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100% SOLIDS RIGID POLYURETHANE COATINGS TECHNOLOGY FOR CORROSION PROTECTION OF BALLAST TANKS

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ABSTRACT

This paper outlines the development of 1:1 plural-component, rapid-cure, edge retentive, 100% solids, rigid and structural polyurethane coatings technology for corrosion protection of ballast tanks. It highlights not only the advantages but also the challenges of the use of the coatings technology in the ballast tank application in terms of coating's edge retention, substrate surface and environmental conditions, application techniques and equipment requirements. The paper discusses case histories and experiences of the coatings technology in several ballast tank applications to highlight these challenges and resolutions.

Keywords: 100% solids coating, rigid polyurethane, structural polyurethane, ballast tank, tank lining, edge retention, field-applied coating.

INTRODUCTION

Ballast tanks are viewed as “corrosion machines” of fleet ships and their corrosion protection is one of the most important measures for reducing hull structural failure[1]. There are many reasons for ballast tanks to act as the “corrosion machine”. First, ballast tanks are exposed to very corrosive conditions – seawater when full; a moist marine atmosphere when empty; continuous sloshing as a result of a ship’s movements; cyclic heating and cooling from atmospheric exposure; and local heating from warm, adjacent cargo tanks and engine rooms. Secondly, ballast tanks often come with complex geometric configurations, having large surface and highly stressed areas, such as corners, edges, and weld seam areas. Coating defects such as insufficient film thickness are often observed, resulting in early coating failure and hence corrosion in these areas. It is therefore essential to select and use a coating material with better edge formation ability or edge retention. Thirdly, applying a protective coating to ballast tanks is a very complex job with many ramifications. The job involves surface preparation, coating application, and quality assurance and inspection not only in a confined space but often in a poor working environment with very limited accessibility. It depends on the type and variety of cargo carried, ballast, surface contamination, work schedule, environmental conditions such as ambient temperature, substrate temperature and humidity, and, importantly, the application characteristics of the applied coating system.

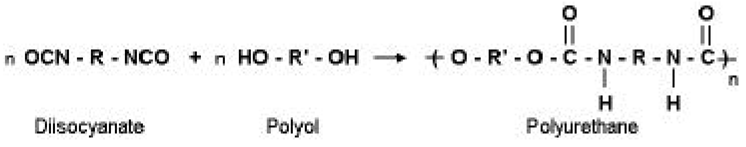
In recent years, there has been an industrial trend towards the development and use of high-performance, edge retentive, plural component, high solids or 100% solids coatings for corrosion protection of ballast tanks. An example is that the U.S. Navy is adopting the use of high solids or 100% solids coatings in lieu of its traditional solvent-borne systems[2]. The driving forces for this trend are life cycle cost, performance, and environmental compliance. The use of these plural component coating systems, together with various aspects of advanced preservation measures, including improved surface preparation and increased quality assurance, is believed to provide performance and cost savings well beyond previous methods and systems. Approximately 30% of application costs can be saved by simply switching to plural component spray equipment in the U.S. Navy applications, compared to conventional airless spray equipment[2]. Among these high solids or 100% solids coatings systems, 100% solids rigid and structural polyurethane coatings technology is particularly promising, because of its various unique advantages over other types of high solids or 100% solids coatings systems, such as cold temperature curing ability, rapid curing speed, unlimited film build, adhesion to an unprimed steel, abrasion and impact resistance, flexibility, etc.

This paper outlines the development of 1:1 plural component, rapid cure, edge retentive, 100% solids, rigid and structural polyurethane coatings technology for corrosion protection of ballast tanks. It highlights not only the advantages but also the challenges of the use of the coatings technology in the ballast tank application in terms of a coating's edge retention, substrate surface and environmental conditions, application techniques and equipment requirements. The paper discusses case histories and experiences of the coatings technology in several ballast tank applications to highlight these challenges and resolutions.

THE 100% SOLIDS RIGID AND STRUCTURAL POLYURETHANE COATINGS TECHNOLOGY

In North America, 100% solids rigid polyurethane coatings were first developed specifically for underground storage tanks in the early 1970s. In 1975, ULC (Underwriters Laboratories of Canada) issued the first listing for cathodically protected steel tanks with a rigid polyurethane coating system. In 1981, the same technology was approved for use in the STI-P$_3$ ® tank by the Steel Tank Institute (STI). By the late 1980s, 100% solids rigid or structural polyurethane technology had almost completely replaced coal tar epoxy and other coatings technologies in the North American underground storage tank industry. By January of 1998, the Steel Tank Institute reported that over 250,000 STI-P$_3$ underground steel fuel storage tanks had been registered and installed in the U.S. In addition, the Steel Tank Association of Canada estimated that 100,000 steel tanks had been installed in Canada. In total, these tanks involved approximately 200 million square feet of steel, and over 80% of the area was coated with 100% solids rigid polyurethane coatings. The technology's performance has been nearly flawless, according to a 1993 report by a U.S. based risk management consulting firm[3]. Since the early 1980s, the use of 100% solids rigid polyurethane coatings technology has been extended from underground tank external coating applications to both underground and aboveground tank interior lining applications for various industries, and later to interior lining and exterior coating applications for pipelines. 100% solids rigid polyurethane coatings technology was among the first very few coatings technologies that are NSF 61 approved for potable water application. In water/wastewater/industrial water transmission pipeline applications, for example, the 100% solids rigid polyurethane coatings have been demonstrated to be by far the most successful protective coating systems used for both exterior and interior applications. The same technology has also gained popularity in utility poles and oil/gas pipeline applications worldwide. Since 2000, the technology has received the attention of the U.S. Navy for naval ship tank applications and gained excellent results from both laboratory and shipboard projects.

