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100% Solids Rigid Polyurethane Coatings Technology and Its Application on Pipeline Corrosion Protection

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Abstract:

The paper reviews the 100% solids rigid polyurethane coatings technology and its increased application on pipeline corrosion protection over the past twenty-five years. The paper begins with the chemistry and performance properties of the technology. The paper then discusses the differences between this technology and other protective coatings systems, providing some guidelines as to the selection of a proper corrosion protective coatings solution for pipelines. Finally, the paper reviews several case histories of the 100% solids rigid polyurethane coatings technology in typical municipal, marine, and oil/gas pipeline applications.

Introduction

One of the most effective and efficient methods for preventing today's pipelines from both internal and external corrosion is the use of a proper protective coating system with or without cathodic protection. The function of a coating system is to act as a barrier that prevents either chemical compounds or corrosion current from contacting a pipe substrate. In order to fulfill this function, however, a modern pipe coating system has to be able to meet the following five challenges: environmental and safety regulations, economics, shop and field application conditions, effectiveness, and high performance (Guan, S., 2001). From the very first years that polyurethanes were introduced into the pipeline market, most engineers recognized the capability of the versatile polyurethane chemistry in meeting these challenges to establish a good shop and field-applied coating technology for new pipeline installation or repair. Over the past ten years particularly, there has been an industrial trend towards the development and use of high-performance 100% solids rigid or structural polyurethane coatings for corrosion protection of all three pipe substrates: steel, ductile iron, and concrete. An example is the most recent AWWA C222 standard that describes the material and application requirements of 100% solids rigid polyurethane coatings for the interior and

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exterior of steel water pipe, fittings, and special sections below (AWWA, 1999). Another example is the current work of NACE Task Group (TG) 281, administered by NACE Specific Technology Group (STG) 03, in developing a NACE standard recommended practice for the use of polyurethane coatings for field repair, rehabilitation, and girth weld joints on pipelines. This standard is applicable to underground steel pipelines in the oil and gas gathering, distribution, and transmission industries.

Chemistry and Performance Properties

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 (Geyer, W., 2000). A tank can be basically viewed as a pipe with two closed ends. If such an underground tank could be installed to eliminate corrosion, why not coat an underground pipe with that very same coatings technology? This idea has resulted in the use of the 100% solids rigid coatings in pipelines. In water/wastewater transmission pipeline applications, 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 100% solids rigid coatings are becoming one of the two preferable plant-applied coating choices of the U.S. steel water/wastewater pipe industry, the other being tape coating. It is expected that within the next five years all tape coating systems will eventually be phased out for steel water/wastewater transmission pipe, and replaced by 100% solids rigid polyurethanes (Dechant, D., 2001). The same technology has also gained popularity in oil/gas pipe installation and repair.

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 (ASTM (2000)). 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.

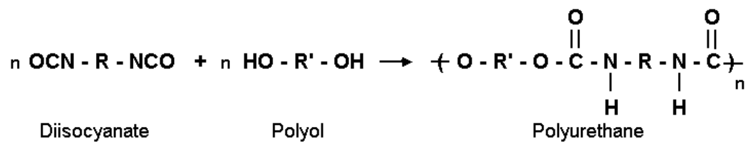

Figure 1. The polyurethane chemistry

Many architectural and industrial coatings available from the market are solvent-based systems. However, 100% solids coatings such as 100% solids rigid polyurethanes are becoming the preferable 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. Further, 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 carriers for pigments and catalysts. In addition to containing no solvents or VOC's, today's 100% solids rigid polyurethane coatings used in the North American water/wastewater pipeline industry contain no styrene, amine, tar 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 both shop and field applications for pipeline corrosion protection. First, because of the rapid curing speed of 100% solids polyurethane coatings, the coated pipe can be holiday tested and buried 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^{o}C (-40^{o}F) and retain their performance characteristics, which is impossible for other types of coatings. Finally, no heat is required during the application process to ensure the polyurethanes will cure, and the coatings can be applied to almost any thickness on any diameter or length of pipe.

