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100% Solids Polyurethane Coatings Technology For Corrosion Protection In Water and Wastewater Systems

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ABSTRACT

The paper presents 100% solids polyurethane technology as a viable alternative to conventional epoxy systems for corrosion protection in water and wastewater systems because it is safer, faster to apply, more economical and offers greater longevity. The paper covers the basic definition and history of the 100% solids polyurethane technology as well as its wide range of applications in a variety of industries. It also highlights the specific advantages of the 100% solids polyurethane technology compared to conventional epoxy systems in terms of environmental and safety issues, application, performance and cost. Finally, the paper chronicles several case histories of the technology in water and wastewater applications in both the Gulf and North America.

1. INTRODUCTION

For years the water and wastewater industry has required a corrosion protective coating/lining system that is able to withstand the corrosive environment heavily experienced by our industrial and municipal infrastructure. In order to fulfill this requirement, a corrosion protective coating/lining system has to be able to meet three challenges: environmental and safety regulations, the economics of each project, and high performance. Engineers must strike a balance between these three areas in refurbishing or designing new water and wastewater treatment facilities. The ideal coating/lining system features maximum efficiency as well as environmental and safety compliance, boasts a long service life and comes at a reasonable cost.

It is indeed not an easy task to meet the above three challenges altogether. Different corrosion natures and requirements from each of today’s water and wastewater sectors further complicate the problem. When compliance with rigorous regulations on volatile organic compound (VOC) emissions has become a must for any coating/lining system, as a minimum, the system being considered and offered for potable water use has to be certified under rigorous standards (e.g. NSF 61 standard) for drinking water safety. In the wastewater area, resistance of a lining against microbiologically influenced corrosion (MIC) becomes more important than ever, thereby reducing the level of use of poorly performed lining systems such as cement-mortar. In the industrial water area, higher flow rate and harsher environments also demand the better performance from all coating/lining systems.

The best overall protective coatings technology for water and wastewater application is 100% solids polyurethane. This simple polyurethane chemistry (the reaction product between an isocyanate and a polyol) plays a vital role in many industries and in our everyday activities. 100% solids polyurethanes are rapidly replacing older coating products like conventional epoxy systems because of proven features and benefits associated exclusively with this technology. 100% solids polyurethanes are less toxic than traditional epoxies for both the water users and applicators. Their performance advantages over other coatings products include outstanding adhesion values, excellent chemical, impact and abrasion resistance, flexibility and resistance to cathodic disbondment and undercutting. In addition, 100% solids polyurethanes offer instant setting times and cold weather cure capabilities, thus reducing the total applied costs while dramatically increasing throughput time.

The paper covers the basic definition and history of the 100% solids polyurethane technology as well as its wide range of applications in a variety of industries. It also highlights the specific advantages and disadvantages of the 100% solids polyurethane technology compared to conventional epoxy systems in terms of environmental issues, application, performance and cost. Finally, the paper chronicles several case histories of the technology in water and wastewater applications in both the Gulf and North America.

2. WHAT IS A 100% SOLIDS POLYURETHANE?

2.1. Definitions

Polyurethane is a very versatile thermoset plastic that was originally developed for military use by Otto Bayer in the late 1930's[1]. It is simply the reaction product of an isocyanate and a polyol (Figure 1):

$$\underset{\text{(Isocyanate)}}{\text{R-NCO}} \quad + \quad \underset{\text{(Polyol)}}{\text{R'-OH}} \quad = \quad \underset{\text{(Polyurethane)}}{\text{R-NH-COOR'}}$$

where R and R’ are reacted group

Figure 1. Polyurethane reaction

It is virtually impossible for anyone in the 20th century world to *not* come in contact with a variety of polyurethanes several times during a day. It is estimated that the average family probably owns somewhere between 10 and 50 kilos of polyurethane[2]. Flexible polyurethane foams are used to make bedding, sofas, cushions, carpet backs and car seats. Rigid foams are used for insulation in freezers, refrigerators and roofs. Many shoe manufacturers use the tough elastomeric polyurethanes for shoe soles. The automobile industry makes over 20% of materials in a modern car out of polyurethane such as dashboards, bumper covers, mouldings, and fenders. There are many types of polyurethane coatings as well, ranging from bridge coatings to floor sealers to tank linings.

