

WINDMILLS – FAST PRODUCTION SCHEDULES WITH NOVEL ZINC PRIMERS AND POLYASPARTIC ESTER TOPCOATS

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Abstract: The rapid curing and rapid project completion characteristics of reinforced inorganic zinc and polyaspartic ester technology enables new windmills to receive two-coat systems and be ready for shipment within 12 hrs. Significant cost reduction and optimization of life cycle costs are achieved for both new construction and maintenance projects using this technology.

The first part of this paper describes the chemistry and laboratory testing of novel reinforced inorganic zinc and polyaspartic ester coatings used for the corrosion protection of windmills.

In the second part of this paper a case history is discussed where these applicator-friendly conventional application - coating systems have been applied to windmills.

INTRODUCTION

As megawatt (MW) output from windmills rise could it be that wind energy capacity growth is actually gusting? With capacity already at 6,300 MW and possibly headed towards 12,000 MW over the next 25 years the answer appears to be yes (1). In the United States there have been a large number of windmills (wind turbines) produced, particularly as certain states have embraced wind energy as one of the favored renewable and alternative sources of “green”, non-polluting energy generation. The American Wind Energy Association notes that wind power has expanded at an average annual rate of 28% in the past five years.

Clearly, windmills are our present day environmental ally – a far cry from medieval times when Don Quixote had the mental aberration of believing them to be his enemy, as he resorted to “tilting at windmills” by attacking them with his lance (2).

Today, the productivity and efficacy of windmills is invariably measured in terms of in-service factors such as electricity generation as a fraction of (a) overall sources of electricity, and (b) renewable sources of energy (e.g. hydropower, geothermal, biomass and municipal solid waste).

This paper, however, will focus on an altogether different aspect of productivity associated with windmills, namely where productivity enhancement is achieved by eliminating a coating from a traditional three-coat system for harsh environments and electing to use instead a novel zinc primer and a polyaspartic ester topcoat. This unique coating system has low temperature application and curing characteristics that enable windmill sections to be shipped in a few hours while at the same time providing long term coating performance requirements (>15 years) and meeting the parameters of the test standard adopted worldwide, namely EN ISO 12944 (3).

BACKGROUND

Coatings are more vulnerable to breakdown on windmills in the ocean compared to those in on-shore service. While the generic coating types used in both instances are typically zincs, epoxies and

urethanes, the overall coating thicknesses of applied systems are higher for offshore windmills where the coating specification must be enforced and greater taken in the coating application to prevent premature failures (4).

For several decades, zinc/ epoxy/ polyurethane coating systems have featured prominently in the war against corrosion in harsh environments as exemplified by their use in offshore windmill projects. Notwithstanding, significant advances have been made in recent years in the realm of coatings technology. These include the development, and evolution of, reinforced inorganic zinc primers (RIOZ) that cure independently of humidity (5) and the invention of unique aliphatic polyurea finish coats based on polyaspartic ester technology (6).

Instead of using organic zinc rich epoxy primers (or metallizing) with epoxy mid-coats and polyurethane or polysiloxane finishes, production enhancement coating systems for windmills can be designed based on reinforced inorganic zinc primers and polyaspartic topcoats, both of which are exceptionally user friendly. The polyaspartic topcoats derive from polyaspartic esters, a class of polyfunctional amines used as co-reactants with aliphatic polyisocyanates (7-9). With careful molecular design of polyaspartic esters, the coating films can be tailored to have fast and low temperature cure, as well as very good anticorrosive and aesthetic properties. Spurred by the success of reinforced inorganic zinc technology in fast track projects, the rapid recoat-rapid curing properties of a two-coat tandem RIOZ/PT system can afford both cost reduction in fast track new construction schedules and excellent life cycle costs for the owner.

To appreciate the advantages of reinforced inorganic zinc coatings it is useful to compare and contrast them with some of the more traditional inorganic zinc coatings.

Inorganic Zinc Coatings:

Inorganic zinc primers are generally characterized as coatings having a very high level of powdered zinc metal pigment and a very small amount of inorganic silicate binder. By design, the ratio of pigment to binder exceeds what is known in paint formulation jargon as the PVC (pigment volume concentration). This means there is not enough vehicle or binder to completely encapsulate all the zinc pigment. As a result inorganic zinc films have a high PVC/CPVC (critical pigment volume concentration) ratio and therefore are weaker than typical barrier films. These coatings have a conductive and porous inorganic matrix and initially provide cathodic protection in which the zinc (that enters solution) acts as a sacrificial anode for the steel in areas where the zinc film is damaged down to bare metal. Although this is the initial protective mechanism of inorganic zincs, as time goes by the porous areas of the coating film fill with the formation of complex zinc reaction products. As a result, the protective mechanism of the inorganic zinc moves through an intermediate cathodic protection – barrier effect and into a final full-scale barrier effect (10).

Alkyl silicate inorganic zinc technology requires sufficient humidity, oxygen (air) and temperature to achieve proper cure and performance of the film. The curing mechanism for alkyl silicate binders depends on atmospheric moisture and carbon dioxide in a series of complex polymerization and condensation reactions (11).

Formed under conditions of low humidity, the inorganic zinc film suffers from incomplete cure and the cure mechanism may take several months to improve. During this time, the inorganic zinc coating densifies, hardens and develops its maximum cohesive and adhesive properties. The ideal curing characteristics for an alkyl silicate inorganic zinc would be ca. 85°F at 85% relative humidity. If

overcoated too soon the inorganic zinc can delaminate during the exertion of contractive curing stresses of the applied intermediate/topcoats.

Reinforced Inorganic Zincs:

With judicious modifications, the inherent defects of a purely inorganic zinc coating can be overcome. Modification of inorganic zinc coatings with an organic polymer, or resin, is not new and takes many forms. For instance, most inorganic zinc coatings use small amounts of organic polymers or organic co-reactant components to improve the anti-settling, initial hardness, film build, toughness, and flexibility properties.

Reinforced inorganic zinc technology maximizes the advantages and minimizes the disadvantages of inorganic zinc-rich coatings. A modified inorganic system is employed which consists of inorganic components and a unique polar resin for the coating's organic component (12). The reinforced inorganic zinc contains hydraulic calcium silicates (and other silicates) which enhance the effectiveness of zinc by protecting the zinc particles from dissolution by chloride ions. By virtue of the trio combination of inorganic/zinc dust/organic materials, the coating can be applied at low or high humidities (down to 0°C) and provide a good balance of physical properties to passivate steel and protect it from chloride attack.