While there are many types of polyurethane coatings available which are already utilized under various conditions, today's polyurethane coatings for pipeline applications refer only to the materials that are defined by ASTM D16 as Type V, two-package, liquid, poly-isocyanate, polyol-cured urethane[4]. Like any polyurethane product, the chemistry of a 100% solids rigid polyurethane coating is based on an exothermic reaction between poly-isocyanates and compounds with hydroxyl end-groups such as polyols, which can be illustrated as in Figure 1.



$$n\,\mathrm{OCN-R-NCO} + n\,\mathrm{HO-R'-OH} \longrightarrow \left[\mathrm{O-R'-O-\overset{O}{\overset{\|}{C}}-\underset{H}{\underset{|}{N}}-R-\underset{H}{\underset{|}{N}}-\overset{O}{\overset{\|}{C}}}\right]_n$$

Figure 1. The polyurethane chemistry

Many architectural and industrial coatings available on the market are solvent-based systems. However, 100% solids coatings such as 100% solids rigid polyurethanes are becoming the preferred technology for many applications today because of the environmental VOC issue. By definition, the term '100% solids' means the coating system does not use any solvent to dissolve, carry or reduce any of the coating resins. Furthermore, the resins normally in a liquid state (not in a solid form), will convert 100% to a solid film after application. The viscosity of the coating system is determined by the selection of the resin components and not by the addition of solvent. Some systems that are classified as 100% solids may contain a small amount of solvent (up to approximately 5-10%) that acts as a carrier for pigments and catalysts. In addition to containing no solvents or VOC's, today's 100% solids rigid polyurethane coatings used in North America contain no styrenes, amines, tars or other carcinogens. They are generally not affected by EPA, OSHA, and DOT scrutiny over the health and safety hazards associated with other polymer systems.

The rapid and exothermic nature of the polyurethane reaction provides many application benefits such as fast setting, cold temperature curing ability, and unlimited film build-up associated with the use of 100% solids rigid polyurethane coatings in corrosion protection for ship tanks. First, because of the rapid curing speed of 100% solids polyurethane coatings, the coated tank can be holiday tested and put into service within hours. Secondly, many 100% solids rigid polyurethanes could have a cold temperature curing ability, making it possible to apply the coating at ambient temperatures as low as –40°C (-40°F) and retain their performance characteristics, which is impossible for other types of coatings. Finally, no ambient air heat is required during the application process to ensure that the polyurethanes will cure, and the coatings can be applied to almost any thickness on either vertical or horizontal substrate surfaces, through a multiple-pass but yet one-coat application.

Early products of industrial polyurethane coatings used in North America were based on an *elastomeric* polyurethane chemistry, with or without coal tar and solvents. Later, in 1989, the elastomeric polyurethane coating family also included a new member called "polyurea", which uses amine resins to partially or completely substitute polyols to react with isocyanates. Elastomeric polyurethane (including polyurea coatings) are products of the reaction of difunctional isocyanates with long chain difunctional polyols or a mixture of di- and tri-functional polyols or amines, using short-chain difunctional polyols or diamines as chain extenders. The major advantages of elastomeric polyurethane/polyurea coatings are their excellent flexibility and elongation properties, impact resistance, and abrasion resistance. The major disadvantages are that they are relatively low in acid, alkali and solvent-resistance, low in adhesion to unprimed substrate, low in cathodic disbondment resistance, low in dielectric strength, low in high temperature resistance, but high in moisture/water absorption and permeability. Many elastomeric polyurethane coatings, often designed more for the purpose of non-pipeline or non-critical corrosion applications such as construction repairs or secondary containment, use high molecular weight and long chain polyether polyols or amines to achieve their elongation or flexibility. This will further reduce the chemical resistance of the coatings. In addition to the performance issues, many elastomeric polyurethane coatings often have a high mixing ratio or contain an unbalanced high viscosity of the components. These formulating weaknesses make the coatings difficult to apply and many coating film defects are associated with application error. As a result, over a long-term period, it has been viewed by some people in the corrosion industry that the general corrosion and chemical resistance of polyurethane is not as great as other corrosion resistant coatings[5-6]. To compensate for the difference in corrosion and chemical resistance, application of 100% solids elastomeric polyurethane and polyurea coatings at a dry film thickness of less than 40 mils (1 mm) is not recommended for corrosion protection[7].

