenon RC-500B “A” was a little less odious. Single exposure cure for a 3x5 inch area can be achieved in 2 minutes when the light source is positioned ~ 1" away from the substrate. The RC-500B power supply is much smaller and the lamp cooling is internal. Coatings cured by both lamps under the conditions described display similar dry and wet (in service) adhesion characteristics.

Sample Preparation and Testing

The samples used as coatings were cured on 3x6 inch ground steel Q-panels that had been pre-cleaned according to the accepted procedure.¹⁵ Formulations were brushed on. While it was being cured the panel was positioned on a permanent magnetic chuck that also served as a heat sink to simulate the thick walled ship hull. Single coats were 4-7 mil thick, and a second coat was applied immediately after the bottom coat was cured. Adhesion and impact resistance tests on the dry (prior to service) coatings were performed according to ASTM D3359 and D2794, respectively. After painting the backside of the panel with rust protecting enamel and sealing the edges with MIL-P-24441 two-part epoxide

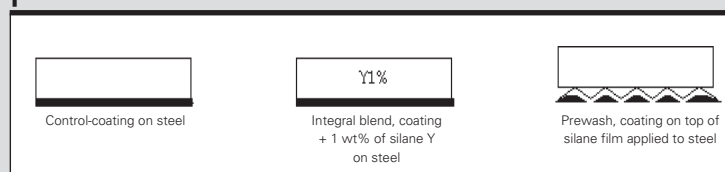
paint static salt water immersion (SWIM) tests were carried out. The panels were immersed in 2.5 wt% “Instant Ocean” prepared by dissolution in tap water at room temperature. The coatings were checked periodically (every two weeks) for appearance and blister formation. Salt fog (SF) exposure was conducted according to ASTM B117. In both tests the coatings were usually X-scribed according to a widely accepted practice. For both SWIM and SF, panel testing was terminated following a predetermined number of days or hours, respectively. Upon termination, the panels were scratched with a spatula to remove any loosely attached coating revealing the underlying steel substrate and evaluated in terms of the amount of adhered coating remaining (% area) and the amount of rust formed (% area) for both SWIM and SF.

Silane Adhesion Promoters

Silane coupling agents (trialkoxiesters, Figure 2) are widely used for adhering hydrophobic small molecules to surface hydroxides such as glass or silica, and were recently introduced for corrosion-inhibiting pretreatment for metals.¹⁶ The silane film acts as the tie-coat between the metal substrate and the protective coating. Given high-surface energy of metal substrates, some silanes may also be bonded “upside down” with the functional tail X forming a weaker bond (i.e., a hydrogen bond) with a metal substrate. This may also promote

FIGURE 3

Methods of incorporation for silane adhesion promoters



adhesion to a degree, though it is not likely to be as hydrolytically stable as the covalent bond previously described.¹⁶

Silanes can be used to promote adhesion in at least two ways. A small amount of a functional silane can be integrally blended directly into the formulation without pretreating the surface. Alternatively, the metal surface may be primed with a dilute solution of a functional silane in an appropriate solvent, most often mildly acidic water or a water/ alcohol mixture (prewash).¹⁷ Both are shown schematically in Figure 3.

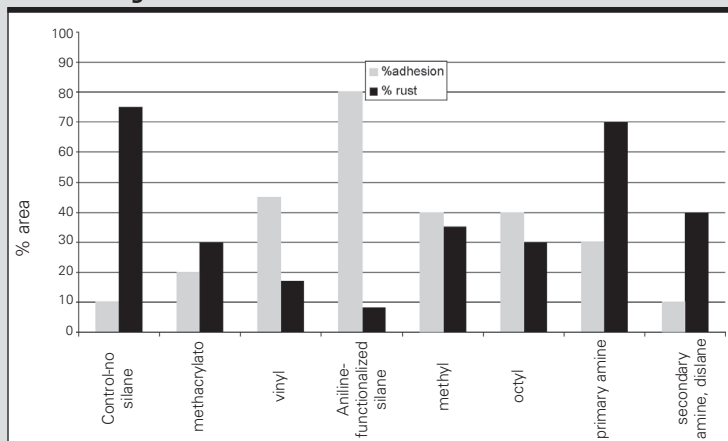
In this study, a variety of silane adhesion promoters were screened varying in the nature of the silane functional tail, silane concentration (integral blend only) and incorporation method. For more efficient screening, a large number of clear coatings were formulated, cured and tested in SWIM. As indicated, clear acrylate-based coatings offer no significant corrosion protection in SWIM. In fact, these coatings blister and develop undercoat rust in a matter of days, thus making silane adhesion promoters' effects more pronounced. The results are shown in Figures 4A, 4B and 4C.