Reinforced inorganic zinc technology is essentially void free in the dry film. The practical and theoretical benefits of this are the ability of the film to accept high build topcoats within a shorter time frame and the virtual elimination of pinholing, or bubbling of heavily applied topcoats. This means the total coating system has substantially more integrity (especially when operating in a chemical environment) and will invariably have a longer service life.

In summary, the attributes of Reinforced Inorganic Zincs that can positively impact

coating schedules for windmills include the following:

- Cure is independent of humidity – no series of complex polymerization, condensation and dehydration reactions
- Essentially void free – do not promote pinholing or bubbling of high build topcoats – contributes to maximum shop or plant production rates.
- Cure to 0°C (32°F)
- Can be self coated if areas are found to be below specification film build.
- Fast recoat time (1 hr @ 70°F and 5 hours @ 40°F)
- No mudcracking even at dry film thicknesses (DFT's) over 12 mils.
- Zinc is premixed thereby eliminating the dispersion of dry zinc powder into the coating before application.
- Elimination of film splitting – excellent flexibility (90° bend) – superior to traditional inorganic zinc technology.
- Improved adhesion and cohesion to abrasive blasted steel and thus less prone to mechanical damage.
- Improved touch-up properties.

Zinc loadings in reinforced inorganic zincs vary from 60 to 74% by weight in the dried film. Success with the earliest types of RIOZ's spanning three decades shows the zinc loadings need not exceed ca. 60% to achieve the expected long-term corrosion protection. This reflects the criteria established by SSPC-SP29 (13) that shows performance requirements for inorganic zinc primers with zinc loadings from 50% and up.

Moreover, this accords well with earlier research (14) that revealed, in part, that (a) inorganic zinc performance was good even with as little as 42% zinc in the dry film, and (b) much of the zinc in conventional primers can be left out, or replaced, without loss of protection. By reducing zinc loadings and maintaining the CPVC using alternative pigments, it was shown that zinc loadings were not as critical as the conditions of application (especially dry spray and low film thickness). The performance of zinc coatings was very much formulation dependent, contingent in part on the available surface area of zinc particles and the selection of effective vehicles and key pigments.

The quick cure, rapid recoat and physical characteristics of reinforced inorganic zincs enable shop, craneage, material movement and delivery times to be extremely fast (Tables 1 – 3). For touch-ups reinforced inorganic zincs can be applied to either SSPC-SP3 or SSPC-SP11 power tool cleaned surfaces.

Polyaspartic Ester Finish Coatings:

In a nutshell, a polyurethane is formed in the reaction between a polyol and an isocyanate, and a polyurea is formed in the reaction between an amine and an isocyanate. Aliphatic polyurethane coatings have a well established place in the world of coating finishes and possess very good gloss and gloss retentive properties, especially the polyester polyurethanes, or acrylic polyurethanes that are well formulated with hindered amine light stabilizers (15). Polyureas have become popular, due in part to their fast cure properties and good chemical resistance. As with all things, improvements can always be made to any family of coatings and in 1990 an impressive array of aesthetic and chemical resistance properties was obtained in the realm of modified polyurea coatings with the development of polyaspartic ester topcoat finishes (6).

Polyaspartic esters are a relatively new class of amine-functional polymers that contain secondary aliphatic diamines that co-react with aliphatic polyisocyanates. Although the resulting coating films can be considered as modified polyurethanes, they are essentially polyaspartic-based polyureas. Polyaspartic esters can be synthesized by a Michael Addition Reaction in which primary aliphatic diamines are reacted with dialkyl maleates (Figure 1).

Aside from the inductive effects of the ester groups, examination of the overall structure of the polyaspartic ester reveals a prominent structural feature where the nitrogen atoms are sterically crowded (Figures 2 and 3). By altering the nature of the steric crowding groups around the nitrogen atoms, a wide range of unique polyaspartic topcoats can be formulated to have superior weathering, fast cure, abrasion resistance properties, and water and chemical resistance properties (7-9). Figure 4 shows the structure of a typical polyisocyanate co-reactant.

In response to escalating regulatory imposition, the polyaspartic topcoats can also be formulated to have very low VOC's. They are non-yellowing, possess good UV resistance and can be applied at very high film build should it be warranted by the service environment. From an anticorrosive perspective, polyaspartic ester topcoats can be formulated as direct-to-metal coatings. In the present work, two polyaspartic topcoats, PT1 and PT2, were tested on both zinc primed steel and as direct – to – metal coating systems.

The faster curing polyaspartic ester topcoats dry in minutes. They overcome some of the downsides of traditional urethane technology where tin based accelerators might be used to help speed up cure where the coating films otherwise take a long time to set and are particularly prone to water spotting during storage.

Properly designed RIOZ/PT coating systems allow for simplification of coating schedules for windmills. Two-coat systems with zinc primers are available without sacrificing long term coating performance. Interestingly, while moisture cured organic zinc primers can be excellent primers for topcoating with polyaspartic ester finishes, the authors elected to use reinforced inorganic zinc primers in the present work.

Despite the benefits of polyaspartic ester topcoat technology there is a potential negative with the application of very fast cure polyaspartic topcoats in high temperature, high humidity shop conditions. Certain formulations may have a propensity to dry spray and therefore it may be necessary to use either slower curing PT technology or adjust shop conditions accordingly.

EXPERIMENTAL AND TEST PROCEDURES

It cannot be overemphasized that while individual laboratory results may provide reasonable “rule of thumb” criteria indicative of good coating field service, the tests must not be over-interpreted. Seldom discussed is the fact that poorly applied shop or field coatings, that resulted from lack of user friendliness, or other deleterious circumstances, would render good laboratory test results essentially meaningless.

Of particular interest to the authors was to investigate the corrosion protection characteristics of the RIOZ/PT system using Electrochemical Impedance Spectroscopy (EIS). This useful analytical technique has been successfully used by the authors to compare and contrast coatings for rapid immersion in marine service and for tank, vessel and pipe linings in the Canadian Oilpatch (16-18).

Both ISO 12944 C5M and ASTM salt spray and humidity tests were carried out. The test regimen in the present work also

included several other tests, viz, adhesion (ASTM D4541), dry time determinations (ASTM D1640), and chemical resistance (ASTM D1308). For the sake of brevity these additional tests will not be described in this paper although the results are given in Tables 4 –10.