100% solids rigid polyurethane coatings are designed to be free from the shortcomings associated with those elastomeric/polyurea polyurethanes that perform poorly. In a rigid polyurethane system, both the isocyanate and polyol reactants are resins that contain multiple functional groups to form a highly cross-linked structure. In contrast to a linear molecular structure of secondary and hydrogen bonding with elastomeric polyurethanes, the rigid polyurethanes have a high density of much stronger, three dimensional, covalent cross-linking. This is achieved through the use of multifunctional polyols, amines, and isocyanates, as well as by the better arrangement of polymers' chain orders, NCO:OH index, and molecular weight of polyols or extenders. Increasing the density of cross-linking also causes a significant increase in the glass transition temperature (T_g) of these rigid polyurethane coatings. This results in many changes in their physical properties, e.g. increased hardness, tensile strength and modules, dielectric strength, cohesive strength, thermal resistance and chemical resistance; decreased elongation, coating tackiness, solubility, and permeability. The better arrangement of the polymers' chain orders, NCO:OH index, and molecular weight of polyols or extenders can impact the coating's adhesion, reactivity, recoatability, and curing properties. The end result of these changes is greatly improved polyurethane coating systems which not only have excellent chemical and corrosion resistance, but also possess superior physical properties and resilience that could match the requirements of being a structural material on their own. Hence, the 100% solids rigid polyurethane coatings can also be described as 'structural' polyurethane coatings. As an example of its improved corrosion and chemical resistance, 100% solids rigid polyurethane coatings have been used as a primary lining material for aggressive chemicals such as saturated NaCl and seawater solutions, toluene, crude oils, saturated NaOH solution, and 25% H_2SO_4, at a dry film thickness of less than 20 mils (500 microns), which is not achievable with 100% solids elastomeric polyurethane and polyurea coatings. While possessing such chemical and corrosion properties that are comparable with the high performance and high solids epoxy systems being used for ballast tank applications, the 100% solids rigid polyurethane coatings technology can still be formulated to have a certain degree of flexibility to overcome the brittleness problems which often occur with the epoxy chemistry.

Figures 2 and 3 illustrate the linear and highly cross-linked molecular structures of the 100% solids elastomeric polyurethane/polyurea coatings and 100% solids rigid and structural polyurethane coatings respectively. Table 1 compares the handling and application properties of 100% solids rigid polyurethane coatings technology with some other typical coating systems currently available for corrosion protection of ballast tanks.

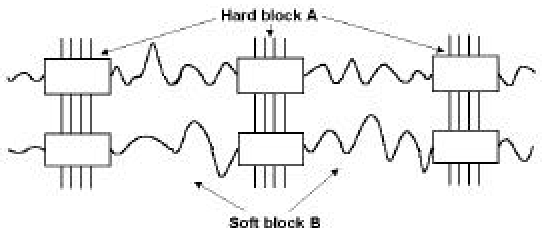


Figure 2. Elastomeric polyurethane coatings[7]

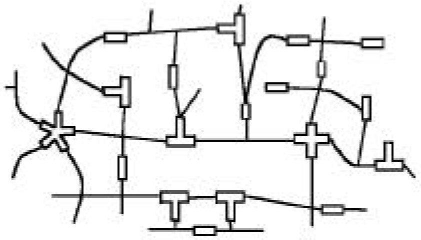


Figure 3. Rigid polyurethane coatings[7]

DEVELOPMENT OF AN EDGE RETENTIVE 100% SOLIDS RIGID POLYURETHANE COATING

When unlimited film build is achieved with 100% solids polyurethanes on either vertical or horizontal substrate surfaces through a multiple-pass but yet one-coat application, the need of developing an edge retentive 100% solids rigid polyurethane coating still exists. New challenges are also faced, because existing mechanisms for an edge retentive coating may not necessarily be applicable to the 100% solids rigid polyurethane due to its rapid curing speed.

The film formation behavior of a liquid coating involves the flow of thin liquid films. A freshly applied liquid coating film normally has an uneven surface. When surface tension can be considered to be uniform, capillary forces tend to reduce surface irregularities to produce a level film. This is the dominant effect leading to relatively uniform, or level, coating film. Such a beneficial effect of surface tension is limited largely to solid surfaces or substrates whose curvature variation is small. In areas where the substrate is highly curved, surface tension can result in defects in the final coating. Highly curved substrates such as edges and corners have an extra surface area. Following the application of a liquid coating to an edge, pure surface tension forces will act to redistribute the coating liquid film. Because of the extra surface energy associated with the edges, the tendency for "pulling" the surface molecules towards the bulk is higher in the edge compared with the adjacent flat areas[8]. As a result, the coating will tend to be thin at the outside edges and thick or "puddle" at the inside edges as the free surface contracts to minimize the surface energy. Moreover, characteristic nodulations can be found in the final coating film. These phenomena result in typical coating corner or edge defects, known as "fat edges", "picture-framing", or "small/poor edge retention". The small edge retention or the lack of coating film thickness at the edges makes the area more vulnerable to mechanical damage, eases the access of chemicals such as water, oxygen, and salts to the steel substrate, and lowers the electrolytic resistance through the coating film which helps the corrosion cell to work, meaning subsequently more aggressive corrosion development at the edges.