Aniline-functionalized silane from Witco Organosilicones Group outperforms every other silane when incorporated at 1wt% as a part of an integral blend. It is not surprising that methacrylato-functionalized silane affords the best performance when used in a pre-wash method.

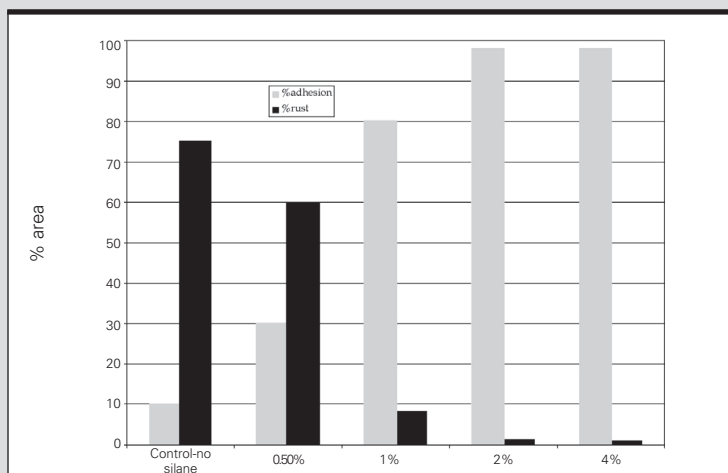
The integral blend method offers improved performance for about the first 50 days of SWIM, Figure 5. The benefit, however, decreases with time. In contrast, pre-wash maintains the adhesion at least ~ 95% through 4 months of SWIM. Thus, if application conditions allow for the extra surface pretreatment step, prewash with a dilute solution of silane coupling agent is recommended. However, the fact that the integral blend may perform as well

FIGURES 4A, 4B, 4C

Effect of various functional silanes addition on the performance of clear coatings in saltwater immersion



3 weeks saltwater immersion performance of the integral blend of aniline-functionalized silane as a function of its concentration



3 weeks saltwater immersion performance comparison between integral blend and pre-wash method of silane incorporation

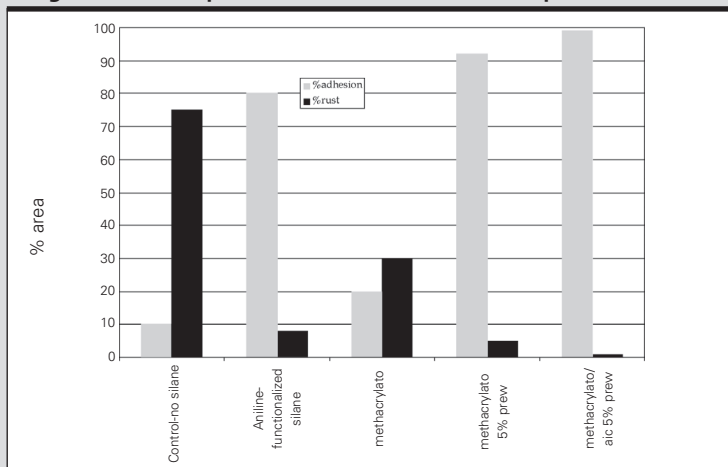
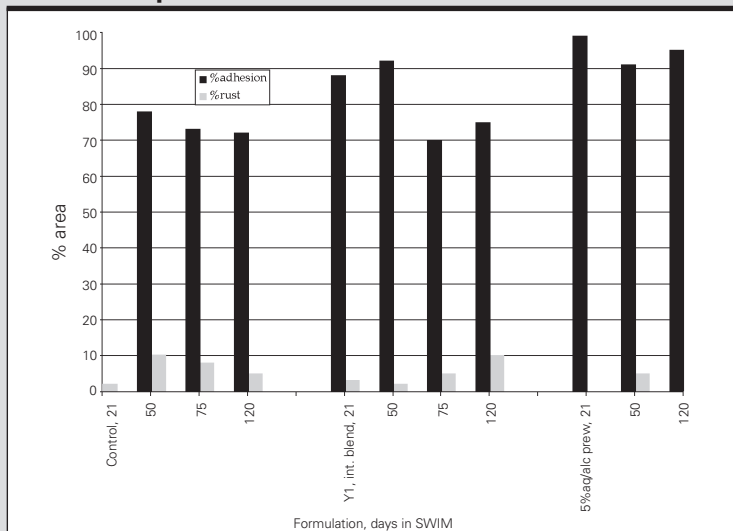