1. Panel Preparation

Coated steel panels (6” x 4” x 1/4”) were prepared by abrasive blast cleaning new steel plate to SSPC-SP10 (NACE 2) near white metal standard to obtain a sharp, angular profile of about 2-4 mils. Ordinarily, the temperature was 70⁰F and relative humidity 60% except for a curing study where temperatures and relative humidities were deliberately varied (Table 6). The reinforced inorganic zinc coatings were spray applied and topcoated with PT technology after a short time interval of approximately 2 hours. The resulting DFT's are included with the test data.

2. Candidate Coating System Selection and Spray Application

The coating systems investigated were representative of some of the more commonly applied systems used in the industrial coatings sector. Of particular interest were panels coated with the zinc/epoxy/urethane coating systems because one of these systems was applied to several thousand of tons of steel for pulp mill projects in the 90s. The approximate total dry film thicknesses (TDFT) in the present work were as follows:

- (a) 2ct RIOZ/PT (8-9 mils TDFT)
- (b) 1ct PT (5 mils or 10 mils DFT).
- (c) 3ct RIOZ/Epoxy/PT (11- 17 mils TDFT).

All systems were spray applied using conventional equipment. Two formulations of polyaspartic topcoat were used (PT1 and PT2). In the EIS study, only PT1 was

investigated and in three different colours, namely white, light grey and blue.

3. Salt Spray and Humidity Testing

Laboratory tests to evaluate coating systems for windmills exposed to harsh offshore environments included the requisite neutral salt spray and humidity testing of ISO12944 C5M, respectively 1440 hrs neutral salt spray (ISO 7253) and 720 hrs humidity exposure ISO 6270. These tests were carried out in the present work as well as the ASTM salt fog and humidity exposure tests, respectively ASTM B117 and ASTM D4585.

4. Electrochemical Impedance Spectroscopy

4.1 General

Electrochemical Impedance Spectroscopy (EIS) is a non-destructive, analytical technique that measures the AC electrical resistance (impedance) of a coating film at different frequencies and has become a good diagnostic tool to evaluate the barrier properties of organic coatings. Basically, the impedance of a coating is related to its permeability to water, gas, and other corrosives.

Defect free coatings with high impedance exhibit good corrosion control. When impedance is seen to diminish as a function of time it indicates increased permeation and ion exchange rates within the coating film, i.e. precursors to coating degradation and under-film corrosion. The higher the impedance of a barrier coating, the lower its permeability to corrosives, and hence the more protective the coating is anticipated to be.

In this study, the impedance of a coating at 0.1 Hz is tabulated and used as the basis of comparison between coatings, or for monitoring the change in a coating as a function of exposure to a test environment. Selection of Log Z at 0.1 Hz is somewhat arbitrary, but represents a compromise

between speed of analysis and selection of a frequency providing good discrimination in coating performance. The key for interpreting the impedance data for barrier coatings is diagrammatically represented in Figure 5.

4.2 Experimental

An EIS measurement consists of attaching a glass cell containing a counter electrode, a reference electrode, and a conductive solution to the coated metal panel. A small sinusoidal AC current signal is applied between the counter electrode and the sample substrate while the resulting voltage response is monitored between the reference electrode and the sample substrate. The AC signal measurement is performed at several frequencies between 100 kHz and 0.1 Hz. From the results obtained the electrical impedance and phase shift of the coated sample are determined as a function of frequency.

The EIS test assembly used in the present work has been described elsewhere (17). The electrochemical cell used for EIS measurements was a modified version of the Gamry PTC1 Paint Test Cell, which is specifically designed for use with coated metal panels. This cell consists of a tube shaped glass cell that is clamped and sealed to the sample panel with a rubber O-ring, which is filled with the test electrolyte. The PTC1 cell contains a saturated calomel reference electrode and an activated graphite rod counter electrode, both of which are inserted through the top of the cell via a rubber bung.

The electronic equipment used to conduct EIS measurements were Gamry PC4/300 Potentiostat/ Frequency Response Analyzer boards that had been installed into a PC. A Gamry EIS300 control software package was used to control the test operation, record test data, and create a custom script for experimental control (from its special scripting language). Importantly, a script

was developed to perform repeated EIS measurements at preset intervals.

The parameters for each EIS measurement were as follows:

Test Area: 14.6 cm²
Frequency Range: 100 kHz to 0.1 Hz
of Data Points: 5 points per decade of frequency
Induced DC Potential: -0.7 V_{SCE}
Induced AC Potential: +/- 0.01V

The circuit model used in the present study has been described elsewhere.

RESULTS AND DISCUSSION

Tables 1 – 16 present the physical data and testing of the different panels coated with the reinforced inorganic zincs, epoxies and variations of polyaspartic topcoat finishes (PT1 and PT2). For the sake of brevity only key points will be highlighted. It can be seen from Table 4 that the results of ASTM B117 salt fog testing were good and for comparison ISO 7253 and Electrochemical Impedance Spectroscopy was also carried out with similar results at the half way stage (ca. 720 hours).

The dry times of the polyaspartic ester finishes are shown in Table 6. The dry times of the polyaspartic topcoats formulated for use in this study (and the PT1 used on various windmill projects) was less than 2 hours. Sometimes these very fast dry times are not required and slower formulations are readily obtained with judicious modification of the polyaspartic topcoat formulation.

While the ASTM D451 adhesion results for PT1 and PT2 exceed 1300 psi for DTM PT1 and PT2, it should be noted that these particular formulations did not have any rust inhibitive pigment additions. Thus they would not be expected to have zero under-creep corrosion resistance as shown in Table 4.

The initial gloss of PT1 was 83, and higher than PT2 (ASTM D4581) as shown in Table 8. With the tremendous versatility to formulate in polyaspartic topcoat technology even higher initial gloss ratings can be obtained. For the work carried out on the windmill project referred to in this paper, the gloss of PT1 was more than acceptable.

It is interesting to note the aged recoat limitations of the polyaspartic topcoat finishes is conservatively estimated at one week (see Table 9). In contrast, the maximum recoat window of the reinforced inorganic zinc is at least 3 months.

Figures 6 – 8 present the EIS impedance (Z) data, obtained before and after the reinforced inorganic zincs (RIOZ) - with and without topcoats of epoxy and polyaspartic topcoat PT1 – were subject to the full ISO 6270 test and halfway through the ISO 7253 test (ongoing at time of writing). Although an in –depth discussion of this data is beyond the scope of this paper, for the sake of brevity the EIS data can be summarized thus:

Initial Condition - Figure 6

- The RIOZ's showed low impedance results as expected. This is due to the high electrochemical reactivity of zinc in the un-aged coating.
- The RIOZ/topcoated panels exhibited high impedance values (10⁸ - 10¹⁰ ohm-cm²) as expected, with the exception of the RIOZ/MMB epoxy which showed only slightly better performance than the RIOZ primer.
- The Fast Cure PT1 DTM with blue pigmented version showed excellent results whereas the white pigmented version showed poor performance.