Early products of polyurethane coatings used in North American pipeline industries 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 so called polyurea coatings) are products of the reaction of difunctional isocyanates with long chain difunctional polyols or a mixture of di- and tri- functional polyols, using short-chain difunctional polyols or diamines as chain extenders. The major advantages of elastomeric polyurethane 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 substrate or existing plant-applied pipeline coatings, 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 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 used often have a high mixing ratio (e.g. 4.5:1) and 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 (NACE, 1992 and Munger, C.G., 1986). Figure 2 is a photo of an elastomeric polyurethane internal lining material which failed due to its poor adhesion to steel, even when a primer was used.

Figure 2. **The** failure of an elastomeric polyurethane lining

100% solids rigid polyurethane coatings are designed to be free from the shortcomings associated with those poorly performed elastomeric polyurethanes. 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 liner 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 (Guan, S., 2002). 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 (Table 1), 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.

Table 1. Performance properties of typical elastomeric polyurethane, elastomeric polyurea, and rigid polyurethane coatings used for pipeline applications

	Elastomeric polyurethane	Elastomeric polyurea	100% Rigid polyurethane
Typical application thickness for steel	1 mm to 1.5 mm (40 to 60 mils)	1 mm to 1.5 mm (40 to 60 mils)	0.38 mm to 0.75 mm (15 to 30 mils)
Typical application thickness for concrete	1.5 mm to 3.8 mm (60 to 150 mils)	1.5 mm to 3.8 mm (60 to 150 mils)	1 mm to 2 mm (40 to 80 mils)
Adhesion to steel (SP10, 2 mil profile)	700–2,200 psi	500–2,000 psi	1,000–4,000 psi
Cathodic disbondment (ATM G95, 3% NaCl, -1.5 volts, 30 days, 23°C)	10 mm to 35 mm disbonding radius	25 mm to 38 mm disbonding radius	3 mm to 15 mm disbonding radius
Chemical resistance (ASTM D716, 1,000 hours immersion)			
20% NaOH	Pass	Pass	Pass
10% H_2SO_4	Pass	Pass	Pass
25% H_2SO_4	Fail	Fail	Pass
3% NaCl	Pass	Pass	Pass
Gasoline	Fail	Fail	Pass
Toluene	Fail	Fail	Pass
Dielectric strength ASTM G149	5-20 V/µm	5-20 V/µm	10-30 V/µm
Elongation, %	50-1,500%	20-1,000%	3-50%
Impact resistance, fully cured, 1 mm (40 mils) DFT	80-200 in.lbs	60–200 in.lbs	30–125 in.lbs or 45–160 in.lbs* * ceramic modified
Shore Hardness	A20 to D65	A20 to D65	D50–D90
Taber abrasion resistance (CS17, 1 Kg, 1000 cycles), fully cured	2–40 mg weight loss	6–70 mg weight loss	30–60 or 10-30* mg weight loss * ceramic modified
Tensile strength	1,000–2,000 psi	1,100–4,000 psi	3,500–7,000 psi
Water absorption (ASTM D570, 48 hours at 50°C/122°F)	5-15%	5–16%	1-2%

100% Solids Rigid Polyurethane Coatings for Pipeline Application

An ideal pipe coating shall be environmentally friendly, work safe, durable and able to expose little or no metal/substrate surface to the environment, while also being resistant to environmental, mechanical and chemical damage from the initial stage of handling and installation through its entire service life. It should also come at a reasonable cost (Guan, S., 2001). This means the implementation of six key consideration attributes in pipe coating selection outlined in Table 2.