FIGURE 5

Saltwater immersion performance of pigmented coatings incorporating silanes via both integral blend and pre-wash



offers more flexibility in silane application as an additive to the corrosion resistant coatings.

Selection of the Anti-Corrosion Filler

Corrosion protection through the introduction of corrosion resistant fillers is generally achieved through anodic cathodic passivation.¹⁸ If ionic filler particles are present in the coating, they dissolve (albeit slowly) in moisture as it passes through the coating. Ions that form tend to accumulate at the metal/

coating interface. With time they increase in concentration, thicken and naturally repair the oxide film that is formed. Generally, rust film is loose and porous, so it does not protect the underlying metal from further corrosion. An oxide film strengthened by incorporating fragments of the corrosion resistant filler effectively passivates the steel surface, preventing electrolyte access to the metal, degradation and transfer of iron ions into solution.

Even though an optimum value for PVC/CPVC ratio is somewhere

around 0.6-0.7, these coatings are extremely viscous and cannot be painted with a brush. Thus, a broad filler evaluation at a PVC/CPVC level of 0.46 was conducted.

Plain and surface treated zinc phosphate provides the best long term performance in SWIM. Salt fog testing also showed that strontium zinc phosphate and zinc phosphates remain the optimum. Incorporating aniline-functionalized silane at 1 wt% improves both SWIM and SF performance for all corrosion inhibitors tested. For example, the SF performance of strontium zinc phosphate can be boosted to 500 hrs., (maintaining the same numbers for % adhesion and % rust previously observed for 200 hrs.) when the silane integral blend is tested.

Hare had previously reported the synergistic effects of a Wollastonite extender on the performance of coatings containing zinc phosphate¹⁹ due to its basic nature and acicular shape leading to coating reinforcement. (Wollastonite is a naturally occurring calcium metasilicate.)

A 50/50 (by weight) 10WC Wollastocoat/surface-treated zinc phosphate mixture (Formulation B, Table 3) offers a significant benefit in adhesion/corrosion protection compared to when these same materials are used individually at the same PVC/CPVC (Formulation B vs. J0806 or D). See Figure 6. Better results are achieved at a

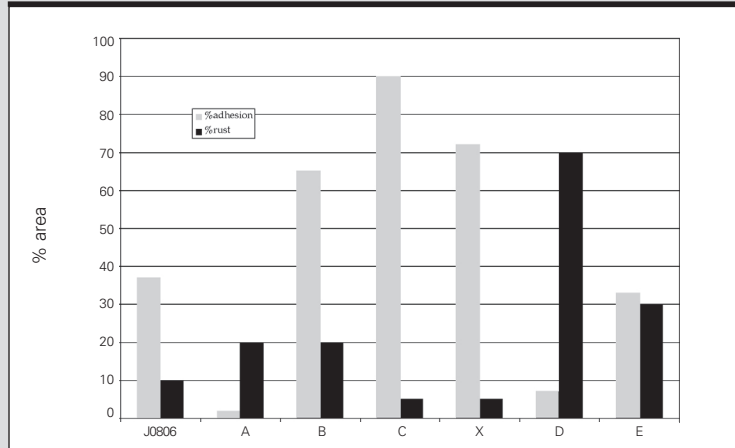
TABLE 3

Range of formulations containing combinations of zinc phosphate and Wollastonite

Formulation, wt%	J0806	A	B	C	X	D	E
Resin	59	75	60	40	50	60	60
PhosguardJ0806	41	12.5	20	30	25	—	—
10WC Wollastocoat, methacrylate surface functional	—	12.5	20	30	25	40	40 (10AS) Amino Functional
PVC/CPVC	59	75	60	40	50	60	60

FIGURE 6

Salt water immersion performance comparison (120 days) of coating formulations containing various amounts of Wollastonite



Formulations are presented in Table 3

PVC/CPVC ratio higher than 0.5 (Formulations A, B vs. X, C), but these are limited due to the lack of brushability.