100% solids polyurethane coatings usually consist of two components: one isocyanate-rich solution and one polyol-rich solution. This has been defined as an ASTM D16 Type V polyurethane coating. Such a polyurethane coating film is formed when the two components are combined; a rapid and exothermic chemical polymerization reaction takes place. 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 supplied to the applicator as liquid components having paint-like viscosities) will convert 100% to a solid film after application. The exact viscosity of the coating system is determined by the selection and design of the resin components. It is not determined by the addition of a solvent, a practice still common in the coatings industry but obviously not a formulation option if the system is to be non-flammable and contain zero VOC's for safety and other reasons.

2.2. Types of 100% Solids Polyurethanes

Depending on the type of isocyanate used, 100% solids polyurethane technology comes in two different forms: aliphatic polyurethane or aromatic polyurethane. Aliphatic polyurethanes are polyurethanes based on aliphatic isocyanates (e.g. HDI and IPDI) and mostly polyester and/or acrylic polyols. Aromatic polyurethanes are polyurethanes based on aromatic isocyanates (e.g. MDI and TDI) and mostly polyether polyols. Aliphatic polyurethanes are more expensive, but provide the best UV resistance and color stability among all types of industrial coatings. They are therefore often used for exterior applications and any other places where color stability is concerned. The design of a 100% solids aliphatic polyurethane system is very difficult and few coatings manufacturers have such a technology. Aromatic polyurethanes are cheaper and often used for interior, lining or underground applications. Depending upon their formulation design, aromatic polyurethanes will exhibit a certain degree of color change ("yellowing") after a few days/months of UV exposure. However, their UV resistance is generally better than that of common epoxies. Most 100% solids polyurethanes available today are aromatic polyurethanes.

Unlike other coatings chemistries like epoxy, the 100% solids polyurethane technology can be formulated from very soft, rubbery elastomers (like running shoe soles) to rigid, ceramic like systems. The chemical bonds in the more rigid systems are highly cross-linked to each other to create hard, dense systems that have very good chemical and moisture resistance (Figure 2). The rigid systems usually have excellent adhesion and are the best choice for the corrosion protection of metals and concrete pipe. On the other hand, the elastomers have a more linear structure with much less cross-linking that allows them to be very stretchy and elastic (Figure 3). These systems normally have great impact strength and flexibility, but relatively poor adhesion, chemical resistance, and cathodic disbondment resistance. Elastomers are better suited to protecting substrates that tend to move and flex like concrete tanks or containment structures but do not work as well on metallic substrates. The chemical and corrosion resistance of the elastomers can be improved if the systems are applied relatively thickly.

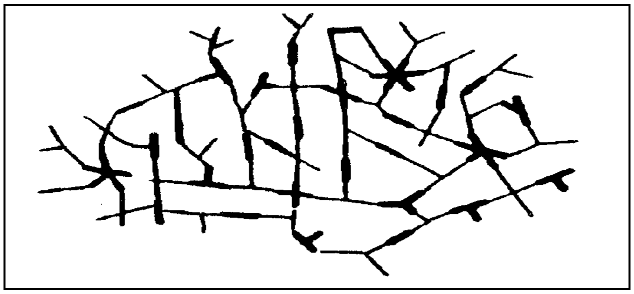

Figure 2. Rigid, high cross-linked polyurethane[1]

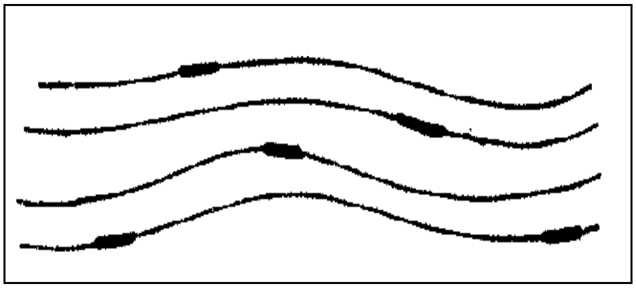

Figure 3. Linear, flexible elastomeric polyurethane[1]

There is a tendency to misunderstand the difference between polyurea and polyurethane coatings. In many cases, people tend to mix up polyurea coatings and polyurethane coatings. Thus, polyurethane coatings have become a generic term for coating systems based on polyisocyanate reaction. Polyurea coatings normally use amines as coreactants to react with isocyanates. This reaction is extremely fast (within a few seconds or minutes). As a result, polyurea coatings tend to have a very limited pot life and their recoat time becomes a problem in cases when multiple coats occur. A polyurea linkage, however, will have better heat and high temperature resistance than a polyurethane system with polyols as coreactants. This paper focuses on polyurethane coatings, which have broad application possibilities and not on polyureas, which have a comparatively limited range of potential uses.

