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ADVANCED 100% SOLIDS RIGID POLYURETHANE COATINGS TECHNOLOGY FOR PIPELINE FIELD JOINTS AND REHABILITATION

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ABSTRACT

This paper describes an advanced 100% solids rigid (or structural) polyurethane technology for field-applied coating of pipeline girth welded joints and pipeline rehabilitation for oil/gas and water/wastewater transmission lines. This technology applies either a castable type resin or a sprayable resin in the field, and allows for encapsulating or coating of steel pipeline joints, or sections, in minutes under a wide variety of conditions. The key technical parameters and requirements associated with the technology for such field coating application are discussed. The lab and field-testing results of the 100% solids structural polyurethane coating technology and case histories are reviewed, including its compatibility with polyurethane, polyethylene, polypropylene and fusion bond epoxy coated pipe operating at standard or elevated temperatures. Comparisons with some other typical liquid-applied field coatings for pipeline girth welded joints and pipeline rehabilitation are also discussed, including coal tar epoxy, 100% solids epoxy, 100% solids elastomeric polyurethane and with fusion bonded epoxy as a reference.

Keywords: 100% solids coating, rigid polyurethane, structural polyurethane, pipeline, girth welded joints, field-applied coating, rehabilitation.

INTRODUCTION

The corrosion-related cost to the transmission pipeline industry has recently determined to be $5.4 to $8.6 billion U.S. dollars annually in the U.S[1]. The use of protective coatings with or without cathodic protection is the most widely used form of corrosion protection in the pipeline sector. Since the 1950s, several coating systems have been utilized, including fusion-bonded epoxy (FBE), extruded polyethylene, coal tar enamel, liquid epoxy, tape, polyurethane, mastic, and wax. Pipelines with each of these coating systems remain in service today. Today, the most widely specified and plant-applied coating used on new oil/gas transmission pipelines in North America is FBE. New multi-layered coatings such as two-layer polyethylene (2LPE), three-layer PE (3LPE), and three-layer polypropylene (3LPP) extruded coatings are also found to be in limited use. These high performance coating systems provide pipeline installations with a design working life of more than 25 years. However, a documented shortcoming of the FBE and the multi-layer PE/PP coatings has been the need for corrosion and mechanical protection at field joint locations. Since the pipe is welded in the field, plant-applied girth weld coatings are not an option. Until recently, economical, simple and quick field-applied joint coatings that could match the performance of the plant-applied coatings did not exist. The same problem is prevalent in the water/wastewater transmission pipeline sector, where use of plant-applied coatings other than FBE, such as liquid epoxy, polyethylene tape, and polyurethane coatings are normally used.

The corrosion-related cost to the transmission pipeline industry can be divided into the cost of failures, capital, and operations and maintenance (O&M) at 10%, 38%, and 52%, respectively. The significant maintenance costs for pipeline operation are associated with corrosion control and integrity management. A recent survey of major pipeline companies indicated that the primary cause of loss of corrosion protection was due to coating deterioration (30%) and inadequate CP current (20%)[2]. With 30% of the operational pipeline corrosion problems being attributed to coating deterioration, a large portion of the corrosion control budget is expended on monitoring, identifying, and repairing coating anomalies. In addition, extreme coating deterioration can, in terms of cost-effectiveness, significantly impact the ability to cathodically protect the pipeline from corrosion. To extend the operating life of a pipeline, an emerging method of pipeline corrosion control is pipeline coating rehabilitation (re-coating the pipeline). This also puts a lot of emphasis on the need of a high performance coating technology that is suitable for in-field application.

Over the years, many field-applied coatings systems have been developed and utilized for pipeline girth welded joints and pipeline rehabilitation. These systems include; liquid applied coal-tar or non-coal tar epoxies, elastomeric polyurethanes, rigid polyurethanes, heat shrink sleeves, cold-applied tapes, hot-applied tapes, cementitious materials, and composite systems of which some coatings are suitable for both joints and mainline rehabilitation, some are limited for joints application only. Advantages and disadvantages of these systems in terms of effectiveness, economy, and long-term performance are yet to be determined. A recent round table discussion was held on the use of pipeline rehabilitation coatings, focusing on testing requirements, surface preparation, and application[3]. For the field-applied joint coating application, the Gas Technology Institute (GTI) is currently undertaking a North American, third party independent evaluation of numerous field applied pipeline coating systems[4].

This paper describes an advanced 100% solids rigid (or structural) polyurethane technology for field-applied coating of pipeline girth welded joints and pipeline rehabilitation for oil/gas and water/wastewater transmission lines. This technology applies either a castable type resin or a sprayable resin in the field, and allows for encapsulating and coating of steel pipeline joints, or sections, in minutes. The paper first discusses the key technical parameters and requirements associated with the technology for the field coating application. It then reviews the lab and field-testing results of the 100% solids structural polyurethane technology and case histories, including its compatibility with polyurethane, polyethylene, polypropylene and fusion bond epoxy coated pipe operating at standard or elevated temperatures. Comparisons with some other typical liquid-applied field coatings for pipeline girth welded joints and pipeline rehabilitation are also discussed, including; coal tar epoxy, 100% solids epoxy, 100% solids elastomeric polyurethane and with fusion bonded epoxy as a reference.

WHAT DEFINES A GOOD FIELD-APPLIED COATING FOR PIPE JOINTS AND REHABILITATION?