After Humidity Exposure – ISO 6270 – Figure 7

- Again, RIOZ's continued to show low impedance behaviour. This is expected as condensation exposure does not promote rapid production of oxides, etc., that would initiate the typical barrier properties of RIOZ.
- The Fast Cure PT1 DTM showed excellent results for both blue and white pigmented versions, which indicates that the white version underwent additional curing by a moisture -cure mechanism. The blue version of the Fast Cure PT1 still showed better performance than the white version, even at the same nominal thickness. The reason for this is not immediately apparent. That the cure mechanism of polyaspartic ester topcoats involves a moisture cure mechanism is well known. Perhaps, given similar humidities at the time of application, in the case of the white (ground) PT1, the pigment was drier whereas in the case of the blue (tinted) PT1 the pigment (or extender pigment) was damp and led to a quicker cure. Different formulation parameters might also account for the observed differences. Further investigation of this humidity-induced cure effect as evidenced by EIS is warranted.
- All coatings applied over the RIOZ primer showed a drop in impedance compared with the initial condition results. It can be argued that this is expected as the pore spaces will have saturated, allowing the reactivity of the RIOZ primer to show.
- The RIOZ /Fast Cure PT1 showed better results than those obtained from the RIOZ/epoxies. Again, these findings indicate an extended moisture cure effect is taking place in the humidity chamber.
- The RIOZ's performed poorly as expected, as strong chlorides promote formation of soluble corrosion products which tend to retard the transition to a barrier coating and keep the zinc exposed and reactive.
- The Fast Cure PT1 DTM white showed poor results, while the blue version was somewhat better, giving moderate results. This is anticipated because polyaspartic ester topcoats are not inherently anticorrosive in and of themselves and will only exhibit moderate behaviour from the perspective of EIS.
- As evidenced in humidity testing all coatings applied over the RIOZ primers revealed a drop in impedance in comparison with the initial condition test results. However, once again this is to be expected because the pore spaces will have saturated thereby allowing the reactivity of the RIOZ to manifest itself.

General Comments

- The blue pigmentation in the Fast Cure PT1 appeared to have a significant beneficial effect because in all cases the blue PT1 showed superior performance in comparison to the white pigmented version. The particular pigments utilized were to produce colour and not rust inhibition. Hence, the authors contend that this is not an anti-corrosive/inhibitive mechanism (that could otherwise be obtained from zinc phosphate/corrosion inhibitors) and speculate that the blue pigments may be damp and artificially enhance the cure of PT1. More work will be undertaken to investigate these findings.
- The untopcoated RIOZ primers and topcoated RIOZ's behaved as expected with the reactivity of the RIOZ indicated strongly by the EIS results.

After Salt Fog Exposure – Half way through ISO 7253 – Figure 8

- The Fast Cure PT1 appeared to have a continued moisture cure reaction when exposed to hot humid conditions. While it lack anti-corrosive properties as evidenced from the EIS studies, it performed well as did all PT1 topcoats in the salt fog and humidity tests.

HOW FAST CAN THE RIOZ/PT SYSTEMS BE SHIPPED?

Table 10 compares the cost per sq. ft of a conventional three-coat zinc/epoxy/polyurethane coating system with a two coat RIOZ/PT system. It can be seen that the savings in labour provided by the two-coat system are offset by the increase in materials cost of the high build PT topcoat.

The 5-7 mils DFT provided by the lower cost mid-coat of epoxy has been replaced by the 7-9 mils DFT of high build PT topcoat. While one realizes savings per sq. ft what is not immediately obvious are the savings accrued from shorter application times. Time is money in any industry and is particularly evident in the coatings industry. The ability to move steel faster through the paint shop allows coatings contractors to coat more steel and generate more profit.

The RIOZ primer has a very fast recoat time thereby allowing the application of the high build PT topcoat within two hours. Additionally, since the surface of the high build PT topcoat hardens rapidly and develops good impact resistance this typically means the finished steel can be moved outside for storage, or shipment, in as little as two hours.

Importantly, there are further positives associated with the reduction of the number of coats required to provide the same level of protection as a three-coat system. Simply by reducing the number of quality controls and inspections will save time and money. The fast-recoat attributes of the RIOZ also reduces the concern for inter-coat contamination. And aside from fast cure cost savings by lowering the number of

inventoried products, there will be less cleaning of machines when switching materials if dedicated pumps are not available.

In the final analysis, if the coating applicators are able to minimize the number of events that can go wrong, then they can take advantage of these opportunities and concentrate more on remaining tasks.

Ultimately, the two-coat RIOZ/PT system affords enhanced efficiency and improved windmill productivity, thereby enabling owners to obtain an improved finished product with the same level of protection of a three-coat system but at a reduced overall cost.

CASE HISTORY – RIOZ/PT1 SYSTEM

Since 2001 numerous windmills have been coated in the USA with fast curing, two coat reinforced inorganic zinc and polyaspartic ester topcoats where the technology replaced three-coat zinc/epoxy/urethane systems.

The carbon steel windmills consisted of three sections at approximately 90ft per section, and a base section at 12ft diameter that tapered to an 8ft top section.

COATINGS SYSTEMS / PROCESSES

SURFACE PREPARATION:

Carbon steel plate was first wheelabrased to SSPC-SP10 Near White Metal standard. A jagged profile of 2.5 – 3 mils was obtained using an abrasive media consisting of 30% steel grit and 70% steel shot.

SHOP APPLIED FABRICATION HOLDING PRIMER:

Approximately 0.8 -1 mils DFT of a reinforced inorganic zinc primer was spray applied to all properly prepared steel plate (both sides) in order to hold the abrasive blast during rolling and fabrication

processes while the tower shell sections of the windmill were being built.

The zinc primed steel plate was processed in the rolling mill to form cylindrical tower rings, and then welded into 90 foot tower assembly sections. Once the tower assembly sections were fully fabricated and welded, each section was hoisted onto a dual wheel axle, and bolted to the wheel axle at the base ring flange. The top end of the tower section was subsequently lifted, leg supports saddled and attached to the top ring flange and the whole tower assembly section subsequently transported within the fabrication facility.