Addition of 1 wt% of aniline-functionalized silane significantly improves both SWIM and especially SF performance (Figure 7).

Field Trials

Visible-light curable anti-corrosion paint formulations that displayed good corrosion protection under laboratory testing (SWIM and SF), were used in field trials that were conducted inside the ballast tanks of submarines. The coatings were formulated and tested as repair paints. Field trial evaluation included: how the paints “handled,” the overall process of curing with a hand-held pulsed Xenon visible light source, and how the coatings performed as corrosion protection materials under long term open sea service conditions. Field trial tests were conducted at the U.S. Navy Trident Refit Facility, Bangor, Wash.

Surface preparation is quite important for coating performance. Rusted and/or damaged repair patch areas were cleaned

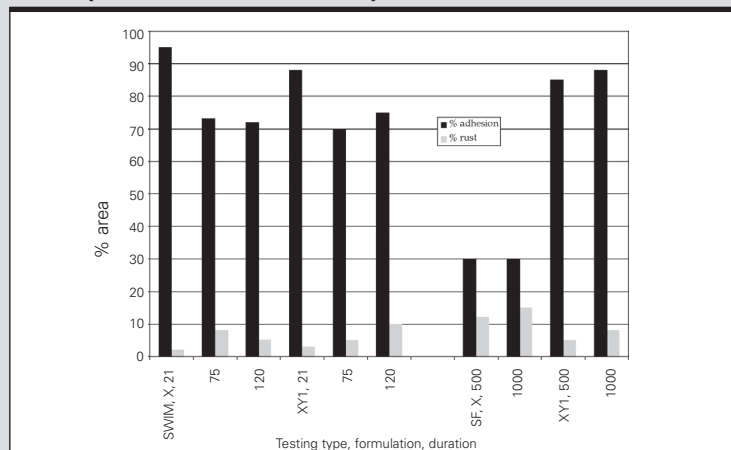
and prepared. The old paint was removed using a needle gun and/or sand grit blasted to near “white metal” (very clean surface) followed by wiping with solvent to remove grease. The paints were then brush applied in the range of 4-7 mils. The U.S. Navy requested 5"x6" patches to be repaired, but due to the RC-500B

linear bulb geometry, it is practical to cure a rectangular area of only 10x30 cm with the per single exposure with this light source. Thus, to cure 5"x6" patches during trial the necessary area was covered by curing with separate overlapping two minute exposures. A second coat was then applied and cured similarly. To prevent worker fatigue, standoff supports are necessary for the operator to lean on the wall with the light head. The presence of such standoff supports dictated a cure distance of 2 cm for both field trials and lab development work.

Three field trials were conducted over a three year period. Generally, the paints handled well in terms of viscosity and “brushability” and adhered to the steel surfaces with little or no sag. The ballast tank with its beams, corners and tight spaces is a difficult place for anyone to move around in, especially with equipment of any sort. We estimated that about 70-80% of the ballast tank could be painted with our current technology. This was acceptable to the U.S. Navy, but must be improved.

FIGURE 7

Salt water immersion (120 days) and salt fog (500 and 1,000 hrs) performance comparison of coating formulations containing various amounts of Wollastonite after 1% aniline-functionalized silane (formulations marked Y1) has been added



Formulations are presented in Table 3

FIGURE 8

Visible-light cured corrosion resistant paints on the submarine ballast tank walls



Needle gun surface preparation (bottom), immediately after cure (middle), 9 months of service (top)

The critical question is the performance of the paints under actual field conditions. Fortunately, the third field trial occurred on board of the same submarine as the second field trial. Repair patches could be evaluated that had seen about 10 months of service in the open seas. Each of the patches of the various visible-light curable anti-corrosion paint modifications showed good adhesion, remaining fully intact regardless of whether they were cured directly on metal or on a pre-applied Navy paint surface (Figure 8). Paints cured with visible light provided good corrosion resistance and only minor rust spots formed inside a few patches. There was also very little blistering.