For years, the transmission pipeline industry has required an effective field-applied corrosion protection coating system with excellent application and performance properties and the ability to withstand corrosive environments for girth welded joints and for pipeline rehabilitation. In order to meet these requirements, a field-applied coating system has to be able to meet five challenges below: environmental and safety regulations, economics, field application conditions, effectiveness, and high performance. Engineers must strike a balance between these five areas in refurbishing or designing new pipeline joint and mainline installations. The ideal field-applied coating system shall be environmentally friendly, worker-safe, durable and able to expose little or no metal/substrate surface to the environment. It must also be resistant to environmental, mechanical and chemical damage from the initial stage of application, handling and installation, through to its entire service life. It should be capable of being applied efficiently and effectively under the restricted environmental and work conditions in the field. Finally, it should come at a reasonable cost. As a result of the above requirements, the design and selection of a field-applied coating system for girth welded joints and pipeline rehabilitation shall be based on careful considerations of the following parameters:

a). Handling and safety characteristics;
b). Field application and repair attributes;
c). Surface preparation requirements,
d). Physical performance requirements;
e). Case histories, and
f). Cost analysis.

Handling and safety characteristics include mixing ratio, solids content, VOC, flammability, application methods, as well as whether the coating contains any hazardous ingredients such as coal tar, amines, solvents, and isocyanate monomers. Over the last ten years, compliance with rigorous regulations on volatile organic compound (VOC) emissions has become a must for any coating system. As a result, many low solids coatings such as solvent-based epoxies are pushed out from the coatings family for pipe coating in water and wastewater application. Requirements of OSHA, EPA, and FDA environmental and health standards have also played a significant role in eliminating or reducing the use of bituminous enamels and coal tar epoxies.

The format of a coating also plays a role here; for instance, the mixing ratio of plural component coating systems. Plural component coatings with a mixing ratio other than 1:1 will be more likely to cause mismetering problems (often called "off-ratio") during application. The greater the ratio is, the higher the possibility it will occur. Furthermore, it is recommended to select those systems in which both components have the same or very close values of medium-ranged viscosities. As high or 100% solids coatings are being used more and more today, too high viscosity values of these coatings may cause application and equipment problems in handling.

Field application and repair attributes determine the construction contractor's ability to achieve the proper results for field joint applications or field rehabilitation. The quality of field application and repairs is very much limited by the number of coats, curing temperature, and cure time required by the field-applied coating materials. The coating system should also be able to be applied under a wide variety of specific field and environmental conditions such as humidity, wind, rain, ambient temperatures, dew point, space limitation, location, etc. If the pipeline is in service during the rehabilitation, any heating or cooling necessary for good coating application is severely limited because product flow temperature will overpower any localized attempt at heating or cooling. Because ambient conditions are difficult to control, rehabilitation coating should be ready to apply and handle as soon as possible.

Surface preparation is essential to the ability of the coating to bond to both the pipe or joint substrate and the existing main plant-applied coating. This bonding is important to eliminate environmental fluid migration between the substrate and the pipe coating. It also assures permanence and the ability to withstand handling during installation without losing effectiveness. It is therefore very important to understand the surface preparation requirements of the coating system to be selected. There must be no shortcut here, because poor surface preparation always results in poor bonding strength of the coating. It is also important to ensure the compatibility of the field-applied coating with the plant-applied mainline coating.

Physical performance requirements: Performance of a pipeline coating depends on many factors. Coulson and Temple[5] identified twelve performance properties that they deemed most essential in a pipeline coating system. These properties are highlighted below as they relate to the requirements of a field-applied coating for pipeline girth welded joints and rehabilitation.

- *Adhesion to pipe substrate*: Adhesion of a field-applied coating to the pipe substrate that it is protecting is very important, and can be measured by ASTM D4541. Adhesion will affect the ability of the coating to resist soil stressing, cathodic disbondment and bending damage. Sand or grit blasting is a normal requirement of all high performance coatings. Adhesion is, to a large extent, directly proportional to surface cleanliness and to the depth and angularity of the blasted profile. Most coating manufacturers normally recommend a minimum surface preparation of a near white SSPC-SP10 (NACE 2) blast with a 2.5 mil profile and the use of a blast media that will provide an angular profile pattern. Chemically, specially designed coating formulations can enable faster and better wetting of the coating to the substrate, which in turn makes the coating not only less sensitive to surface contaminants but also more adherent to the substrate. This requirement is particularly important for a field-applied coating as it is also related to the coating's compatibility with the existing plant-applied coating in the two adjacent sides of a joint.

- *Abrasion, impact, and penetration resistance (hardness)*: Although a field-applied coating used for pipeline girth welded joints and pipeline rehabilitation is not subjected to the rigors of excessive handling, storage and transportation, like that of a plant-applied coating, it is still required to provide resistance against abrasion, scratches and penetration. These may be caused by rocks, frozen backfill, or debris left in the trench from the removal of the old coating or from the installation site. The ability of a field-applied coating to resist penetration if set in stones on the trench can be determined by: ASTM G17, ASTM D785, ASTM D5, and ASTM D2240. The resistance of a pipe coating against damage by rock in back fill can be evaluated by ASTM G13 and ASTM G19. ASTM G14 impact resistance testing methods can be used to test the coatings ability to withstand damage due to direct impact with another object. Hardness of the coating can be measured by ASTM D2240.

- *Chemical and corrosion resistance*: The corrosive environmental and service conditions that a field-applied coating is going to be exposed to plays an important role in the coating selection and design. For example, resistance of the coating against microbiologically influenced corrosion (MIC) becomes important in many soils today. A field-applied coating material must resist any chemical solution that will be encountered by the coated pipe during the coating, backfilling and operation of the pipeline. In service, the coating will face corrosive soil conditions that involve resistivity, chemical contamination, pH, moisture content, and existence of stray electrical currents. Corrosive soil conditions demand a coating system that has the proper chemical resistance (ASTM D714 / ASTM D543 / ASTM G20), high adhesion (ASTM D4541) to the substrate and adjacent plant-applied coating, and low permeability (ASTM G9 / ASTM E96 / ASTM D570).