Table 2. Key consideration attributes in pipe coating selection

Attribute	Main Considerations
Handling and safety characteristics	Format, mixing ratio, solids content, compliance with OSHA, EPA, and FDA environmental and health standards such as VOC and industrial or standard requirements such as NSF 61 for water safety, flammability, application methods; Containing of any hazardous ingredients such as coal tar, amines, solvents, etc.
Shop/field application and repair attributes	Quality and inspection; Technical support of the coating's manufacturer; Ease of application and repair; Environmental conditions (e.g. humidity, ambient temperatures, dew point, etc).
Surface preparation requirements	There should be no short cut here; Blasting profiles; Surface containment levels; Surface preparation for field coating.
Physical performance requirements	Properties such as adhesion; permeability; impact, penetration, and abrasion resistance; cathodic disbondment resistance; flexibility; chemical resistance, as results of considering the type of soil and back fill; the use of cathodic protection; pipe installation methods and location; corrosive environmental conditions.
Case histories	Performance and capability of shop/field technical support, particularly while selecting and launching new pipe coating systems.
Cost analysis	The true coating cost is the sum of materials cost + application cost + maintenance cost +hidden cost Coats to be applied; Hidden costs such as project timing; flow efficiency of the lining; installation and repairs; and operation cost.

In Table 3, advantages and limitations of 100% solids rigid polyurethane coatings are compared with several pipe coating/lining materials commonly used today. Compared with the other pipe coating systems, 100% solids rigid polyurethanes have been demonstrated to be by far the most successful protective coating systems used for both exterior and interior applications. These polyurethane coatings have excellent adhesion to steel, ductile iron and concrete, combined with excellent chemical resistance, impact resistance, resistance to cathodic disbondment, and abrasion resistance. The fast setting (drying) nature of the 100% solids polyurethane coatings also means that they are very suitable for rapid application lines during pipe production, and they can be applied to any film thickness at virtually any ambient temperatures. The success of the 100% solids polyurethane coatings on steel, ductile iron and concrete pipes has been confirmed in water and wastewater as well as oil and gas distribution systems in North America, the Middle East, several European countries, and very recently, in a number of Asian countries.

Table 3 Comparison between several common pipe coatings with 100% solids rigid polyurethane

Coating system	Advantages	Limitations	Application
Bituminous enamels	Easy to apply; Minimal surface preparation required; Long track record; Permeable to cathodic protection; Very Economic	Subject to oxidation and cracking; Soil stress has been an issue; Limitations at low application temperatures; Environmental and exposure concerns; Associated with corrosion and stress crack corrosion failures	Exterior; Usage has been diminished
Tape coating	Simple application	Poor shear stress resistance; Many documented failures; Easy damage; Adhesives subject to biodegradation; Exterior only; Shield effect to CD possible	Exterior; Water & wastewater pipe
2 LPE	Excellent track record; Good handling	Limited temperature range; Poor shear stress resistance; Limited pipe size (<24); Field application	Mostly oil & gas pipe; Main line
FBE	Excellent corrosion resistance	Low impact resistance; limited to pipe size (< 43 inch); Field application	Mostly oil & gas pipe; Main line
Solvent or 100% solids epoxy	Economical; long history; Most uses conventional airless equipment to apply; can be brushed on	Slow curing; Poor low temperature curing ability; Multiple coats; Poor impact and flexibility	Pipe and joints
Cement mortar	Minimal health and safety or environmental issues; fast to apply; no blasting; well proven and documented history; inexpensive; total applied cost is low	Easily damaged; Can't be applied in cold weather; Add significant weight to pipe; Reduces pipe diameter and pipe capacity; Difficult to use apply in fabricated pipe (elbows, fittings, etc.); poor abrasion and chemical resistance	Mostly water pipe & interior
Polyethylene encasement	Simple application; Very economical	Restrict the subsequent use of cathodic protection; Easy damageable	Exterior and DIP only
T Lock system	Cast in application; no surface preparation	Limited success; Corrosion due to damage of the sheet	Interior and concrete
100% solids rigid polyurethane	Low temperature curing; Fast setting; Excellent abrasion and impact resistance; Adhesion	Need to use plural component system; Application complexity; Sensitive to moisture	Both shop and field; Mainline and joints

The polyurethane coatings can be used in conjunction with cathodic protection systems for protecting ductile iron and steel pipes, where the function of the coatings is both to improve degree of protection and also to reduce the capacity of the cathodic protection installation required to achieve complete immunity from corrosion attack. In the interior application of a concrete sewer pipeline, good results are achieved with 100% solids polyurethanes if the concrete surface is dry, clean and free of any visible bug holes or cracks. Otherwise, suitable rendering materials such as an epoxy-polyurethane hybrid are manually applied before the 100% solids polyurethane is sprayed, providing a holiday-free coating film for corrosion resistance.