Cured-paint patches continued to be intact and maintained good corrosion resistance through 33 months of service (Figure 9).

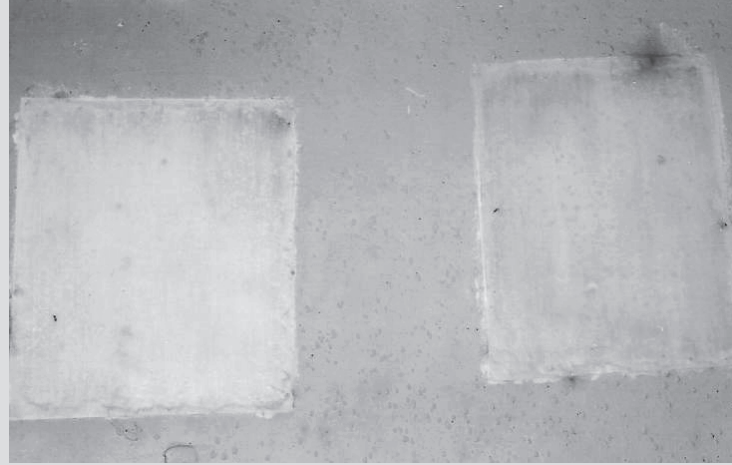
Curing Corrosion Resistant Paints with LED Light Sources

Newly available LED sources are lighter and more compact. See Table 4.

The emissive power output for the commercial off-the-shelf device Clearstone Tech CF1000 power supply,

FIGURE 9

Visible-light curable corrosion resistant paints on the submarine ballast tank walls after 33 months of service



5.4W 395 nm LED head is comparable to that of RC-500B¹⁴ (Table 5). It is conceivable that a light meter device measuring in the range of 250-400 nm is favoring the LED, since almost all of its radiation is emitted at 395±15 nm, while the Xenon source emits its energy across the near UV and visible spectrum (Figure 10).

Unlike RC-500B, which has a rectangular footprint, the CF1000 emits as a round source. A larger cure distance is necessary with the LED head to avoid a central “hot spot” (Figure 10). Uniform acceptable cures over an area of about 10x10 cm can be achieved at 12 cm.

Therefore, at the current use conditions, 12 cm distance for the CF1000 LED head and 2 cm distance (field trials) for the RC-500B, the latter provides higher emissive output.

In order to achieve acceptable cures of the visible-light curable anti-corrosion paint with the LED head, the paint’s photoinitiator package had to be modified. The modified paint was cured up to 150 µm thick in about 2-2.5 min with the source held 12 cm from the surface.

The cure afforded by the RC-500B and CF1000 was tack-free for the original and modified version of the

TABLE 4

Dimensions of portable sources

Light Source	Mass of power supply (kg)	Mass of lamp (kg)	Dimensions of power supply (cm)	Dimensions of lamp (cm)
RC-500	15	3.5	20 x 25 x 40	20 x 25 x 40
CF1000, 5.4W 395-nm LED head	5	0.6	18 x 18 x 16	10 x 8 x 6

TABLE 5

Output comparison for different light sources

Distance from light head to substrate, cm Power, mW/cm ²	5.4W 395 nm LED	RC-500B Power, mW/cm ²
2	46.5	14.9
4	20.9	6.8
6	11.6	4.5
8	7.0	2.9
10	4.5	1.6
12	3.0	1.2

Measurements were performed with IL393UV light meter from International Light Technologies Inc., recommended for UVB-UVA range, nominal range 250-400 nm according to the manufacturer.

pigmented anticorrosion metal paint with acceptable abrasion resistance and surface hardness. LED-cured paint does appear a little softer and oilier to the touch immediately after cure. The most significant result is a good cross-hatch adhesion for all tested light sources (Table 6).