- *Dielectric strength and resistance to cathodic disbondment*: In many cases a pipe coating is supplemented by cathodic protection, which can prevent corrosion where defects or holidays exist in the coating film. A field-applied coating used with cathodic protection must have good dielectric strength so that both cathodic protection potentials and current flows will not affect its ability to act as a corrosion protection barrier. Coatings with a low dielectric strength, or those that will allow some current flow, often allow the buildup of cathodic deposits on the surface or under the coating, causing coating breakdown. This is not an uncommon occurrence where coatings contain metallic pigments. ASTM D149 can be used to evaluate the dielectric strength of a coating.

  It is also necessary for the coating to withstand cathodic disbondment. Cathodic protection places extra demands on a coating by potentially breaking the bond between the coating and the substrate of a pipeline joint or a pipeline section. No coating can completely resist damage due to cathodic protection. However, experience has clearly shown that coatings/linings with better cathodic disbondment resistance have better corrosion resistance and greater longevity. There are several standard testing methods that can be used, such as ASTM G95, ASTM G8, and CSA Z245.

- *Flexibility or bendability*: Flexibility for field-applied for pipeline girth welded joints and pipeline rehabilitation is not an essential attribute because pipe bending has already taken place in most cases. The coating, however, still requires enough flexibility to accommodate the field coating process and associated pipe handling, including installation. Different installation methods affect the coating design and selection. For instance, directional drilling requires both the plant-applied and field-applied coating to exhibit a certain degree of flexibility, impact resistance, and abrasion. Flexibility of a coating can be evaluated by ASTM D522 / ASTM G10.

- *Stability at low or elevated temperatures and service conditions*: Some field-applied coating systems such as mastics, enamels, tapes, or epoxies may exhibit curing problems as well as brittleness in cold temperatures.

The impact of environmental and service temperature conditions on the coating selection also include the ability to withstand elevated operation temperatures (ASTM G8, ASTM D870, and ASTM D2485) and the resistance to weathering if the pipe is being stored or used aboveground (ASTM G11 / ASTM G53).

- *Water absorption or water vapor permeability*: The ability of a field-applied coating to resist moisture permeation is important because an increase in moisture content at the coating/substrate interface or within the coating itself may result in a loss of adhesion or a reduction in the coatings dielectric strength. This can be measured by ASTM D570 or D1653.

Case histories: As a result of rigorous environmental VOC regulations and high performance requirements, many coating manufacturers are in a rush to develop and launch new pipe coating systems. While the industry should appreciate the variable choices of coatings and coating suppliers, it is very important to select those coating systems, and coating suppliers, that are backed by solid case histories in terms of both performance and capability of plant/shop technical support.

Cost analysis: The true cost of any field-applied coating system is not the 'cost per bucket' or even the applied cost per square feet or square meter. The true coating cost is the sum of *Materials Cost + Application Cost + Maintenance Cost + Hidden Cost.* This true cost should cover the initial costs of coating and also installation and handling throughout the entire operation period. An example to highlight the impact of both materials cost and application cost on the total coating cost is to compare epoxy and 100% solids polyurethanes. 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 the multi-coat application of epoxy coatings. While dealing with costs, maintenance costs and hidden costs cannot be avoided either. Maintenance costs of a field-applied joint and rehabilitation coating project are related to the performance of the coating. High performance coatings, although normally having higher initial material costs, often provide the advantage of lower maintenance costs. An example of the hidden costs is the one due to project delay; hence the high production rate of a field-applied coating is important. The ability to bring the pipeline brought back into service almost immediately can mean significant economic and other benefits.

THE ADVANCED 100% SOLIDS RIGID POLYURETHANE TECHNOLOGY

From the very first years that polyurethanes were introduced to the pipeline market, most engineers recognized the capability of the versatile polyurethane chemistry in meeting the challenges outlined above to establish a good field-applied coating technology for pipeline girth welded joints and pipeline rehabilitation. While there are many types of polyurethane coatings available and already utilized in various conditions, today's polyurethane coatings for pipeline applications refer only to the materials that are 100% solids and are defined by ASTM D16 as Type V, two-package, liquid, polyisocyanate, polyol cured, urethane.[6] There are many reasons why 100% solids polyurethane coatings technology has received attention from the pipeline industry. First, 100% solids polyurethanes have excellent handling and safety attributes. They are safer and more environmentally friendly than traditional anti-corrosion coatings. They contain no solvent, VOC's, 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. Secondly, because of the rapid curing speed of 100% solids polyurethane coatings, the coated pipe section and joints can be holiday tested and buried within hours. Thirdly, many 100% solids polyurethanes 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.

However, most field-applied polyurethane coatings used for pipeline girth welded joints and pipeline rehabilitation applications have been traditionally based on 100% solids *elastomeric* polyurethane chemistry, with or without coal tar or petroleum tar. The 100% solids elastomeric polyurethane 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 100% solids 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 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. In addition to the performance issues, many elastomeric polyurethane coatings used in field joints and rehabilitation come often with a high mixing ratio (e.g. 4.5:1) as well as 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.