Since the “pulling” effect referred to above decreases with surface tension, one would expect that the decrease in surface tension of a coating system should contribute to an improved edge retention[8]. This is not necessarily true, as revealed recently by researchers at Hyundai Industrial Research Institute (HIRI), who found that an epoxy coating with 60% solids content and a surface tension value of 56.6 dyne/cm had much better edge retention than another epoxy coating with 80% solids content and a surface tension value of 44.4 dyne/cm[9]. It is believed that the bulk surface tension of a coating is neither the only nor the predominant factor affecting its edge retention, and surface tension gradients also play a strong role in the dynamics of a drying film in the vicinity of sharp edges/corners[10-11]. Surface tension gradients will occur at the edge due to many factors, such as compositional changes, viscosity changes, and solvent evaporation (hence localized dry times of the coating) during the drying process of a coating. In a solvent based system, for example, solvent tends to be released from the film at the edge of the structure faster than it is released from the film at the plane. This results in the coating at the edge being higher in viscosity and surface tension than the still wet areas within the plane. Under this surface tension gradient, coating tends to flow towards the drying edge and thus the surface tension gradients may help remediate the edge retentive problem. Ideally, however, in order to achieve more uniform coating film thickness at both edges and adjacent areas, it is suggested to eliminate the surface tension gradients by application of proper surfactants[10].

Table 1. Handling and application properties of coatings systems for corrosion protection of ballast tanks

	System 1	System 2	System 3	System 4
Product type	Epoxy coating	Epoxy coating	Elastomer polyurea coating	Rigid polyurethane coating
Primer	No	Yes	No	No
Solids Content (by volume)	98%	>98%	100%	> 98%
Mix Ratio	4:1	4:1	1:1	1:1
VOC (g/L)	40 – 80	71	0	0 – 15
Contains amines	Yes	Yes	Yes	No
Application methods	Brush, Roller and spray	Brush, Roller and spray	Plural component spray	Plural component spray
MFRecommended dry film thickness	18 – 22 mils	12 – 20 mils	30 – 250 mils	25 mil or more
Surface preparation	SSPC – SP10	SSPC – SP10	SSPC-SP10	SSPC-SP10
Blast profile	2- 3 mils	2 – 3 mils	2 – 3 mils	2.5 mil +
Ambient temperature	40 ^{0}F (min)	50 to 90 ^{0}F	-20 ^{0}F to 120 ^{0}F	- 40 to 150 ^{0}F
Substrate surface temperature	> 41 ^{0}F and 5 ^{0}F above dew point	> 41 ^{0}F and 5 ^{0}F above dew point	-20 ^{0}F to 120 ^{0}F and 5 ^{0}F above dew point	- 40 to 150^{0}F and 5 ^{0}F above dew point
Material temperature	50 – 77 ^{0}F	50-90 ^{0}F	150 – 170 ^{0}F (160^{o}F recommended)	100 to 130 ^{0}F
Airless spray pump	Single (60:1) minimum	Single (45:1) minimum	1:1 Plural (35:1)	1:1 Plural (30:1)
Spray pressure	5000 – 6000 psi	3000-5000 psi	2500 psi @ 160^{o}F	1800–2500 psi
DFT per coat	5-6 mils/coat first and then additional coat(s)	4-8 mils (primer) 10 mils (coat)	10 - 100 mils	Unlimited @ multiple passes
Dry to touch	5 hrs @ 77 ^{0}F	24 hrs @ 70 ^{0}F	3 min @ 73 ^{0}F	3-5 min @ 75^{0}F.
Dry to handle	16 hrs @ 77 ^{0}F	48 hrs @ 70 ^{0}F	2 hours @ 73 ^{0}F	5-10 min @ 75 ^{0}F
Time to service	3-4 days @ 75 ^{0}F	7 days @ 75 ^{0}F	12 hours @ 73 ^{0}F	30 min – 1 hour @ 75^{0}F
Ultimate cure	7 days @ 73 ^{0}F	7 days @ 73 ^{0}F	24 hrs @ 73 ^{0}F	5-7 days @ 73 ^{0}F
Recoat time	8 hrs (min) @77^{0}F	10 hrs (min) @70 ^{0}F	3 min - 16 hrs @ 73 ^{0}F	30-45 min @ 73 ^{0}F

However, the edge retention behavior of a 100% solids polyurethane/polyurea coating system is so complex that it cannot simply be explained by either one or both of the mechanisms of surface tension and surface tension gradients. It is important to note that the very simple polyurethane chemistry shown in Figure 1 actually provides a great deal of versatility to coatings formulators that no other coatings resin chemistries could provide. There are hundreds of different isocyanates and thousands of polyols and amines available for the formulator to choose from, resulting in millions of permutations and combinations. If the entire epoxy coating formula could be contained in an egg size space, for example, the formula of 100% solids polyurethane coatings would need a football field size to contain. This analogy is very important, because it tells us that when most high performance, high solids or 100% solids epoxy coatings are quite similar in terms of formulating properties, application properties, and performance properties, two polyurethane coating formulations could have dramatically different application and performance behaviors. Unlike most 100% solids epoxies which normally have a high viscosity and high surface tension, 100% solids polyurethane coating systems can be formulated either with a very low viscosity and surface tension or a very high viscosity and surface tension. The beneficial effect of the surface tension gradients at edges due to solvent evaporation is no longer there with 100% solids polyurethane systems, because of the absence of solvents. Rapid curing behavior of the coating system will also result in dramatic changes of coating compositions, viscosity, surface tension, and surface tension gradients in the vicinity of sharp edges.