FINISH COATINGS: SURFACE PREPARATION:

All zinc primed surfaces were cleaned according to SSPC-SP1 to remove fabrication contaminants, followed by an SSPC-SP7 Brush Blast to provide surface tooth. All welds and hold back areas were abrasive blasted to SSPC-SP10 Near White Metal standard.

Primer for Bare Metal: One coat RIOZ applied @ 3 mils DFT. Two hrs after application of the RIOZ primer the PT1 topcoat was applied for external surfaces (and epoxy could be applied for internal surfaces). See Figures 9 – 14.

Internal Tower Surfaces: One coat Fast Cure MMB Epoxy (White) applied @ 4-6 mils DFT. The epoxy coating could be walked on in 5-6 hrs at typical temperatures of 55⁰F and 60-70% Relative Humidity.

External Tower Surfaces: One coat Fast Cure Polyaspartic Topcoat PT1 (Tower Gray) @ 8.5 – 9.5 mils DFT. The PT1 coating was hard dry in 3-4 hrs and the towers could readily be moved outside in winter conditions ca. 6 hrs after completing the entire coating system application. Due to the rapid curing nature of the PT1 topcoat

there was essentially no fear of rain spotting on the finish coat. Nevertheless, plans were implemented to remove any ponding water that may develop should the storage containment covers become damaged at the ends of the tower sections.

CONCLUSIONS

- The central core of using two-coat reinforced inorganic zinc (RIOZ) /polyaspartic ester topcoat (PT) systems for windmills is that the systems have rapid recoat – rapid curing characteristics (12 hrs).
- For windmill applications, the two coat RIOZ/PT systems investigated here meet the ISO EN 12944 C5M standard requirements in the humidity tests, ISO 6270. At the time of writing ISO 7553 neutral salt fog is still underway.
- Electrochemical Impedance Spectroscopy (EIS) was employed to investigate the coating performance of the coating systems. Results indicate that the polyaspartic topcoats examined are subject to ongoing cure from humidity exposure under accelerated test conditions. The magnitude of this effect was formulation dependent. While it is recognized that polyaspartic topcoats are not present because of strong anticorrosive properties, early EIS investigations further suggest that the polyaspartic topcoats examined could benefit from further improvement in anticorrosive properties.
- The two-coat RIOZ/PT systems have been used with good success for windmill coating applications.

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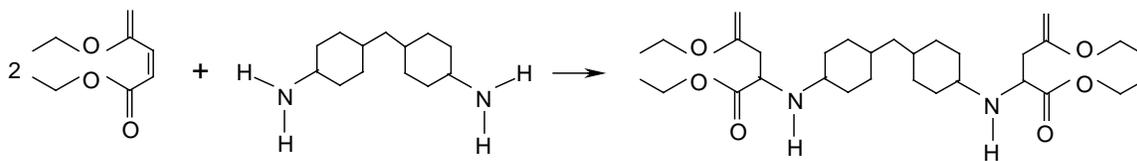


FIGURE 1 Polyaspartic Ester Formation: Michael Addition Reaction

Courtesy of Ed. Squiller, Bayer Corporation

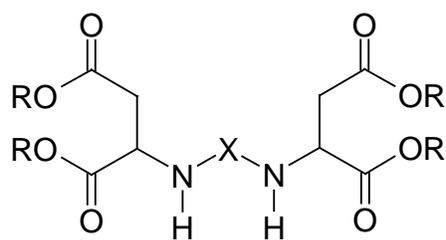


FIGURE 2 Polyaspartic Ester Structures

Courtesy of Ed. Squiller, Bayer Corporation

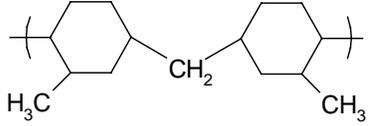
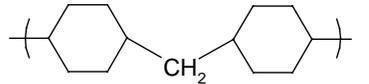
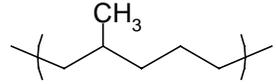
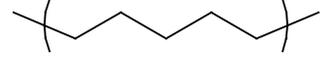
| Raw Materials | | | |
|---|----------------|---------|----------------------|
| X | Diamine | Maleate | Name |
|  | Laromine C-260 | DEM | Desmophen NH XP-7068 |
|  | PACM 20 | DEM | Desmophen NH 1420 |
|  | Dytek A | DEM | Desmophen NH 1220 |
|  | HAD | DEM | XP-7161 |

FIGURE 3 Polyaspartic Ester Products

Courtesy of Ed. Squiller, Bayer Corporation

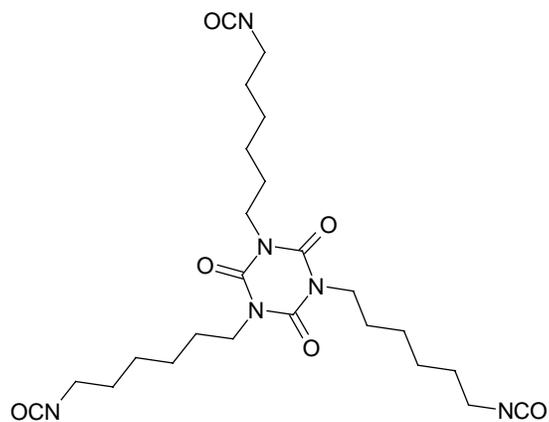
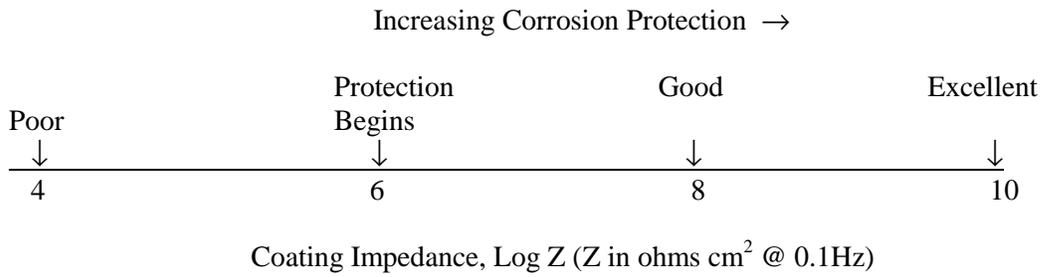