Over the past ten years, there has been a movement in North America 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. Rigid (or structural) polyurethanes are much more highly cross-linked than elastomers and, when skillfully formulated with multifunctional polymeric isocyanates and polyols/amines, are free from all of the above shortcomings. In water/wastewater transmission pipeline applications, the 100% solids structural polyurethane coatings have been demonstrated to be by far the most successful protective coating systems used for both exterior and interior applications.[7] The 100% solids rigid (or structural) 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.[8] The most recent AWWA C222 describes the material and application requirements of 100% solids rigid polyurethane coatings for the interior and exterior of steel water pipe, fittings, and special sections.[9]

Accompanying the 100% solids rigid polyurethanes for plant-applied pipeline coating applications is the development of an advanced 100% solids rigid polyurethane technology for field-applied coating of pipeline girth welded joints and pipeline rehabilitation. Differing from the linear polymeric structures of a 100% solids elastomeric polyurethane system, a 100% solids rigid polyurethane forms a three-dimensional, cross-linked structure, thus providing the coating film with superior resistance to chemicals, water penetration, cathodic disbondment, and temperature extremes. This is readily accomplished with the polyurethane technology by employing at least one reactive component that contains three or more reactive groups in the molecule. In many applications, both the isocyanate and polyol reactants can be resins that contain multiple functional groups to form such a highly cross-linked structure. The finished product is ‘structural’ in nature because it forms a strong polymeric solid similar in feel and appearance to the casing on a laptop computer and having structural rigidity.

The 100% solids rigid polyurethane field-applied coating technology consists of a sprayable resin version and a castable type resin version. The sprayable resin version involves various formulations that have a 1:1 mixing ratio with balanced viscosities between the two reactive components: Part A – polyisocyanate rich component and Part B – polyol rich component. Relatively lower viscosity (between 700 to 1,000 cps at 70^{o}F) of both the components can be obtained by a skilled formulator. This enables easier metering of the components, requiring less in-line heating and offering better atomization for spray. There are no significant changes made in the field-applied coating formulations from their sister coatings for in-plant application. However, special setting times are often made or adjusted, in order to meet the manual spray application needs in-field as well as the need for faster back to service times. The plural component material is transferred from the containers to a plural component airless pump, heated as it moves through the in-line heaters, and is then applied with a plural component spray gun or, for slower setting polyurethanes, through a whip hose and then the gun. The gun and hoses are held by the sprayer and the coating is applied to the required thickness in a one coat multi-pass operation. Depending on its setting time design and pipe surface temperature conditions, the coating material can set up over the ditch within minutes. The pipeline can be holiday tested and be brought back into service within hours.

The castable resin version is basically a “mix, pour, and cast” approach. It involves the development of a unique process to allow a pipeline joint or a short pipeline segment to be wrapped with a sealed sleeve mold, while a specially designed 100% solids rigid polyurethane coating is mixed and poured into the mold, thereby setting and coating the joint in minutes. This simple and economical process does not require special equipment other than the mold (Figure 1 and Figure 2). However, it does require proper formulation design in terms of polymeric cross-linking, pot life, viscosity, and curing time of the coating.

More recently, two innovations have been also added into the 100% solids rigid polyurethane coating technology. One innovation involves the modification of the rigid polyurethanes by using fine ceramic powders, which leads to the improvement of their abrasion and impact resistance, achieving the same levels of an elastomeric polyurethane system. Another innovation involves incorporating a non-leachable anti-microbial additive into the polyurethane formulation, which improves the protection of the coating and coated substrate from microbiologically influenced corrosion (MIC).

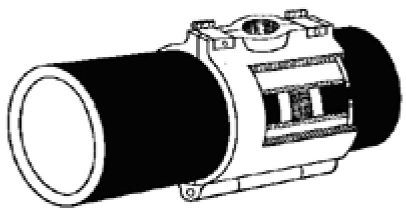

FIGURE 1 - Castable resin in the mold

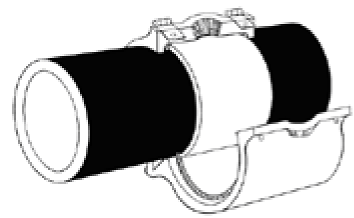

FIGURE 2 - A coated joint is ready in minutes

TABLE 1
PRODUCT HANDLING AND SAFETY CHARACTERISTICS OF VARIOUS JOINT COATING SYSTEMS

	Coal-tar epoxy	100% solids epoxy	Elastomeric PU	Rigid PU (spray)	Rigid PU (cast)	Fusion bonded epoxy
Product type	Coal-tar, polyamide cured epoxy	Polyamine cured epoxy	Coal tar or pure aromatic polyurethane	Aromatic polyurethane	Aromatic polyuretha ne	Epoxy powder coating
Primer	No primer required	Self priming or use others	No primer required	No primer required	No primer required	No primer required
Solids content	74%	100%	100%	100%	100%	100%
Mix ratio	4:1	2:1	4.5:1	1:1	1:1	1:1
VOC	1.9 lbs/gallon	0	0	0	0	0
Contain amines	No	Yes	No	No	No	No
Contains coal tar	Yes	No	Yes / No	No	No	No
Contains flammable solvents	Yes	No	No	No	No	No
Application methods	Brush, roller, conventional spray	Brush and conversional spray	Plural component spray	Plural component spray	Cast in a mold	Electrostatic spray, fluidized bed, heat cured
Shelf life	24 months	18 months	12 months	6 months	6 months	6 months

Table 1 highlights the product handling and safety characteristics of the 100% solids rigid sprayable resin version and castable resin version (both of the structural type), together with some other typical liquid-applied field coatings that are used today in the market for pipeline girth welded joints and pipeline rehabilitation. Examples of these typical coatings include a coal tar epoxy, a 100% solids epoxy, and a 100% solids elastomeric polyurethane. The characteristics of a Fusion Bonded Epoxy (FBE) coating are also listed as a reference. Over the past decade, the use of coal tar epoxy coatings has significantly declined in North America due to the hazardous and carcinogenic nature of coal tar and solvents according to OSHA, EPA, FDA, and NSF environmental and health standards.