2.3. New Developments in the 100% Solids Polyurethane Technology

In North America, 100% solids aromatic polyurethane coatings were first developed specifically for the 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 polyurethane coating. In 1981, the aromatic polyurethane coating technology was approved for use in the StiP$_3$ ® tank by the Steel Tank Institute (STI). Since the late 1980s, 100% solids aromatic polyurethane technology has almost completely replaced coal tar epoxy and other coatings technologies in the North American underground storage tank industry. Since then the coatings technology has also become one of the predominant protective coatings technologies for industries such as water and wastewater pipes and tanks, large utility power poles, oil and gas, marine, and transportation.

Recent developments in the 100% solids polyurethane coatings technology have resulted in two 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 MIC 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 conditions through the use of an anti-microbial additive[3]. With the anti-microbial fortification, 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 unbelievable durability, impact resistance and corrosion and chemical resistance.

As can be seen, the great versatility in polyurethane resin chemistry and formulations result in a wide range of selections of polyurethane coatings available in the marketplace. By setting out tough performance requirements which only the best corrosion protection systems are capable of meeting, standards help engineers separate out the systems that are suitable for the corrosion protection of water and wastewater structures from those that are not. An example of such standards is the newly released ANSI/AWWA C222 Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings[4]. AWWA C222 requires minimum adhesion of the polyurethane coating to the steel of 1500 psi. In comparison, AWWA C210 (for liquid epoxy) requires minimum adhesion of the epoxy coating to the steel of only 400 psi[5]. Different from rigid polyurethanes, most elastomeric polyurethanes will not meet the performance requirements of AWWA C222 in terms of adhesion, hardness, and cathodic disbondment resistance.

3. HANDLING AND SAFETY CHARACTERISTICS

One of the most impressive characteristics of 100% solids polyurethane is its unique handling characteristics and inherent safety features. This includes mixing ratio, solids content, VOC, flammability and application methods, as well as whether the coating contains any hazardous ingredients such as amines, solvents, and isocyanate monomers. Table 1 summarizes these characteristics for typical NSF 61 certified lining systems for potable water service[6].

Table 1: Product Attributes and Safety Characteristics[6]

Product Type	Solvent Amine Based Epoxy	100% Solids Epoxy	100% Solids Elastomeric Polyurethane	100% Solids Rigid Polyurethane	Cement-Mortar
Mixing Ratio	1:1 1:4 1:5	1:1 1:4	1:1 2:1	1:1	1 cement < 3 sand water
Average % Solids	67%	100%	100%	100%	100%
V.O.C. (lbs/gallon)	2.84	0.30	0.00	0.00	0.00
Contains Amines	Yes	Yes	No	No	No
Contains Monomeric Isocyanate	No	No	No or very minimal	No	No
Flammable	Yes	No	No	No	No
Application Method	Brush, roller, single component spray	Single (King type) or plural component spray	Plural component spray	Plural component spray	Centrifugal, mechanical, pneumatic, hand application

In the past, there has been a misinformed impression in the coating industry that, compared to an epoxy system, polyurethane coating and lining systems were not as safe to use as epoxies due to the toxicology of the resins (polyols and especially isocyanates). The main hazardous pre-cursor of a polyurethane is isocyanate monomer. While there are many different types of isocyanates available in the market, most isocyanates used today in 100% solids polyurethane coatings are of the MDI (Diphenylmethane Di-isocyanate) type. In these lining systems, particularly in rigid polyurethane systems, polymeric MDI and special formulating technology are also used to further reduce the level of isocyanate monomer in the finished system. As a result, the polyurethane systems are in fact safer to use compared to most epoxy systems. The isocyanate and polyol are much safer than epoxies even in their liquid states. The oral toxicity (as indicated by the MSDS's of the suppliers of the raw materials for polyurethanes and epoxies) is two times greater for epoxies than it is for polyols and five times higher than for isocyanates (Table 2)[7]. All isocyanates react with water. If unreacted isocyanate is leached or released into the water in any way, it simply reacts to form an inert, harmless polyurea solid.

Table 2 Oral LD_{50} Value Comparison
Between Polyurethanes and Amine-cured Epoxies[7]

Products	LD_{50} (mg/kg)
Polyurethane	
Polymeric MDI	5,000 -10,000
Polyol	2,000 - 5,000
Amine-cured Epoxy	
Amine	500 - 4,000
Epoxy Resin	Less than 2,000

The 100% solids polyurethane systems for lining potable water tanks are safer than conventional solvent-based epoxies because the polyurethane raw ingredients are less toxic than epoxies and because solvents are not required in the systems.