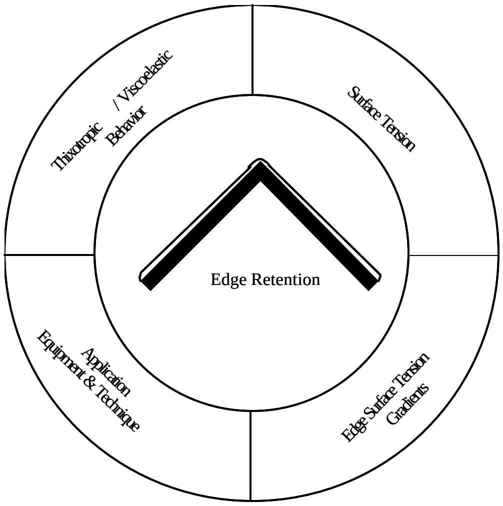


Figure 4. The edge retention behavior of a coating system is the result of combined effects

Our R&D work suggests that the edge retention of a coating system including 100% solids rigid polyurethanes is the result of combined effects of many variables as illustrated in Figure 4. These effects include: 1) thixotropic/viscoelastic behavior of the coating; 2) surface tension of the coating, 3) edge surface tension gradients, and 4) application equipment and technique. A systematic approach will therefore be applied in order to address all the above effects in the development of an edge retentive coating system.

In order to have good edge retention, the coating must first have a rheological or viscoelastic structure which exhibits a thixotropic behavior – being a thixotropic fluid. Thixotropy results from reversible formation of such a rheological or viscoelastic structure within a liquid coating. The coating will first appear to be a thick liquid. When a force is applied to the liquid coating for a sufficient time (for example, shear force from airless spray), it becomes relatively mobile, having lower viscosity. When the shear force is removed, the coating recovers its rheological or viscoelastic structure quickly. A drying coating has a viscoelastic structure, because it is neither pure liquid nor solid during the drying process that transits a coating from a liquid to a solid form. Sometimes this is called a "complex fluid behavior". As a result, the flow of a drying coating or its mechanical properties (shear/strain response) is a combination of viscous flow (liquid-like) and elastic deformation (solid-like) in a dynamic time scale. Figure 5 illustrates the viscoelasticity of a drying coating.

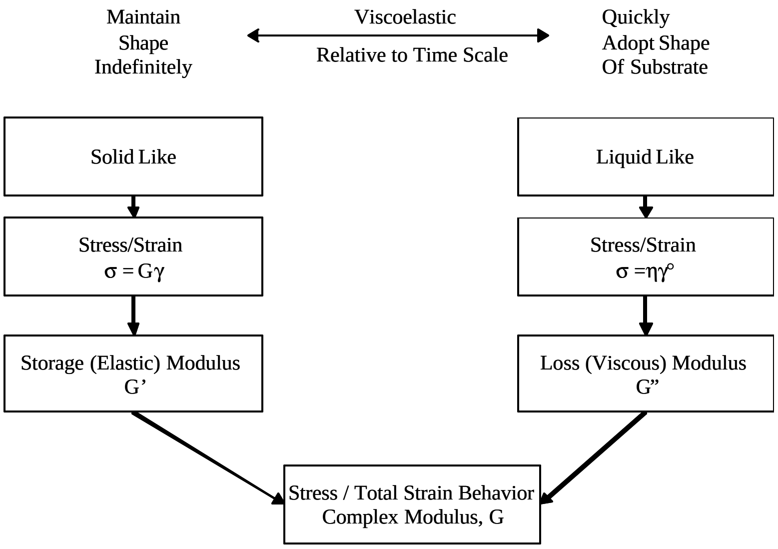


Figure 5. Viscoelastic structure and its dynamic deformation of a drying coating

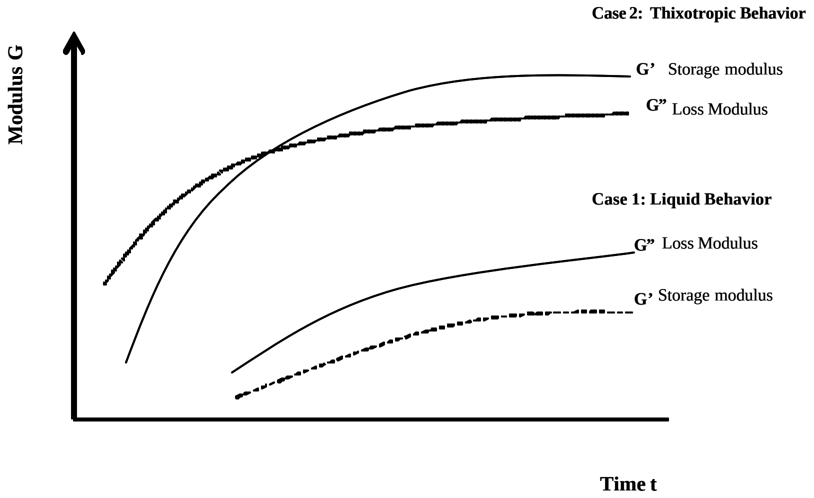


Figure 6. Two different viscoelastic properties of two different coatings

Figure 6 demonstrates the different viscoelastic properties of two different coatings as related to their thoxotropic behavior and edge retention. After the interval with very high shear (the spraying of the coatings), both coatings regenerate their structure. However, how they regenerate their structure differs for each coating. In Case 1, after spraying or shearing at a high shear rate, the coating requires a long time before it sets. The two corresponding curves show the mechanical condition of the coating. If the loss (viscous) modulus of the coating is higher than the storage (elastic) modulus, the coating is displaying liquid behavior. This means that the coating still flows (runs) after a period of time and it will adopt the shape of the substrate, leading sagging on a flat and vertical surface or poor edge retention at edges. In Case 2, on the other hand, immediately after spraying, the viscosity of the coating increases rapidly and after a short period of time, the storage modulus curve is higher than the curve of loss modulus. From then on, the coating behaves like a solid.