Recent developments in the 100% solids polyurethane coatings technology have resulted in three innovations from which the water and wastewater industry can particularly benefit. One innovation involves the development of a protective lining that incorporates anti-microbial additives. There are two commonly used methods for protecting wastewater structures from corrosion. The most common method is the use of a membrane or barrier between the structure and its corrosive environment. 100% solids rigid polyurethane coatings have been used for this purpose for years because of their flexibility, adhesion, inertness, and their resistance to abrasion and chemical attack. A second and newly established protection method involves altering the characteristics of the environment to diminish or eliminate the corrosive environment. With the anti-microbial modification, the 100% solids rigid polyurethane linings offer long-term corrosion protection by modifying the environment while protecting the substrate.

While 100% solids rigid polyurethanes feature superior abrasion resistance, applications involving extremely high flow rates and unusually abrasive instances demand something more. Newly developed ceramic modified coatings are engineered to meet the challenge of highly abrasive or high flow applications, offering even better durability, impact, corrosion, and chemical resistance.

The third innovation is the development of edge retentive polyurethane coating systems. When an unlimited film build could be obtained by 100% solids rigid polyurethane coatings, the improvement of edge retention per coat makes them perfect for structures involving a lot of corners, edges, and difficult-to-reach areas such as ballast tanks, pilings, and complicated storage tanks.

Case History

The Northwest Tacoma/Federal Way Transmission Main is a joint effort by Tacoma Water and Lakehaven Utility District. It supplies Lakehaven Utility District in Federal Way with additional water from Tacoma Water's surplus supply. The project includes 8.7 miles of 48" to 60" inch diameter spiral welded steel pipe. The Washington-Oregon border experienced some of the largest earthquakes in the United States between 1872 to 1987. The earthquakes' epicenters were felt over an area of at least 50,000 square kilometers or were rated VII or more on the Modified Mercalli Intensity Scale. Tacoma Water was reluctant to line the pipe with cement mortar due to fluctuating water quality concerns with pH levels, and also cement mortar failures under seismic conditions. During the course of the pipe laying operation the contractors experienced 10 earthquakes occurrences about 5-6 miles below the surface of the earth with magnitudes between 0.8 and 2.1 and the pipeline remained undamaged. The rigid polyurethane chemistry has been engineered to meet the elongation, flexibility, and deflection characteristics of steel pipe. It was a definite choice for Tacoma Public Utilities when they were researching alternate lining systems for this pipeline system. The total Tacoma Pipeline will consist of over 30 miles of steel pipe lined with the 100% solids rigid polyurethane. The cold cure property of a 100% solids rigid polyurethane allowed the general contractor to line the joints during winter and summer months. The production rate was on average 20-25 field joints per day.

During 1997 and 1998, Newfoundland Transshipment Limited (NTL), a joint venture of several major oil companies, constructed a transshipment terminal at Whiffen Head, Newfoundland, in order to store crude oil from the Hibernia oilfield. Oil will be shipped from Hibernia to the terminal on shuttle tankers and taken from the terminal to market on second-leg tankers. The marine offshore facilities include an approach causeway, tug basin, trestle, and jetty, with berthing and marine topside facilities (crude transfer and control system). On behalf of NTL, Friede Goldman Newfoundland Ltd. constructed two escort and docking/firefighting tugs, the Placentia Pride and Placentia Hope. These purpose-built, state of the art 5600 horsepower tugs, measuring 38 metres long, are used to escort and assist crude oil tankers into and out of the terminal port. Each tug is capable of effective emergency firefighting - shooting 13,000 gallons of water and / or foam every minute. The steel marine pilings used for these tugs were coated a 100% solids rigid polyurethane coating system. The rigid polyurethane technology not only provided the capability of field coating application at below freezing temperatures (up to -20^{o}C) during the construction, but has been protecting the steel structure under harsh and cold marine corrosion environment, due to its cold temperature flexibility, excellent impact resistance, and corrosion and chemical resistance.