TABLE 2
FIELD APPLICATION AND REPAIR CHARACTERISTICS
OF VARIOUS PIPE AND JOINT COATING SYSTEMS

	Coal-tar epoxy	100% solids epoxy	Elastomeric PU	Rigid PU (spray)	Rigid PU (cast)	Fusion bonded epoxy
Application methods	Brush, roller, conventional spray	Brush and conventional spray	Plural component spray	Plural component spray	Cast in a mold	Electrostatic spray, fluidized bed Heat cured
Recommended dry film thickness	16 mils or more	25 mils or more	40 to 80 mils	25 mils or more	40 mils or more	16 mils (12 mils minimum)
Surface preparation	SSPC-SP10	SSPC-SP10	SSPC-SP10	SSPC-SP10	SSPC-SP10	SSPC-SP10
Blast profile	2.0-3.0 mils	2.0 mils +	2.0 to 3.0 mils	2.5 mils +	2.5 mils +	2.0 mils +
Ambient temperature	50 to 110^{o}F	>41^{o}F	50 to 140^{o}F	-40 to 150^{o}F	-40 to 150^{o}F	Not applicable
Substrate surface temperature	50 to 110^{o}F and 5^{o}F above dew point	>41^{o}F and 5^{o}F above dew point	50 to 140^{o}F and 5^{o}F above dew point	-40 to 150^{o}F and 5^{o}F above dew point	-40 to 120^{o}F and 5^{o}F above dew point	425 to 488^{o}F
Materials temperature	50 to 90^{o}F both A and B	150^{o}F (A) 120^{o}F (B) (spray grade)	120 to 140^{o}F both A and B	32 to 150^{o}F both A and B	32 to 80^{o}F both A and B	Not applicable
Airless spray pump	Single (30:1 ratio)	2:1 plural (25:1 ratio)	4:1 plural (70:1 ratio)	1:1 plural (30:1 ratio)	Not applicable	Not applicable
Spray pressure	2100-2500 psi	About 2200 psi	4260 psi	1800-2500 psi	Not applicable	Not applicable
DFT per coat	Up to 24 mils	Up to 45 mils	Unlimited @ multiple passes	Unlimited @ multiple passes	40 to 100 mils	25 mils maximum
# of coats required	1 to 2	1	1	1	1	1
Dry to touch	4 hours @75^{o}F	1 hr 45 min. @75^{o}F	<10 min. @75^{o}F	1-10 min. @75^{o}F	Up to 15 min. @75^{o}F	Up to 90 sec. @ 450^{o}F
Dry to handle	12-24 hrs @75^{o}F	3 hrs @75^{o}F	6-8 hrs @75^{o}F	5-60 min. @75^{o}F	Up to 45 min. @75^{o}F	Upon completion of coating
Holiday testing	24-48 hrs @75^{o}F	3 hrs @75^{o}F	2 hrs @75^{o}F	5-60 min. @75^{o}F	2 hrs @75^{o}F	Upon completion of coating
Backfilling	24-48 hrs @75^{o}F	3 hrs @75^{o}F	6-8 hrs @75^{o}F	30-180 min. @75^{o}F	2 hrs @75^{o}F	After holiday testing
Ultimate cure	7days @75^{o}F	7 days @75^{o}F	7 days @75^{o}F	7 days @75^{o}F	5 days @75^{o}F	Not applicable
Recoat time	6 hrs (Min) 24 hrs (Max) @75^{o}F	Within 3 hrs @75^{o}F	2-6 hrs @75^{o}F	0.5-1.5 hrs @75^{o}F	Twice the dry to touch time	No recoat allowed
Repair material	Brush grade	Brush grade or patch compound	Self or brush grade	Self or brush grade	Self or brush grade	Patch component or liquid epoxy

As to the field application, both the spray-applied 100% solids elastomeric polyurethane system and the spray version of the 100% solids rigid polyurethane have their own limitations. First, the economics of applying the spray-applied coating must be large enough to substantiate the cost of transporting and operating a plural component spray system to the site. Secondly, since the polyurethanes are a liquid spray system, precautions must be taken in heavily traveled and built up areas to ensure that buildings and people are not adversely affected by overspray or exposed to any health risk. This, of course, is true for all the spray applied coatings systems including liquid epoxies. Finally, again due to the use of a plural component spray system, the spray application process can be very sophisticated and therefore the coating personnel must be experienced and trained to ensure that the proper procedures are being followed at all times. These limitations, however, are overcome by the castable version of the 100% solids rigid polyurethane. Being a very simple and easy casting process, its requirements for site management and application training can be minimal. The drawback of this castable version is that its current formulation has a limited pot life (less than five minutes), and thus will not be suitable for any pipe with a diameter size of 36 inches or more. Also as a result of the limited pot life, the castable 100% solids rigid polyurethane version will only serve as a girth welded joint coating, but not for a large segment of pipeline rehabilitation. Table 2 outlines the field application and repair attributes of the 100% solids rigid polyurethane technology.

As shown in Table 2, liquid applied epoxy systems are characterized by long cure times and an inability to cure in cold ambient temperatures. FBE, because of its substrate preheating requirement, is costly and difficult to use in the field.