100% solids polyurethanes also offer substantial advantages over conventional technologies in terms of applicator safety. The hazards of polyurethane application are easily recognized and controlled. Contrary to popular beliefs isocyanate is *not* carcinogenic[8]. The only problems are allergic reactions to isocyanate monomer. A very small percentage (<1%) of the population will exhibit immediate allergic reactions when exposed to isocyanate and should avoid all contact with the material. The average individual however, will only exhibit temporary irritation of the respiratory systems, skin and eyes when over-exposed. This isocyanate hazard is easily recognized. Most applicators will know they are being over-exposed because they get runny noses, itchy eyes and irritated throats. Once the over-exposure is stopped, the allergic reactions end. These 'early-warning' discomforts are a very effective way to avoid over-exposure. Only prolonged unprotected exposure to isocyanate can cause irreversible sensitization problems. As a result, applicators using the 100% solids polyurethane coatings can be assured that these systems are safer to handle than most epoxies or conventional painting systems.

4. APPLICATION OF 100% SOLIDS POLYURETHANES

4.1. Application Characteristics

A number of unique advantages of the 100% solid polyurethanes over conventional coating/lining technologies are found in the application of the systems. Fast cures and high application rates give the polyurethanes a much faster turn around time over epoxy systems.

Typically, the setting (or cured-to-touch) time for the 100% solids polyurethane systems ranges from one minute to one hour. Most coating formulators also make compatible slower setting systems that can be brushed or rolled for doing ‘hard-to-spray’ roof areas or small repairs. For most fast setting systems, the pot life is effectively zero to 5 minutes. Two component airless spray pumps meter the components (isocyanate and polyol) in the correct ratio[9]. The components are kept apart until they meet at (or just before) the spray gun. This type of equipment, although slightly specialized, is readily available from the main airless painting equipment manufacturers.

It is this fast setting time that provides many of the advantages. First, the coating can be applied to virtually any required thickness in one coat. Depending on the thixotropic properties, the applicator can usually put on 200 to 400 microns (8-16 mils) in one pass. Within 5-10 minutes (for some systems, seconds for others), this first pass has cured enough so that a second pass can be applied. This multi-pass process is continued until the required thickness is achieved. Typical minimum specified dry film coating thickness for water/wastewater is given in Table 3, depending on the condition of substrate.

Table 3 Typical minimum specified dry film coating thickness for water/wastewater application

Substrate Type	Internal Application	External Application
Steel	20 mils (500 microns) – normal	20 mils (500 microns) – normal 50 mils (1250 microns) - slip bore
Ductile iron	40 mils (1000 microns)	25 mils (625 microns) 50 mils (1250 microns) – slip bore
Reinforced concrete	60 mils (1500 microns)	40 mils (1000 microns)
Pre-stressed concrete cylinder	25 mils (625 microns)	30 mils (750 microns)

In addition to curing quickly, the 100% solids polyurethanes will fail by blistering or not curing almost instantly if there is a problem with the surface preparation or the mixing ratio. If the coating is not dry-to-the-touch in the standard 1 to 15 minute time frame, the applicator and/or inspector knows that something is wrong. If there is any water on the substrate surface, the polyurethane will foam immediately with the water to create an easily identified problem area. Within minutes the film thickness can be checked with a magnetic gauge and the adhesion to the substrate can be tested with a knife. Typical slow curing epoxies may take several days or weeks to develop any recognizable problems. This 'early warning' characteristic helps the applicator, inspector and owner easily recognize and correct application problems *before* the tanks or pipes are put into service.

4.2. Application Cost

The true cost of any coating system is not the ‘cost per bucket’ or even the applied cost per square meter. The true coating cost is the sum of ***Materials Cost + Application Cost + Maintenance Cost + Hidden Cost .***

The materials cost of 100% solids polyurethanes may be slightly higher than that of epoxy coatings. However, the application cost of 100% solids polyurethanes is substantially lower, because of its one coat application (less labor and faster completion time) versus multi-coat application of epoxy coatings.

The exothermic nature of the 100% solids polyurethane reaction enables one coat application at virtually any ambient temperatures (-40^{o}C and up) for any thickness, and also rapid curing of the coating ready for service (e.g. as fast as one hour after the application). There is no other coatings technology that can offer the same rapid turnaround. In the underground steel fuel storage tank and pipeline industries, where 100% solids polyurethanes are used extensively, it is not uncommon for applicators to apply the materials at temperatures down to -20°F (-29°C). Epoxy systems normally require temperatures above 50°F (10°C).