Located in Tianjin, China, DaGang oilfield is the third largest oil field in that country and one of the main oil and gas suppliers to northeastern Chinese cities. The 100 km x 21-inch diameter DaGang-CangZhou gas pipeline was installed in 1973, originally protected by a petroleum asphalt enamel coating. Since then the pipeline has faced severe corrosion problems, which were not resolved even after numerous localized rehabilitation applications. In 2001, the gas company decided to completely refurbish the pipeline. The 100% solids rigid polyurethane coating technology was selected for a river crossing and some underground/aboveground portions. The applications were conducted between November 2001 and May 2002, with field application temperature ranging from -15^{o}C to 30^{o}C. The field inspection included two elements: in-situ adhesion and holiday inspection and field sample preparation for lab testing. At -15^{o}C, the field-applied coating cured in 5 minutes. Adhesion and holiday testing were then conducted within 60 minutes of the coating application. It was found that at that time, the coating breakdown testing voltage already reached 12 kV (more than 342 volts per mil). The field-coated samples were sent out immediately to the Pipeline Coating Testing Centre of the Research Institute of Engineering Technology of China National Petroleum Corporation. Results of both field inspection and lab evaluation showed that the properties of the 100% solids rigid polyurethane coating exceeded all liquid-applied epoxy systems utilized in China.

In the State of Texas, U.S.A. in 1998, a new 48” (1.2 m) water transmission pipeline was being constructed in order to permit the City of Corpus Christi to double in size. A 3,400 foot slip bore section crossing the Guadalupe River and the Victoria Barge Canal is believed to be the world’s longest directional drill, slip bore river-crossing project ever completed. The project involved the use of a 20 mil, potable water grade internal lining and a 40 mil external coating. The pipeline project originally specified an FBE coating system; however, the specification was then changed to 100% solids rigid polyurethane for both mainline and field joints due to the concern of abrasion and corrosion protection for such a long directional drilling application. The consequent corrosion survey along the pipeline rated the effectiveness of the corrosion protection as “very good levels” at 93% or higher.

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Summary

100% solids rigid polyurethanes are rapidly replacing older coating products in pipeline applications because of proven features and benefits associated exclusively with this technology. In addition to offering excellent handling and safety advantages plus application capabilities such as instant setting times and cold weather cure, differing from elastomeric polyurethane or polyurea systems, 100% solids rigid polyurethane coatings also provide performance advantages over other products including outstanding adhesion values, excellent chemical, impact and abrasion resistance, flexibility, resistance to cathodic disbondment and undercutting.

References

ASTM (2000). ASTM Standard Terminology for Paint, Related Coatings, Materials, and Applications, D16.

AWWA (1999). AWWA C222-99, “Polyurethane Coatings for the Interior and Exterior of Steel Pipelines and Fittings”, AWWA, Denver, CO.

Dechant, D. (2001). Private communications

Geyer, W. (2000). Handbook of Storage Tank Systems Available Now, Marcel Dekker, Inc.

Guan, S. (2001) “Corrosion protection by coatings for water and wastewater pipeline”, Appalachian Underground Corrosion Short Course, Water and Wastewater Program, West Virginia University, PA, May 15, 2001

Guan, S. (2002). “100% solids polyurethane and polyurea coatings technology”, The proceedings of the 2nd China International Corrosion Control Conference, Beijing, P.R. China, November 4-8, 2002

Munger, C.G. (1986). Corrosion Prevention by Protective Coatings, NACE International, 1986, p.112

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