PERFORMANCE EVALUATION

For pipeline girth welded joints and pipeline rehabilitation applications, one of main concerns of a field-applied coating is whether its adhesion/bonding to the existing mainline coating is strong enough to prevent the penetration of any water or water vapor which could cause corrosion of the steel pipeline underneath. A test was therefore proposed and conducted.

A sample joint was made by chiseling a 3 cm wide ring on a 3.5” (9 cm) diameter three-layer polypropylene 3LPP coated steel pipe. The three-layer coating was composed of a polypropylene top layer, an intermediate adhesive layer, and a fusion bonded epoxy bottom layer. All of the three layers of one half section of the ring were removed and the exposed steel surface was given a near white sandblast. For the other half section of the ring, only the top two layers (the polypropylene and the adhesive) were removed and the FBE layer was used for testing its adhesion with the castable version of the 100% solids rigid polyurethane. A 2.5 cm overlap area on either side of the joint was ground into a slope from the steel surface to the top of the polypropylene coating. The surface of this overlap area was sandblasted as well. A non-pigmented version of the castable rigid polyurethane was cast onto the pipes within a mold. The joint area was 7-7.5 cm wide, 2 mm over the three-layer coating. The cast rigid polyurethane was allowed to cure at least 12 hours before this test. Three samples were tested. For each sample, two joints were prepared and tested.

Individual cast samples were then immersed in a 100^{o}C (212^{o}F) water bath for 24, 48 and 72 hours. The water was dyed deep blue to allow a visual examination of water penetration through or under the non-pigmented cast rigid polyurethane. After the immersion, each joint was broken immediately by a sledgehammer and cold chisel along the interface of the polyurethane and the three-layer coating to check the migration of water. Test results are shown in Table 3.

TABLE 3
BONDING BETWEEN THE CASTABLE POLYURETHANE JOINT COATING AND 3LPP PIPELINE COATING SYSTEM

Sample	Bathing period at 212^{o}F	Migration of water between the castable rigid polyurethane coating, a 3LPP coating, and steel	
		First Joint	Second Joint
#1	24 hours	No	No
#2	48 hours	No	No
#3	72 hours	No	No

TABLE 4
PERFORMANCE PROPERTIES OF VARIOUS PIPE AND JOINT COATING SYSTEMS

	Coal-tar epoxy	100% solids epoxy	Elastomeric PU	Rigid PU (spray)	Rigid PU (cast)	Fusion bonded epoxy
Average coating film thickness	20 mils	27 mils	53 mils	30 mils	40, 50, 80, 100 mils	18 mils
Adhesion to steel ASTM D4541	750 psi	1850 psi	1000 psi	2000 psi	1750 psi	1650 psi
Abrasion resistance ASTM D4060, CS17, 1 Kg, 1000 cycles	160 mg loss	135 mg loss	40 mg loss	80 mg loss 35 mg loss (ceramic version)	52 mg loss	120 mg loss
Flexibility ASTM D522	Failed at 180^o 1" mandrel	Failed at 180^o 1" mandrel	Pass at 180^o over 1" mandrel	Pass at 180^o over 1" mandrel	Pass at 180^o over 1" mandrel	Failed at 180^o 1" mandrel
Elongation ASTM D638	3.2%	2.8%	59%	4.8%	4.5%	4.8%
Cathodic disbondment CSA245.20M (-3.5 V, 48 hrs)	17.5 mm radius	6.0 mm radius	10.0 mm radius	4.0 mm radius	3.0 mm radius	8.0 mm radius
Dielectric strength ASTM G149	5.1 kV @20 mils 255 V/mil	7.1 kV @27 mils 263 V/mil	31.0 kV @53 mils 585 V/mil	22.4 kV @40 mils 568 V/mil	24.2 kV @40 mils 604 V/mil	20.7 kV @18 mils 1150 V/mil
Hardness ASTM D2240	65 Shore D	82 Shore D	68 Shore D @75^{o}F	72 Shore D @75^{o}F	75@75^{o}F 63@176^{o}F	85 Shore D @75^{o}F
Impact resistance ASTM G14	28 in-lbs	29 in-lbs	76 in-lbs	50 in-lbs	120 in-lbs (80 mils)	160 in-lbs
Penetration resistance ASTM G17	13%	NIL	6.6%	5.0%	3.1%	NIL
Stability (wet) ASTM D870	-30^{o}F to 120^{o}F	-30^{o}F to 120^{o}F	-30^{o}F to 150^{o}F	-40^{o}F to 150^{o}F	-40^{o}F to 195^{o}F	-100^{o}F-230^{o}F
Water absorption ASTM D570	1.2%	2.0%	2.0%	1.4%	1.0% (40 mils)	0.83%
Water vapor permeability ASTM D1653	12 g/m^2/24 hrs	3.8 g/m^2/24 hrs	37 g/m^2/24 hrs	12 g/m^2/24 hrs	10 g/m^2/24 hrs	7.5 g/m^2/24 hrs
Volume Resistivity ASTM D257	3.5x10^{14} ohm.cm	8.6x10^{14} ohm.cm	2.6x10^{14} ohm.cm	5.8x10^{15} ohm.cm	6.0x10^{15} ohm.cm	1.3x10^{15} ohm.cm
Salt spray ASTM B117, 2000 hours	<3/8" undercutting	<3/8" undercutting	Pass	Pass	Pass	Pass
Chemical resistance CSA245.20M (10% HCl, 10% NaOH, 5% NaCl)	Pass	Pass	Pass	Pass	Pass	Pass