Even at such temperatures, epoxies still need seven to ten days to fully cure and to allow the solvents to evaporate.

The large capacity of standard spray machines combined with the fast curing characteristics for these polyurethane systems generally result in very high application rates. A contractor doing large water storage tanks in the Abu Dhabi reported spraying over 150 m^2 per hour (1500 ft^2/hr) on complicated roof areas and up to 400 m^2 per hour (4000 ft/hr) on the clear floor area[10]. Those figures involved the application of a total film thickness of approximately 500 microns (20 mils). Conventional epoxy application equipment rarely achieves rates above 125 m^2 per hour (1250 ft^2/hr) for only one (of several required) coat (5 mils or 125 microns dft)[11].

While dealing with the subject of costs, maintenance cost and hidden cost must be included. Maintenance cost of a coating project is related to the performance of the coating. Given the high performance of the 100% solids polyurethane coatings over other conventional coatings, as will be discussed in Section 5, maintenance cost or cost/m^2/year of life is expected to be lower with the polyurethane technology. An example of the hidden costs is the pump efficiency, which is related to the water/wastewater flow efficiency. Because the polyurethane has better abrasive resistance and is smoother than cement-mortar lining, for example, its pump efficiency is significant higher particularly for large size diameter pipes, thereby reducing the operation cost.

5. PERFORMANCE OF THE 100% SOLIDS POLYURETHANES

The performance of any coating/lining system depends on many variables, such as surface preparation, film thickness, temperature, damage in handling, cathodic protection and so on. All these factors affect the longevity of a coating.

Standard performance tests have been developed and used over many years to evaluate various coating and lining systems for their use as corrosion protection coating and lining systems. Typically, performance tests were conducted according to the following testing standards[6]:

- Abrasion Resistance (ASTM D4060)
- Adhesion (ASTM D4541)
- Cathodic Disbondment (ASTM G95)
- Chemical Resistance (ASTM D714)
- Flexibility (ASTM D522)
- Impact Resistance (ASTM G14)
- Salt Spray Resistance (ASTM B117)
- Water Absorption (ASTM D570)

Table 4 outlines typical performance testing results of typical NSF 61 certified lining systems for potable water service.

It is well known in the coatings industry that among all organic coatings available in the market, polyurethane coatings are the best in terms of abrasive resistance. For any pipeline internal lining application, the lining must be able to withstand the constant flow of liquid and any particles. Normal municipal pipeline velocities are in the range of 8 to 16 feet per second (2 to 4 meters per second) but these rates can increase in some cases to over 30 feet per second. The corrosion protection lining must be capable of withstanding the constant abrasion caused by the passing water at the various velocities. Premature failure of the lining system can occur, thereby exposing the steel substrate to the corrosion cycle.

Table 4. Performance Testing Results of Typical NSF 61 Certified Lining Systems

Performance Testing Data	Solvent Amine Based Epoxy	100% Solids Epoxy	100% Solids Elastomeric Polyurethane	100% Solids Rigid Polyurethane	Cement-Mortar
Abrasion (ASTM D4060 1Kg, CS17, 1000 cycles)	122 mg loss	183 mg loss	15 mg loss	50 mg loss	1500 mg loss
Adhesion (ASTM D4541)	1280 psi (8.8 Mpa)	925 psi (6.4 Mpa)	1000 psi (6.9 Mpa)	2000 psi (13.8 Mpa)	0 psi (0 Mpa)
Cathodic Disbondment (ASTM G95; 3% NaCl, -1.5 volts, 30 days, 23^{o}C)	15 mm avg.	15 mm avg.	30 mm avg.	8 mm avg.	Complete Disbondment
Chemical Resistance (ASTM D714, 1000 hours)	Pass (20% Na_2SO_4, 3% NaCl, 3% H_2SO_4, gasoline)	Pass (20% Na_2SO_4, 3% NaCl, 3% H_2SO_4, gasoline)	Pass (20% Na_2SO_4, 3% NaCl, 3% H_2SO_4, gasoline)	Pass (20% Na_2SO_4, 3% NaCl, 3% H_2SO_4, gasoline)	Pass (20% Na_2SO_4, 3% NaCl, 3% H_2SO_4, gasoline)
Flexibility (ASTM D522)	Failure at 180^o over a 2” (5.08 cm) mandrill	Failure at 180^o over a 2” (5.08 cm) mandrill	Pass at 180^o over a 2” (5.08 cm) mandrill	Pass at 180^o over a 2” (5.08 cm) mandrill	Failure at 180^o over a 2” (5.08 cm) mandrill
Impact Resistance (ASTM G14)	38 in.lbs (4.3 J)	15 in.lbs (1.7 J)	80 in.lbs (9.0 J)	50 in.lbs (5.7 J)	2 in.lbs (0.2 J)
Salt Spray Resistance (ASTM B117)	Pass at 1000 hours	Pass at 1000 hours	Pass at 1000 hours	Pass at 1000 hours	Pass at 1000 hours
Water Absorption (ASTM D570, 50^{o}C, 48 hours)	2%	2%	6%	2%	7%