The objective of developing an edge retentive, 100% solids rigid polyurethane coating system is therefore very clear: to formulate a coating system that has a viscoelastic structure to behave as a thoxotropic fluid; that has a proper surface tension in bulk and a proper surface tension gradient at edge so that it could spread uniformly over both flat surfaces and edges; and that has proper dynamic formulating and application properties with adequate application equipment and technique, so that the coating will be able to set immediately or quickly only after it spreads around the edge.

The objective was fulfilled. Figure 7 shows a rheogram that follows data generated at 45°C (113°F) by pre-shearing coatings at 100 sec^{-1} for 30 seconds and measuring the recovery of structure (G' growth) with time by an oscillation time sweep at 0.5% strain. The growth of the storage modulus (G') was monitored and the data indicates a significant improvement in the rate and degree of structure recovery with the edge retentive modified coating with the controlled and unmodified coating. This test simulates the actual application since the oscillation is done at a strain that does little or no damage to the sample's structure while the structure is recovering.

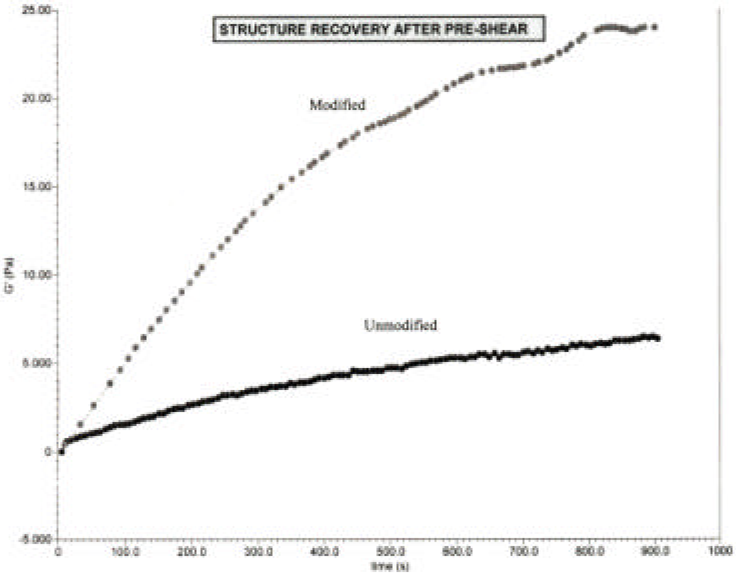


Figure 7. Structure recovery of 100% solids rigid polyurethanes after pre-shear at 100 sec^{-1} and 45°C (113°F)

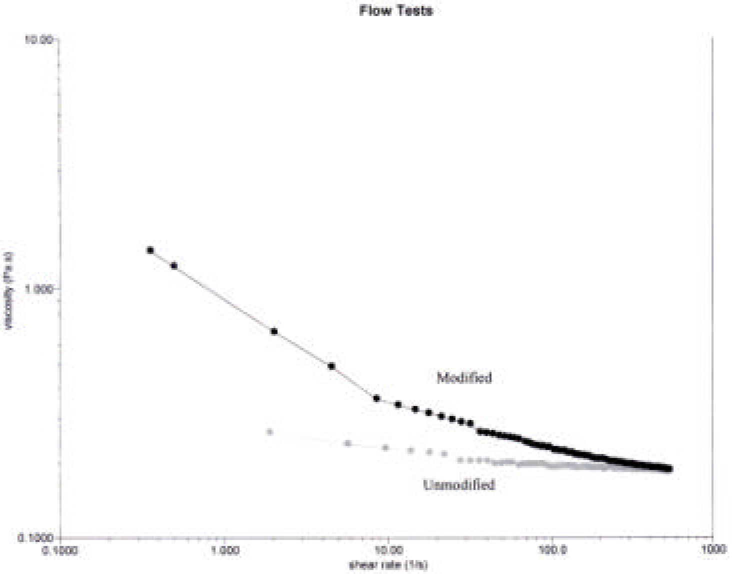
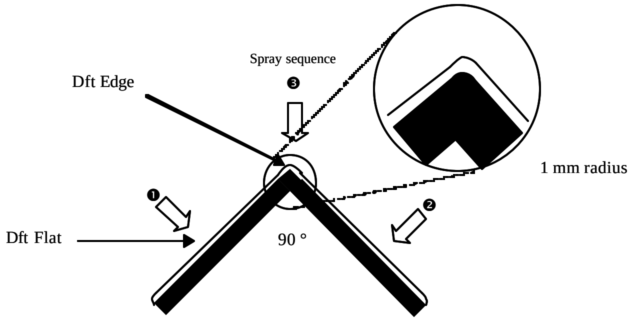


Figure 8. Flow test of 100% solids rigid polyurethanes at 45°C (113°F)

The flow test results illustrated in Figure 8 confirm the higher structure of the edge retentive modified 100% solids rigid polyurethane by its higher viscosities at low shear rates while the convergence of viscosity at higher shear rates would indicate that the modified version would have similar and excellent sprayability to the controlled and unmodified coating at the testing temperature of 45°C (113°F). The excellent sprayability of both modified and unmodified 100% solids polyurethane coatings is supported by the fact that their viscosity is significantly lower than the viscosity values of those other coating systems available in the market for ballast tank applications. Other types of coatings are needed to be pre-heated and applied at much higher temperatures than 45°C (113°F), in order to achieve a suitable viscosity for proper mixing and atomization.