While acceptable dry adhesion with the RC-500B is achieved within 40 seconds (2 minutes used at trials as mentioned) it seems that no less than 2 minutes of cure is necessary with CF1000 to ensure acceptable dry adhesion. Besides, there are clear limitations on how thick 395 nm LED can cure. Severe under cure and delamination results if paint film thickness exceeds 150 μm (6 mil). The RC-500B, due to its pulsed nature, affords better penetration depth, and can cure paint almost twice as thick.

Because excellent dry adhesion to steel panels has been achieved, the large number of test panels cured with 395 nm LED has been prepared for SWIM to commence shortly.

It is clear that commercial, off-the-shelf LEDs are capable of curing highly filled, pigmented anti-corrosion paints, but in order to maximize this light source's potential for the given application, custom design is necessary.

Addition of shorter UV wavelength LEDs to the array may slightly increase the cost, but it will also provide for better surface cure as a result. It is important that such an array fires sequentially, with longer wavelength (395 nm) LEDs going first to cure the film through, and shorter wavelength (365 nm) LEDs finishing off the surface on the second step. Coupling LED

heads or using bigger arrays will allow covering bigger areas in one shot. Also, proper positioning of multiple LED heads should allow the user to bring the light source closer to the surface without the danger of creating a central "hot spot." Getting closer to the surface should also reduce the cure time. Currently, CF1000 can support up to three LED heads simultaneously.

While both Xenon and mercury lamps require bulky and complex power supplies, a single 395 nm UV LED can be operated for extensive periods of time by a 6V battery, and arrays of these LEDs require a simple 16-24V power supply powering the LEDs with almost no evolution of heat. Ultimately, to make the LED light source truly portable it should operate on battery power. The 5.4W LED head consumes 1.65A at 24V DC, which is well within the power range of available, portable battery packs.

Conclusion

A light-cured, highly pigmented anti-corrosion repair paint performs well in field trials inside the ballast tanks of

TABLE 6

Properties of anticorrosion metal paint cured by different light sources

	Cure Grade (tackiness) ^a	Cross-hatch Adhesion ASTM D2359	Coated Surface Hardness (max. 14), ASTM D2134	Abrasion Resistance ^b
RC-500B, 2 cm, 2 min.	3	>4B	2	2
LED*, 12 cm, 2 min.	3, slightly oily upon immediate light removal	>4B	2	2

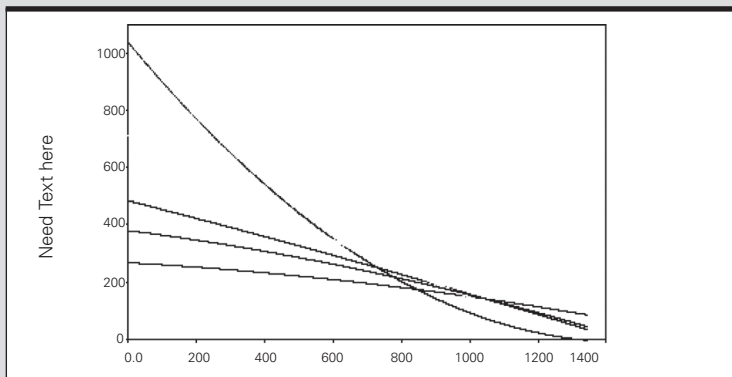
* photoinitiator package: modified proprietary blend

^a Cure Grade (tackiness) is determined by physical touch: 0—wet; 1—panel can be lifted with finger touch; 2—surface slightly sticks to finger, no panel lift; 3—dry, tack-free surface.

^b Abrasion Resistance is evaluated by assessing coating surface appearance after 100 rubs with 0000 fine steel wool: 0—complete loss of coating; 1—partial loss of coating; 2—no loss of coating, some loss of gloss (hazy); 3—coating remains with no loss of gloss.

FIGURE 10

Power distribution for the 5.4W 395 nm LED source, as a function of distance from the center of illumination



* Including cost; the power supply and three LED heads have a combined price comparable to the RC-500B.

submarines. UV LEDs can be used as acceptable alternatives to conventional light sources for curing a variety of formulations for different applications. A version of the anti-corrosion paint described here, optimized for 395 nm LED cure, displays acceptable adhesion in dry testing and is currently undergoing saltwater immersion testing. LED sources should prove themselves adaptable to true portability, using either primary or rechargeable battery packs. ▀

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