FIGURE 4 HDI Trimer Polyisocyanate co-reactant with Polyaspartic Esters

Courtesy of Ed. Squiller, Bayer Corporation



**FIGURE 5 Corrosion Protection of Organic Coatings:
Coating performance related to EIS Measurements**

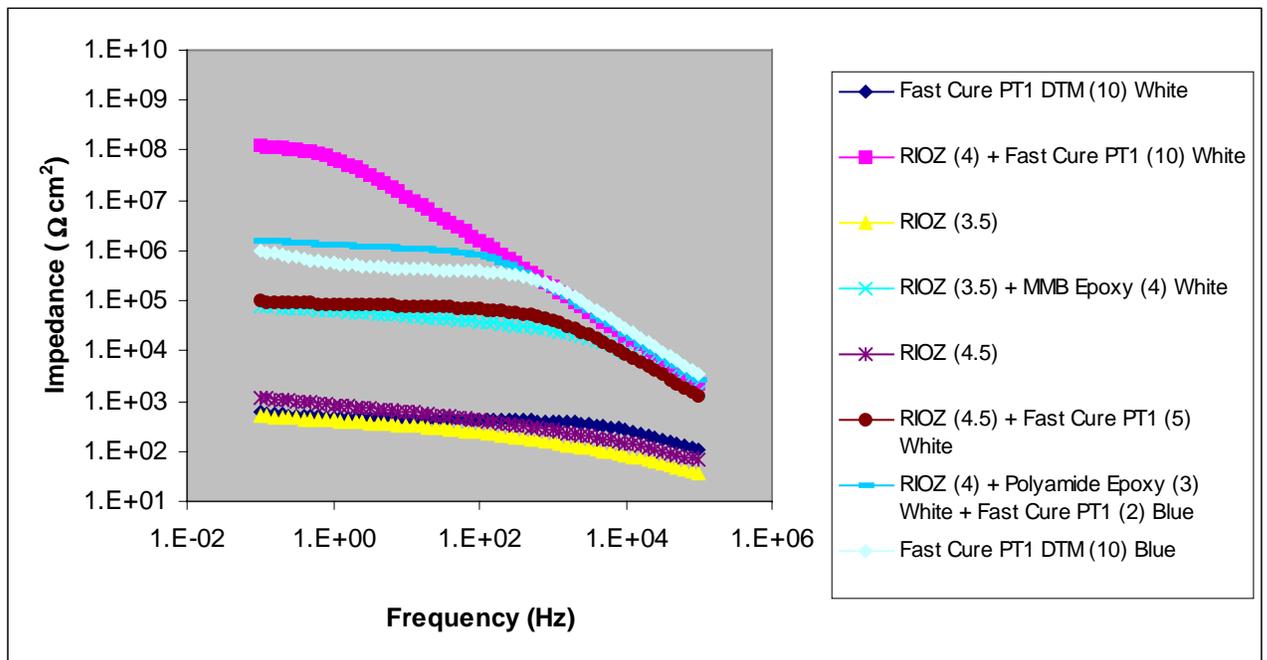


FIGURE 6

**EIS Measurements – Initial Measurements
Averaged Dry Film Thicknesses in Parentheses**

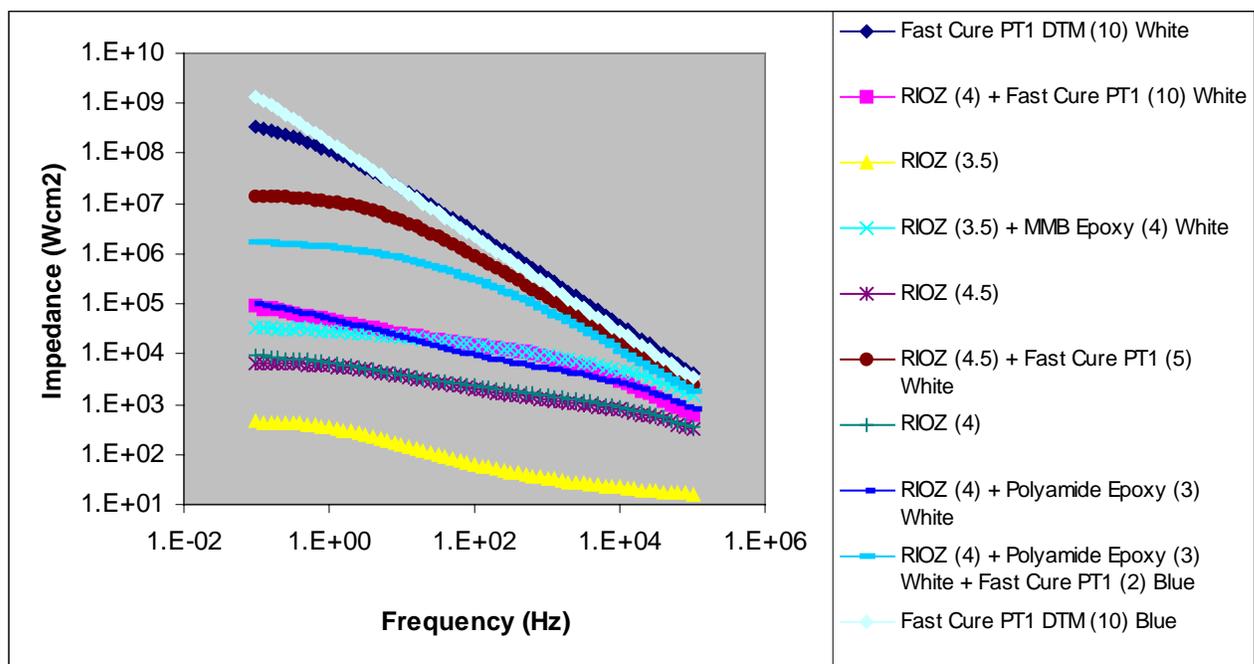


FIGURE 7

**EIS Measurements – After ISO 6270 (720 hrs Humidity)
Averaged Dry Film Thicknesses in Parentheses**

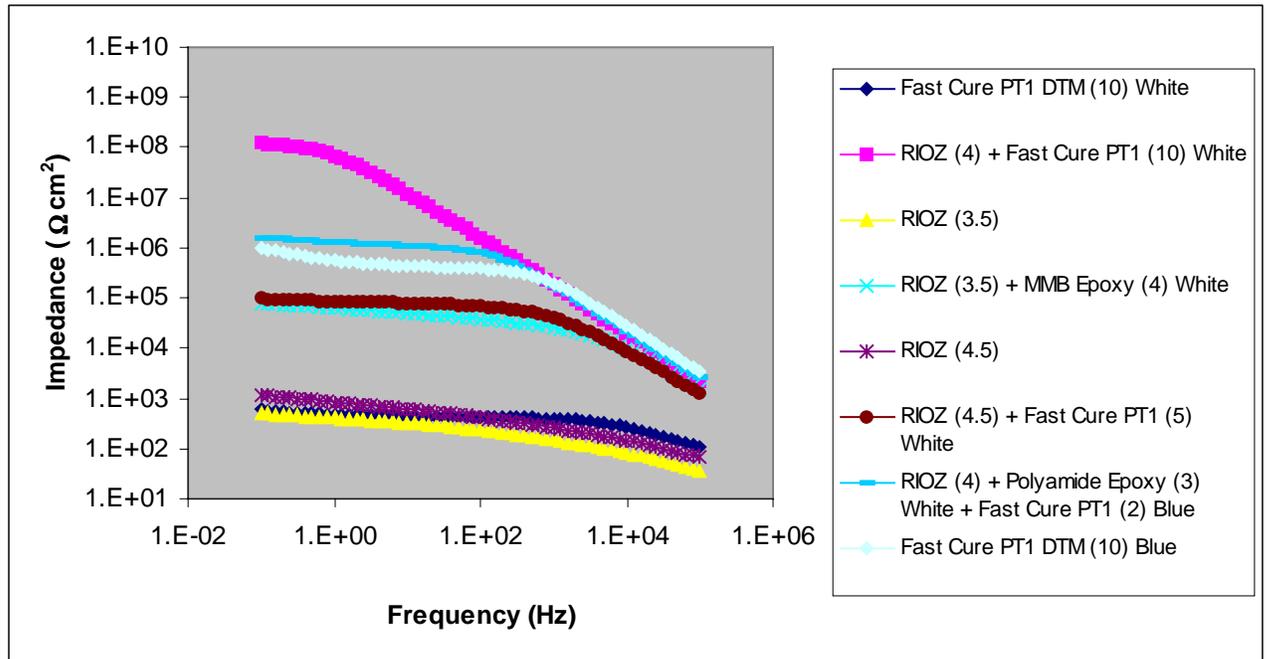


FIGURE 8

**EIS Measurements – After 729hrs ISO 7253 neutral salt spray
Averaged Dry Film Thicknesses in Parentheses**



FIGURE 9
Application of Reinforced Inorganic Zinc



FIGURE 10
Application of Reinforced Inorganic Zinc



FIGURE 11
Reinforced Inorganic Zinc/MMB Epoxy



FIGURE 12
Reinforced Inorganic Zinc/Polyaspartic Topcoat PT1



FIGURE 13
Reinforced Inorganic Zinc/Polyaspartic Topcoat PT1



FIGURE 14
Reinforced Inorganic Zinc/Polyaspartic Topcoat PT1

TABLE 1

**RECOAT GUIDELINES
REINFORCED INORGANIC ZINC/FAST CURE POLYASPARTIC TOPCOATS**

| Substrate Temperature | Minimum Time to Recoat | Relative Humidity Required for Curing |
|-------------------------------------|-------------------------------|--|
| 5 ⁰ C/41 ⁰ F | 5 hrs | N/A |
| 10 ⁰ C/50 ⁰ F | 4 hrs | N/A |
| 15 ⁰ C/59 ⁰ F | 2 hrs | N/A |
| 20 ⁰ C/68 ⁰ F | 1 hr | N/A |
| 25 ⁰ C/77 ⁰ F | ½ hr | N/A |
| 30 ⁰ C/86 ⁰ F | ½ hr | N/A |

RIOZ @ 3 mils DFT

TABLE 2

**DRY THROUGH TIME FAST-CURE POLYASPARTIC TOPCOATS VS.
CONVENTIONAL POLYURETHANE TOPCOATS
(ASTM #D 1640, Fed Std. 141B Method 4061)
(APPLIED TO REINFORCED INORGANIC ZINCS)**

| Substrate Temperature ⁰F(⁰C) | Fast Cure Polyaspartic @ 6 mils DFT | Conventional Polyurethane @ 6 mils DFT |
|---|--|---|
| 40 ⁰ F (4 ⁰ C) | 9 hours | 48 hours |
| 60 ⁰ F (16 ⁰ C) | 5 hours | 16 hours |
| 80 ⁰ F (27 ⁰ C) | 2.5 hours | 9 hours |

Conditions causing deviation – excessive film thickness, poor ventilation, excessive humidity.

TABLE 3**TESTS ON REINFORCED INORGANIC ZINC AND TRADITIONAL
INORGANIC ZINC PRIMERS**