The new edge retention behavior of the 100% solids rigid polyurethane coating was tested with the help of cross section microscopic photography of coated aluminum angles of 1 mm radius, by following a modified testing protocol of MIL 23236 Specification[12] as shown in Figure 9.



$$\% \text{ Edge Retention} = \frac{\text{Dft Edge}}{\text{Dft Flat}} \times 100$$

Figure 9. Testing protocol for edge retention of a coating

Actual edge retention measurements for the edge retentive 100% solids polyurethane coatings system produced data ranging from 83 to 100%, with an average of 91%. Examples of these edge retention measurements on the edge retentive modified 100% solids rigid polyurethane coating samples were as given in Table 2. Figure 10 and 11 give an example of cross-section views for edge retentive modified and unmodified 100% solids polyurethane coatings respectively.

Table 2. Edge retention measurements of a 100% solids rigid polyurethane coating for ballast tank

	ER reading 1 (%)	**ER reading 2 (%)**	**ER reading 3 (%)**	**Average**
Sample 1	19/19 (100)	17/19 (89.47)	17/20 (85.00)	91.49
Sample 2	18/20 (90)	18/20 (90)	20/21 (95.24)	91.75
Sample 3	20/24 (83.33)	20/23 (86.95)	20/22 (90.90)	87.08
Overall average ER (%) Average coating film thicknesses were around 32 mils, 0.016” module, 1 mm radius				90.91

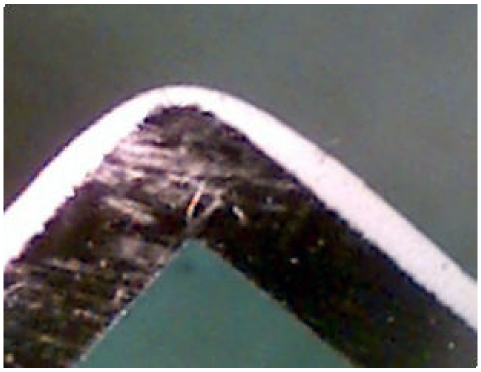


Figure 10. An unmodified 100% solids rigid polyurethane coating had 52% of edge retention

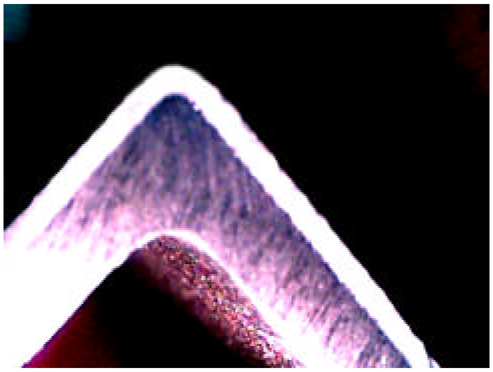


Figure 11. A modified 100% solids rigid polyurethane coating had 95% of edge retention

The use of adequate application equipment and technique also plays a role in the edge retention of the final coating film. As per the earlier discussion in this paper, edge surface tension gradients are related to compositional changes, viscosity changes, and dry time during the drying process of the coating. This is particularly true for multi-component coating systems cured by a chemical curing mechanism. The use of different equipment configuration, such as mixing modules, tip output, spray pressure, would affect the extent of proper mixing, spray fan atomization, and the chemical reaction of reactive components, hence affecting the surface tension gradients at the edges. Table 3, for example, shows the difference in edge retention of the same coating formulation used in Table 2 when a different mixing module was used. The best size selection of mixing module for this 100% solids rigid polyurethane coating for the spray gun that was used was 0.016”.

Table 3. Effect of application equipment on the edge retention of a 100% solids rigid polyurethane coating

	ER reading 1 (%)	ER reading 2 (%)	ER reading 3 (%)	Average
Sample 1	19/25 (76.00)	21/24 (87.50)	19/27 (70.37)	77.96
Sample 2	21/28 (75.00)	20/28 (71.43)	20/26 (76.92)	74.45
Sample 3	21/25 (84.00)	18/21 (85.71)	18/22 (81.81)	83.84
Overall average ER (%) Average coating film thicknesses were around 34 mils, 0.018” module, 1 mm radius				78.75

CASE HISTORIES

USS Gunston Hall

Tank 3-121-1-W on the USS GUNSTON HALL (LSD 44) was coated with 100% solids, rapid-cure, rigid polyurethane coating. The coating was applied by approved applicators. The objective of this trial is to test the rapid cure, 100% solids rigid polyurethane coating and application in real conditions. The tank was successfully completed and put in service (Figure 12 and 13).

During this project, one of the most important lessons learned was the importance of planning the spray sequence and level of teamwork required to have adequate quality control. For this coating application, it was recommended to have an inspector with calibrated dry film thickness (DFT) gauges in the tank with the applicators to identify areas with low DFT so they can be recoated within the specified time window under the environmental and ambient temperature conditions. The equipment utilized was a plural component pump with a mechanical purged gun. The spray gun utilized was an old version that produced excessive off-ratio spit every time the gun was triggered. This and other considerations were taken into account to improve the equipment.