There was no water penetration under the steel substrate causing any undercutting corrosion, indicating the strong bonding between the cast rigid polyurethane and the three-layer coatings as well as the steel substrate. Nor was there any water penetration through the cast rigid polyurethane due to its extremely low water permeability. The FBE layer was more easily removed by the sledgehammer and cold chisel from the steel substrate than the cast rigid polyurethane. This demonstrates that the adhesion of the cast rigid polyurethane to steel is better than that of the FBE to the steel. It was also found that adhesion of the rigid polyurethane to the polypropylene layer or steel substrate was affected by the total curing time of the rigid polyurethane before immersion. If immersion was done after one hour of curing from the initial molding it was easy to separate the cast rigid polyurethane from the polypropylene. Strong bonding between the cast rigid polyurethane and polypropylene, or steel, was achieved after it had cured for up to 6 to 12 hours. On the other hand, the cast rigid polyurethane adhered very well to FBE even in the first few hours. When the cast polyurethane and FBE layers were removed from the substrate after immersion, the latter often adhered tightly to the backside of the cast rigid polyurethane.

The performance properties of the advanced 100% solids rigid sprayable resin version and castable resin version were carried out both in-house and through independent laboratories.[10, 11, 12, 13] Tests were conducted on pipe samples where the coatings had been applied over surfaces prepared as per manufactures specifications. Test results of these performance properties were obtained and compiled with the results of tests performed by independent laboratories on other coatings systems. Table 4 lists the typical testing results of these performance properties. The test results shown in Table 4 suggest that the two 100% solids rigid polyurethane versions outperform liquid applied epoxies and the 100% solids elastomeric polyurethane, with properties comparable with those of the typical FBE system.

TABLE 5
ADHESION AND CATHODIC DISBONDMENT TESTS FOR TESTING
THE COMPTABILITY OF THE SPARY-APPLIED STRUCTURAL POLYURETHANE
WITH FBE AND POLYETHYLENE

Type of Surface Preparation	Adhesion (ASTM D4541)	Cathodic disbondment resistance (CSA245.20M, -1.5 V, 80°C, 72 hours)
Rigid polyurethane over “new” and “old” FBE		
No surface preparation between PU and fresh FBE	800 psi adhesion failure between PU and FBE	3.0 mm radius (FBE base), complete disbonding between PU and FBE
MEK wipe, fresh FBE	1650 psi adhesion failure between PU and FBE	4.3 mm radius (FBE base), no disbonding between PU and FBE
Brush blast and air blown off, fresh FBE	3500 psi cohesive failure of PU	3.8 mm radius (FBE base), no disbonding between PU and FBE
Brush blast and MEK wipe, fresh FBE	3500 psi cohesive failure of PU	2.8 mm radius (FBE base), no disbonding between PU and FBE
Brush blast and air blown off, old FBE	3300 psi cohesive failure of PU	3.2 mm radius (FBE base), no disbonding between PU and FBE
Rigid polyurethane over three-layer polyethylene 3LPE		
No surface preparation between PU and fresh 3LPE	500 psi adhesion failure between PU and 3LPE	2.6 mm radius (3LPE base), complete disbonding between PU and 3LPE
MEK wipe, fresh 3LPE	1200 psi adhesion failure between PU and 3LPE	3.2 mm radius (3LPE base), 15 mm radius disbonding between PU and 3LPE
Brush blast and air blown off, fresh 3LPE	3500 psi cohesive failure of PU	2.8 mm radius (3LPE base), no disbonding between PU and 3LPE
Brush blast and MEK wipe, fresh 3LPE	3500 psi cohesive failure of PU	2.7 mm radius (3LPE base), no disbonding between PU and 3LPE
Brush blast and air blown off, old 3LPE	3200 psi cohesive failure of PU	2.9 mm radius (3LPE base), no disbonding between PU and 3LPE

Additional tests were conducted to evaluate the compatibility of the 100% solids rigid polyurethane system with various pipe samples coated with the plant-applied mainline FBE or polyethylene. Two sets of samples were produced. The first set of samples was made by spraying the 100% solids rigid polyurethane coating onto the top of a “fresh” FBE or 3LPE coated steel pipe section. Being fresh meant that the initial FBE or 3LPE coating had been plant-applied within three hours before they were surface prepared and top-coated with the rigid polyurethane. Four surface preparation methods were employed to the fresh FBE or 3LPE coated pipe samples before receiving the polyurethane coating: a) there was no surface preparation; b) the sample was given an MEK wipe; c) the sample was brush blasted and then blown off with compressed air, and d) the sample was brush blasted and then given a MEK wipe. The second set of samples was made by spraying the 100% solids rigid polyurethane coating onto a 2 month-old FBE or 3LPE coated pipe section. A brush blast was employed. Adhesion tests (ASTM D4541) and cathodic disbondment tests (CSA245.20M, -1.5 V, 80^{o}C, 72 hours) were then conducted on the multi-coated samples, with results shown in Table 5.

It is interesting to note form Table 5 that a good bonding between the 100% solids rigid polyurethane and FBE or 3LPE has been achieved by simply an MEK wipe or a brush blast. This feature could provide a new avenue for the use of the 100% solids rigid polyurethane technology to protect the FBE coating on steel pipe under aggressive conditions such as directional drills, river crossing slip bore, and rock shield application.