| Test | Reinforced Inorganic Zinc Primer | Traditional Inorganic Zinc Primer |
|--|--|--|
| Adhesion – ASTM D 4541 | > 700 psi | >700 psi |
| Exterior Exposure – 1 year Florida facing South at 45° angle | No blistering, rust, cracking or loss of adhesion | No blistering, rust, cracking or loss of adhesion |
| Humidity Resistance – ASTM D 2247, 2000 hours | No effect on film integrity or loss of adhesion, no rusting, no blisters | No effect on film integrity or loss of adhesion, no rusting, no blisters |
| Salt Fog Resistance – ASTM B 117, 3000 hours | No rusting or blisters | No rusting or blisters |
| Elongation – ASTM D 522, Method B | Passes 180° bend ¼ inch Mandrel | Fails 180° bend ¼ inch Mandrel |

TABLE 4**FAST CURE POLYASPARTIC TOPCOATS:
SALT SPRAY ASTM B117**

| System | Duration (hrs) | Field Rust | Field Blisters | Scribe Blisters | Scribe Rust |
|---------------------------|-----------------------|-------------------|-----------------------|------------------------|--------------------|
| MMB Epoxy / Fast Cure PT1 | 1000 | 10 | 10 | 10 | 1/32" |
| RIOZ / Fast Cure PT1 | 400 | 10 | 10 | 10 | 10 |
| IOZ / Fast Cure PT1 | 400 | 10 | 10 | 10 | 10 |
| Fast Cure PT1 DTM | 1000 | 10 | 10 | F #4-6 | 1/16" |
| Fast Cure PT2 DTM | 1000 | 10 | 10 | MD #2-4 | 1/16" |
| RIOZ/ Fast Cure PT1 | 1440 | 10 | 10 | 10 | 10 |
| RIOZ/Fast Cure PT1 | 2000 | 10 | 10 | 10 | 10 |

Scribed panels cured for seven days. Spray Conditions I

TABLE 5**FAST CURE POLYASPARTIC TOPCOATS:
CLEVELAND HUMIDITY ASTM D4585**

| System | Duration (hrs) | Field Rust | Field Blisters |
|---------------------------|---------------------------|-----------------------|---------------------------|
| MMB Epoxy / Fast Cure PT1 | 1000 | 10 | 10 |
| RIOZ / Fast Cure PT1 | 1000 | 10 | 10 |
| IOZ / Fast Cure PT1 | 400 | 10 | 10 |
| Fast Cure PT1 DTM | 1000 | 10 | 10 |
| Fast Cure PT2 DTM | 1000 | 10 | MD #2 |
| | | | |
| | | | |

After curing for seven days panels were exposed to Cleveland condensing humidity per ASTM D-4585
Substrate: ¼ inch abrasive blasted steel. Cure was obtained at 75°F and 48% R.H.