Figure 12. A corroded ballast tank of USS Gunston Hall

Figure 13. The ballast tank was coated with a 100% solids rigid polyurethane coating

USS Whidbey Island (Figure 14)

Two ballast tanks on USS Whidbey Island were coated with the 100% solids rigid polyurethane coating: T 1-003 and T1-029.

The USS Whidbey Island project was postponed several times for chloride contamination on the steel surfaces. The maximum allowable chloride and salt presence according to specifications is 3 μg/cm^2 (micrograms per square centimetre) or 30 μs/cm (microseams per linear centimeter). An approved applicator team performed the application. Prior to this date, the applicators received refresher training and the pump was set up for the application. One important modification done on this project was the colour selection of the coating. The parent coating was selected in white to help the painters to identify low spots and holidays. The stripe coating was also adjusted in different shade of white to help the quality assurance.

The equipment utilized for this application was adjusted with the previous experience in the USS Gunston Hall. The gun was a new version of a mechanical purged gun with direct impingement, to reduce off ratio spitting. The pump and the hoses were also modified to be more flexible.

Figure 14. USS Whidbey

Figure 15. USS George Washington

USS George Washington (Figure 15)

The USS George Washington was the first nuclear powered aircraft carrier to have a ballast tank repaired with the 100% solids rigid polyurethane coating. A wing ballast tank was assigned for this project. The project was successfully completed and the tank was coated with excellent results. An approved applicator team again applied the coating for this project.

The equipment was further enhanced for this project. The pump was located further away for this application and a longer heated hose system was utilized. Also a new temperature control system was installed in the pump and hoses. These improvements allow the applicators to achieve complete control in the application. The large output of the gun became an issue for small and geometrically complicated structures. A low-output gun was determined to be the best option.

SUMMARY

An advanced, 1:1 plural-component, rapid-cure, edge retentive, 100% solids, rigid and structural polyurethane coatings technology for corrosion protection of ballast tanks has been presented. Results of both laboratory and shipboard projects indicate this technology is a very promising coatings technology to offer corrosion protection, fast throughput, and cost savings in ballast tank applications.

When unlimited film build is achieved with 100% solids polyurethanes on either vertical or horizontal substrate surfaces through a multiple-pass but yet one-coat application, the need for developing an edge retentive 100% solids rigid polyurethane coating still exists. New challenges are also faced because existing mechanisms for an edge retentive coating may not necessarily be applicable to the 100% solids rigid polyurethane due to its rapid curing speed.

The edge retention of a coating system including 100% solids rigid polyurethanes is the result of combining effects of many variables as illustrated in Figure 4. These effects include: 1) thixotropic/viscoelastic behavior of the coating; 2) surface tension of the coating, 3) edge surface tension gradients, and 4) application equipment and technique. A systematic approach will therefore be applied in order to address all of the above effects in the development of an edge retentive coating system.

New challenges also accompany the 100% solids rigid and structural polyurethane coatings technology in terms of substrate surface and environmental conditions, application techniques and equipment requirements.

REFERENCES

1. Erik Arkheim, “Ballast Tanks and Cargo Holds”, Protective Coatings Europe, 1997, p 26

2. Arthur A. Webb, Beau Brincherhoff, Lee Rice, and Paul Bizot, “Reducing Navy Fleet Maintenance Costs with High-Solids Coatings and Plural-Component Spray Equipment”, Journal of Protective Coatings and Linings, March, 2003, p54

3. Wayne Geyer, Handbook of Storage Tank Systems Available Now, Marcel Dekker, Inc., 2000

4. ASTM, Standard Terminology for Paint, Related Coatings, Materials, and Applications, D16-00

5. Charles Munger, Corrosion Prevention by Protective Coatings, NACE International, 1986, p.112

6. NACE International, Standard Recommended Practice for Lining Over Concrete for Immersion Service, RP0892-92, 1992, p. 6

7. Shiwei William Guan, “100% Solids Polyurethane and Polyurea Coatings Technology”, Coatings World, March, 2003, p.49

8. Mario P. De Paiva and Joao Martins, “An Edge Retentive Coating Solution Based on a Tolerant Solvent-Free Epoxy System”, The Proceedings of the Seminars of SSPC 2000 , Nashville, Tennessee, November 12-16, 2000, p. 54

9. M.K. Chung, C.S. Park, C.H. Lee, and K.K. Baek, “Approachies for Achieving Successful High Build Coatings on Sharp Edges in Ship’s Ballast Tanks”, National International Corrosion 2003 Conference, San Diego, California, March 16-20, 2003. Paper No. 03010

10. Clive Hare, “Paint Flow Defects”, Journal of Protective Coatings and Linings, May, 2001, p. 78
11. D.E. Weidner, L.W. Schwartz, and R.R. Eley, “Role of Surface Tension Gradients in Correcting Coating Defects in Corners”, Journal of Colloid and Interface Science, Vol. 179, 1996, p.66-75

12. MIL-PRF-23236C(SH), Performance Specification – Coating Systems for Ship Tanks and Steel Structures, October 27, 1997