In the Taber Abrasion Test (ASTM D4060), a sample was rotated under a specific weight (1 kilogram) against a grinding wheel (CS17) for a defined number of revolutions (1,000 cycles). The samples were evaluated by measuring the weight of the sample before and after the test. The resulting weight loss indicated the comparative ability of the lining to resist abrasion and wear. The lower the reported weight loss, the more abrasion resistant the lining/coating is. The recent developments in ceramic modified rigid polyurethanes enable these rigid systems to have the same level of abrasion and impact resistance as elastomeric polyurethanes, while maintaining their superior adhesion and chemical resistance.

The adhesion of a protective coating system to the substrate is considered to be a good indicator of the coating’s ability to resist corrosion and therefore represents longevity of the coating. Generally, the better the adhesion, the longer the coating will last. Most elastomeric polyurethane coatings have lesser adhesion values than rigid polyurethanes when a primer is not used.

Cathodic disbondment is one measure of the undercutting resistance of a coating/lining system. Experience in the oil and gas pipeline industry has clearly shown that coatings/linings with better cathodic disbondment resistance have better corrosion resistance and greater longevity. The coating/lining systems with good adhesion to the steel substrate tend to have a similar resistance to cathodic disbondment. If a coating/lining is able to adhere to the steel substrate, it will therefore tend to resist the undercutting damage of corrosion, thereby offering a longer service life.

Flexibility is a good indicator of a coating/lining's ability to withstand the cracking, disbonding, or other mechanical damage of the coating/lining that can occur from handling and bending the steel pipe not only in the field but also in the factory.

The impact resistance test method represents the coating's ability to withstand damage due to a direct impact with another object. This test method is often required for pipeline coating performance results where impact and damage resistance is of greater importance. This test is also relevant for evaluation of internal lining systems due to its ability to predict good lining performance and resistance to damage.

When selecting a coating system, a specifier should consider these performance measures to make the best choice. Based on these standard tests, the polyurethane systems can be considered to outperform the epoxies in most cases. This higher level of performance means that the 100% solids polyurethane will last longer.

6. CASE HISTORIES

For decades 100% solids polyurethane coatings technology has offered a variety of applications involving both potable water and wastewater. The following are a few examples:

6.1. Abu Dhabi – Large Water Tanks.

Abu Dhabi's Water and Electricity Department (WED) owns and operates the city's two power and desalination plants. Prior to 1990, the WED experienced a number of water tank lining failures. Some systems failed within three years. The WED's challenge was finding a tank lining that could withstand the aggressive conditions created by the combination of the hot desalinated/deionized water stored inside the tanks and high temperatures in the desert reaching 140°F (60°C).

Over the past ten years, the WED has lined 16 water storage tanks (new and rehabilitated) with a 100% solids, rigid, NSF certified polyurethane coating. After two years of service the water tanks passed their first inspection. Dry film thickness checks and cross hatch adhesion tests were performed on the entire steel surface; not one instance of coating failure was found in over 450,000 square feet (41,806 square meter) of lined steel. Rigorous inspections of the water tank linings over the past eight years have yielded similar results, and the life expectancy of the lining system is estimated at thirty to fifty years.

6.2. Fiesta Island Replacement Project - 111 Years Design Life

In 1991 the City of San Diego, California, embarked on Phase One of the Fiesta Island Replacement Project. The project involved six miles of ductile iron pipe protected from corrosion by 25 mils (625 microns) of a 100% solids rigid polyurethane coating. Sacrificial magnesium anodes also were used to protect the 12 inch (30.5 cm) diameter pipeline from corrosion. Two years later, DeC Consultants Inc. tested the pipeline's corrosion protection system.

DeC's analysis showed the coating system to have an installed efficiency of 99.66 percent. The pipe had an actual current requirement for corrosion protection three times less than the design value. The report went on to state that, given the condition of the polyurethane coating and the corresponding low anode consumption rate, the system had a projected design life of 111 years before the anodes would need to be replaced. In theory, the pipe will last for centuries.