TABLE 6**FAST CURE POLYASPARTIC TOPCOATS:
DRY TIMES ASTM D1640**

| Temperature / Humidity / System | Dry Touch | Tack Free | Dry Hard | Dry Through |
|--|----------------------|-------------------------------|-----------------|------------------------|
| <i>66°F, 55%R.H.</i> | | | | |
| Fast Cure PT1 DTM | 23 min | 65 min | 1 hr 45 min | 2 hrs |
| Fast Cure PT2 DTM | 29 min | 2 hrs + | | |
| <i>75°F, 20%R.H.</i> | | | | |
| Fast Cure PT1 DTM | 1 hr 25 min | 2 hrs | | |
| Fast Cure PT2 DTM | 1 hr | 2 hrs | | |
| <i>50° F, 74%R.H.</i> | | | | |
| Fast Cure PT1 DTM | 45 min | 1 hr 45 min | 3 hrs | 4 hrs |
| Fast Cure PT2 DTM | 1 hr 45 min | 5 hrs (surface cured only) | | |

4" x 6" Phosphated steel panels were used.

TABLE 7

**FAST CURE POLYASPARTIC TOPCOATS:
ADHESION ASTM D4541**

| System | PSI |
|-------------------|------------|
| Fast Cure PT1 DTM | 1675 |
| Fast Cure PT2 DTM | 1300 |

TABLE 8

**FAST CURE POLYASPARTIC TOPCOATS:
AGED RECOATABILITY**

| System | 4 hrs | 24 hrs | 4 day | 1 wk | 4 wks |
|----------------------------------|--------------|---------------|--------------|-------------|--------------|
| Hydrocarbon Epoxy/ Fast Cure PT1 | Wet-exc. | Wet-exc. | Wet-exc. | Good | Poor |
| RIOZ/Fast Cure PT1 | Wet-exc. | Wet-exc. | Wet-exc. | Good | Poor |
| MMB Epoxy/Fast Cure PT1 | Wet-exc. | Wet-exc. | Wet-exc. | Good | Poor |
| Fast Cure/Fast Cure PT1 | Wet-exc. | Wet-exc. | Wet-exc. | Good | Poor |

Primed panels (SSPC-SP10) were topcoated with Fast Cure Polyspartic Topcoat 1 and aged at a 45° angle facing south in Louisville, KY. The panels were re-coated with PT1 and allowed to cure for seven days at 77°F. The dry adhesion was then checked. The panels were then exposed in a humidity drum for one week. Panels were removed, and the intercoat adhesion was checked while wet. Panels were also checked after a 24 hour recovery period.

TABLE 9

**FAST CURE POLYASPARTIC TOPCOATS:
ASTM D1308 CHEMICAL SPOT TESTING (24 HRS.)**

| Chemical / System | Blisters | Film Softening | Gloss Loss |
|-----------------------------|-----------------|-----------------------|-------------------|
| Water | | | |
| Fast Cure PT1 DTM | None | None | None |
| Fast Cure PT2 DTM | None | None | None |
| 5% Acetic Acid | | | |
| Fast Cure PT1 DTM | None | None | Slight |
| Fast Cure PT2 DTM | None | None | Slight |
| 50% Sulfuric Acid | | | |
| Fast Cure PT1 DTM | Yes | Yes, recovered | Yes |
| Fast Cure PT2 DTM | Yes | Yes, recovered | Yes |
| 50% Sodium Hydroxide | | | |
| Fast Cure PT1 DTM | None | None | None |
| Fast Cure PT2 DTM | None | None | None |
| Xylene | | | |
| Fast Cure PT1 DTM | None | None | None |
| Fast Cure PT2 DTM | None | None | None |
| Methyl Ethyl Ketone | | | |
| Fast Cure PT1 DTM | None | Yes, recovered | Yes |
| Fast Cure PT2 DTM | None | Yes, recovered | Yes |
| Butyl Acetate | | | |
| Fast Cure PT1 DTM | None | None | Yes |
| Fast Cure PT2 DTM | None | None | Yes |
| Skydrol | | | |
| Fast Cure PT1 DTM | None | None | None |
| Fast Cure PT2 DTM | None | None | None |
| Gasoline | | | |
| Fast Cure PT1 DTM | None | None | None |
| Fast Cure PT2 DTM | None | None | None |

4" x 12" 16 gauge mild sand blasted steel panels primed with Hydrocarbon Epoxy were used. After curing for seven days at 77° F, panels were exposed to various reagents for 24 hours in accordance with ASTM D-1308.

TABLE 10
COMPARATIVE COST DATA (US \$) PER FT²

| Material Costs | 3-coat system | 2-coat system |
|-------------------------------------|---------------|---------------|
| Primer – RIOZ @ 2-4 mils | 0.10 | 0.10 |
| Mid-Coat – Epoxy @ 5-7 mils | 0.14 | N/A |
| Topcoat – PU @ 2-3 mils | 0.13 | N/A |
| Topcoat – HB PU @ 7-9 mils | N/A | 0.35 |
| Total Materials | 0.37 | 0.45 |
| | | |
| Labour Costs | 3-coat system | 2-coat system |
| Surface Prep SSPC-SP6 | 0.47 | 0.47 |
| Application of Primer | 0.19 | 0.19 |
| Application of Mid-Coat | 0.22 | N/A |
| Application of Topcoat | 0.19 | N/A |
| Application of HB Topcoat | N/A | 0.29 |
| Total Labour | 1.07 | 0.95 |
| | | |
| Total Materials & Labour | 1.44 | 1.40 |

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