CASE HISTORIES

DaGang – CangZhou natual gas pipeline rehabilitation

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 5^{o}F to 86^{o}F. For the river crossing and aboveground pipe segments, a high solids aliphatic polyurethane was also used to coat over the 100% solids rigid, field-applied, aromatic polyurethanr coating for protection against ultra-violet (UV) light. Application coating film thickness ranged from 35-40 mils. The field inspection included two elements: in-situ adhesion and holiday inspection and field sample preparation for lab testing. At 5^{o}F, 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. Representatives from the China oil and natural gas industry spoke highly the high performance, the field-application capability, and particularly the cold temperature curing ability of the 100% solids rigid polyurethane. Based on the success of this project, Chinese oil/gas officials are expanding the use of the 100% solids rigid polyurethane technology. [14]

Lake Texana to Corpus Christi Pipeline (mainline and field joints)

Another noteworthy case history took lace 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 direction 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 direction drilling application. Both mainline and field-applied joint coating applications were conducted successfully. The consequent corrosion survey along the pipeline rated the effectiveness of the corrosion protection as “very good levels”, as appraised by various major corrosion engineering firms in the U.S. who were closely watching the performance and application of the 100% solids rigid polyurethane coatings technology for both plant-applied mainline coating application and field joint coating applications.[15]

Victoria Pipeline Replacement

In the summer of 2001, Upper Peninsula Power Company ("UPPCO") in Michigan, U.S.A. began replacing the 42-year-old aboveground wooden pipeline at its Victoria Hydro facility near Rockland. The old Douglas fir pipeline had reached the end of its lifespan and was to be replaced by a 9.5-foot-diameter spiral-welded steel pipeline. 100% solids rigid polyurethane mainline and field-applied coatings were selected for this project.

Work started right on schedule the week of July 9, 2001 and was completed at the end of November, 2001. During this time, there was increased truck traffic in the area and also limited access for fishing and general recreation, both at the reservoir and below the powerhouse, because of equipment and construction activities. On July 9, 2001 the original head gate went down for the last time on the wooden pipeline. Once the water was drained from it, the contractor started the demolition and removal of the old 6,050-foot pipeline. The first 54-foot-length of spiral-welded steel pipe was unloaded at Victoria on Tuesday, July 10, 2001. On October 9, the last large section of steel pipeline was lowered into place, but there was plenty of work to be done before Victoria could be placed back on line. Installing drain lines, air valves and vacuum breakers, applying coating to some of the seams, completing some thrust blocks, and backfilling around the pipes were expected to take at least a month.

Victoria was back on line by December. The color of the polyurethane coating on the pipeline was carefully chosen to ensure that it blended into the now-peaceful landscape; the commotion of construction was soon buried and forgotten in the quiet of a mid-winter snow.

The above timelines given in this case history demonstrate the effectiveness and efficiency of the 100% solids field-applied coating technology to meet the challenges of the project deadline, application location, and sensitive environmental conditions in today's world of pipeline field joint applications.

SUMMARY

An advanced 100% solids rigid (or structural) polyurethane technology for field-applied coating of pipeline girth welded joints and pipeline rehabilitation for oil/gas and water/wastewater transmission lines has been presented.

This technology applies either a castable type resin or a sprayable resin in the field, allowing for setting and coating of steel pipeline joints, or sections, in minutes at virtually any application conditions.

Being 100% solids, VOC free, cold temperature curable, quick setting, easy 1:1 mixing, and balanced viscosity, the 100% solids rigid (or structural) polyurethane coatings technology provides unique handling, safety and application characteristics to the market of girth welded joints and pipeline rehabilitation. Results of both laboratory testing and field application case histories suggest that 100% solids rigid polyurethane field-applied coating technology outperforms the liquid applied epoxies and 100% solids elastomeric polyurethanes currently available in the market and that it possesses properties compatible with existing plant-applied mainline coating systems.

REFERENCES

1. Gerhardus H. Koch, Michiel P.H.Brongers, Neil G. Thompson, Y. Paul Virmani, & Joe H. Payer, "Corrosion Costs and Preventive Strategies in the United States, Appendix E, Gas and Liquid Transmission Pipeline," Report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Report FHWA-RD-01-156, September 2001.

2. “Best Practices Benchmarking Study,” Independent Survey of Pipeline Companies, October 1999.

3. Coatings Round Table, “The Use of Coatings In Rehabilitating North America’s Aging Pipeline Infrastructure”, Pipeline & Gas Journal, February 2001

4. “GTI Pipeline Coatings Test Facility Coating Specification,” The Gas Technology Institute, April 04, 2002

5. K. E. Coulson and D.G. Temple, “Pipeline Coatings, Is It Really A Cover-Up Story? Part I,” National Association of Corrosion Engineers, Proceedings, Corrosion 84.

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

7. S. Guan, “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

8. Dennis Dechant, Private communications, 2001

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

10. China Dagang Oil Field Committee of Science and Technology, “A Report on Natural Gas Pipeline Rehabilitation Coatings and Applications, ” July, 2002

11. “A Testing Program for External Pipeline Rehabilitation Coatings”, SPIE Report, 1992

12. “Laboratory Testing Program: Performance Evaluation of Madison Chemical Industries Black CorroPipe P.W.”, ITI-Anti-Corrosion, Inc., 1992

13. “Laboratory Testing Program: Performance Evaluation of Madison Chemical Industries CorroClad 2000.”, ITI-Anti-Corrosion, Inc., 1992

14. Tianjin Dagang Oilfield Natural Gas Company, “100% Solids Rigid Polyurethane Coating Technology and Application for Natural Gas Pipe Rehabilitation – A Project Evaluation Report”, July, 2001

15. M.J. Szeliga and D.M. Simpson, “Final Acceptance Testing Cathodic Protection Systems – Lake Texana to Corpus Christi Water Pipeline Contact Number 9, Water Course Crossings Guadalupe Rive and Victoria Barge Canal 48-Inch Raw Water Pipeline, Port of Corpus Christi Authority”, Russell Corrosion Consultants, Inc., February 2, 1999.