6.3. Denver Water Marston Reservoir Project - No Required Repairs in 2 Years

In 1997, the Denver Water Board (Denver, Colorado) initiated construction of a pipeline to bypass the Marston Reservoir during periods when the lake was suffering from taste and odor problems caused by seasonal turnover. Eight thousand linear feet of 108 inch (2.75 meter) diameter steel pipe were manufactured by Northwest Pipe and lined with a two component, rapid setting, 100 percent solids rigid polyurethane specifically designed to protect potable water pipelines. The coating is covered by American Water Works Association Standard ANSI/AWWA C222.

Officials from the Denver Water Board and Northwest Pipe inspected the pipe on December 15, 1999, and determined that the lining remained in excellent condition; no touch-up or repairs were needed to any of the 225,000 square feet (20,903 square meter) of steel surface.

6.4. Hampton Roads Sanitation District – Standard Specifications Since 1988

Hampton Roads Sanitation District (HRSD), headquartered in Virginia Beach, Virginia, was among the first utilities in North America to use 100% solids rigid polyurethane coatings to protect pipe internals against aggressive sewage and microbiologically influenced corrosion (MIC).

In their initial evaluation of polyurethane, HRSD made a standard two inch tap into the side of a three foot (0.9 meter) long piece of ductile pipe lined with a 100% solids polyurethane. The pipe was then suspended into a manhole known for its extremely corrosive conditions. After 6 months the pipe was removed and the coating inspected. While there was some minor corrosion right at the saw cut, there was very little evidence of undercutting or loss of adhesion around the unrepaired area. Based on these results, HRSD has gone on to specify 100% solids polyurethane material wherever they expect to come across aggressive sewage conditions. HRSD reports no problems or difficulties with any of their polyurethane lined pipe currently in operation.

Currently HRSD is using the company's coatings and linings for the Lake Ridge Interceptor Force Main, which runs from HRSD's Atlantic Wastewater Treatment Plant, servicing Virginia Beach and Chesapeake. HRSD knows conditions within the sewer line will be extremely aggressive. HRSD and their design engineers, Buck, Siefert, & Jost, chose to line 10,000 feet (3 km) of spiral welded steel pipe with 20 mils (500 microns) of a 100% solids polyurethane specifically designed for wastewater, because it is designed to handle extreme conditions, such as when pH levels fall below 1.

6.5. Table Mountain Sequencing Batch Reactor – Wastewater Interior and Exterior

Every year, patrons of the Table Mountain Casino, California, spend millions of dollars gambling for fun and profit. The Table Mountain wastewater treatment facility is critical to the operation of the casino. If any component of the system fails, the casino must stop operations.

Installed in 1994, the Table Mountain mild steel sequencing batch reactor (SBR) system consists of five large steel tanks, each about the size of a tractor-trailer. Both the steel internals and externals were coated with 16 mils (400 microns) of a 100% solids, fast setting, polyurethane coating. Sacrified zinc anode were factory installed internally and externally for back-up protection.

In 1999, the external coating of the Table Mountain SBR was inspected using a standard reference cell and voltmeter that measures tank-to-soil potential for each unit. The readings demonstrated that the external coating was in excellent condition. The results of the internal inspection were equally compelling. Although the liquid level in the tanks could not be dropped completely, in the vapor phase areas, where corrosion is usually the worst, there was no evidence of corrosion or coating breakdown. The inspector noted that “the coating looked as bright and shiny as the day it was applied”.

6.6. Barrick GoldStrike Mine – Industrial Processing Water

In the spring of 1993, Barrick GoldStrike Mine of Carlin Nevada used a 100% solids polyurethane lining to coat the interior of a steel pipeline carrying brine and light slurry. The pipe was spiral welded steel manufactured by Ameron Corp. of Tracey, California. The pipes were approximately 72” (1.8 meters) in diameter by 40’ (12 meters) long. The total length of the line was almost 4 miles (6.5) kilometers.

The effluent carried in the pipeline is more aggressive than most. It flows at an average speed of 10 feet/second (3 m/s) and at temperatures of up to 140^{o}F(60°C). By comparison, common municipal sewer force mains operate at 3-5 feet/second (1-1.5 m/s) and 70^{o}F(20°C).

Of particular note in this application was that all of the interior coating was applied automatically. An electrically powered cart with a rotating spray nozzle applied the entire thickness of 20 mils (500 microns) in one pass down the length of the pipe. The blasting was also done in the same manner.

This process combined with the very fast cure rate of the coating allowed the applicator to complete over 20 pipes (blasting and coating) or almost 1400 square meters each day.

The project was completed in less than 1/3 of the time that it could have been completed with any comparable epoxy system at only 2/3rds of the cost.

In their 1996 inspection, Barrick GoldStrike’s engineers reported no deterioration of the 100% solids polyurethane coating in three years of continuous operation under the highly abrasive environment.

6.7. Eagle Pass - Concrete Water Tank Rehabilitation

In January of 1990, the City of Eagle Pass, Texas, in the Rio Grande Valley, acquired and filled a new concrete water tank. To their horror, they discovered the tank leaked so profusely it was unusable.

After a failed attempt to patch the tank, the City of Eagle Pass asked the engineering firm of Groves and Associates of San Antonio, TX, to advise them on solving their problem. They needed to get the tank sealed and put into service immediately. The engineering firm recommended a 100% solids, NSF certified polyurethane, applied to a thickness of 60 mils (1500 microns).

The interior surface of the tank was prepared for coating simply by sweep blasting the laitance off of the concrete. The entire surface area of the 8,000 square foot (743 m^2) tank was coated in one coat in approximately 10 hours. The repaired tank was put into service 48 hours after it was coated, and no coating failure was reported in the past 10 years.

6.8. Rubes Creek Pump Station – Concrete Sewer Pipe

A recent inspection was carried out on an active reinforced concrete sanitary sewer line that connects with the Rubes Creek Pump Station of the Noonday Creek Water Reclamation Facility in Cobb County, a northern suburb of Atlanta, Georgia. The pipeline was installed during the spring of 1990. The dry cast concrete pipe was manufactured and internally coated with 40 mils (1000 microns) of a 100% solids polyurethane coating by CSR Hydro Conduit.

The conditions to which the line was exposed were, in the words of one design engineer, "as bad as it gets…anywhere". High sewage sulphate content resulted in high levels of hydrogen sulfide production. The low flow rate of the sewer line at this point, just before its entry into the treatment plant, gave the bacteria ample time to metabolize the hydrogen sulfide gas into sulfuric acid. The pH on the crown of the pipe was extremely low (between 1 and 0.5). In addition, the low flow rate meant the sewer pipes were less than half full much of the time. Therefore, the flow could never wash away the acid or the acid-producing bacteria. Finally, the line took input from some nearby industries and therefore regularly saw elevated effluent temperatures. All of these conditions created a very tough environment that would be expected to limit a coating's service life.

During the inspection, the internal coating was found to be in excellent condition without damaged or deteriorated areas.

6.9. Yelm Hydroelectric Plant– High Flow Rate Bypass

The Yelm Hydroelectric Plant is fuelled by the waters of the Nisqually River and the energy produced services the residents of the City of Centralia, Washington. Designed by the engineers at CH_2M Hill, the bypass system captures water from the plant during emergency shutdown, conveying the water back to the river. On average, the bypass is 6 feet (1.82 meters) in diameter, covers approximately 1000 linear feet (305 meters), and features a vertical drop of 265 feet (81 meters). The bypass is a prototype because specialized energy displacing rings were installed on the interior of the pipe to slow down the flow of water during the large drop. Conventional designs would incorporate a large energy dissipation structure at the bottom of the pipeline.

While the specialized energy displacing rings help slow the water down, flow rates within the 54" (1.4 meter) section of the bypass can still reach up to 800 ft^3/s (23 m^3/s). CH_2M Hill chose to coat and line the bypass systems with two 100% solids rigid polyurethane coatings precisely because of the high flow rates generated by the vertical drop. The internal surface was coated at 30 mils (750 microns) and the external was coated at 60 mils (1500 microns). The project was completed in May 1999.

The engineers for the City of Centralia were very pleased with the performance of the lining/coating system. As a result, Centralia will continue to use the 100% solids polyurethane technology as part of ongoing design changes to the bypass system.

7. SUMMARY

The best overall protective coatings technology for water and wastewater application is 100% solids polyurethane. 100% solids polyurethanes are rapidly replacing older coating products like conventional epoxy systems because of proven features and benefits associated exclusively with this technology. 100% solids polyurethanes are less toxic than traditional epoxies for both the water users and applicators. Their performance advantages over other coatings products include outstanding adhesion values, excellent chemical, impact and abrasion resistance, flexibility, resistance to cathodic disbondment and undercutting. In addition, 100% solids polyurethanes offer instant setting times and cold weather cure capabilities, thus reducing the total applied costs while dramatically increasing throughput time.

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