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PIPELINE REHABILITATION AT ALL ENVIRONMENTAL TEMPERATURES WITH ADVANCED 100% SOLIDS STRUCTURAL AND RIGID POLYURETHANE COATINGS TECHNOLOGY

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ABSTRACT

Pipeline rehabilitation at all environmental temperatures, particularly in cold winters, provides a great challenge and many requirements to the oil and gas industry for the need of an effective field-applied corrosion protective coating system with excellent application and performance properties. In meeting the challenge and requirements, this paper presents the advanced 100% solids structural and rigid polyurethane coatings technology for pipeline rehabilitation. It highlights the specific advantages of the 100% solids structural and rigid polyurethane technology over other rehabilitation coating systems in terms of coating formulating properties including environmental and safety issues, surface preparation, field-application properties, performance and overall cost. Finally, the paper chronicles the case history of the Dagang-Cangzhou gas pipeline rehabilitation project with the advanced polyurethane coatings technology, at field application temperatures ranging from -15°C to 30°C. Performance testing results on both lab and field prepared samples are discussed.

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

INTRODUCTION

Corrosion is the primary factor affecting the longevity and reliability of pipelines throughout the world. In the U.S., there are more than 528,000 km (328,000 miles) of natural gas transmission and gathering pipelines, 119,000 km (74,000 miles) of crude transmission and gathering pipelines, and 132,000 km (82,000 miles) of hazardous liquid transmission pipelines. The corrosion-related cost to the gas and liquid transmission pipeline industry has been recently determined to be $5.4 to $8.6 billion U.S. dollars annually in the U.S[1]. The corrosion-related cost of operation and maintenance makes up 80% of this cost. A recent survey of major pipeline companies in the U.S. 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 the People's Republic of China, about 20,000 km (12,500 miles) of long-distance transmission pipelines and 250,000 km (155,500 miles) of gathering pipelines have been constructed till 1999, and most of the coatings on these buried pipelines have aged so severe that the steel pipes are subject to corrosion environments underground[3]. To extend the operating life and reduce life cycle costs of a pipeline, an emerging method of pipeline corrosion control is pipeline coating rehabilitation (re-coating the pipeline). This puts a lot of emphasis on the need of a high performance coating technology that is suitable for in-field application.

However, a challenge in pipeline rehabilitation is the capability of field-applying the coating at all environmental temperatures, particularly in cold winters, when aspects such as coating properties, surface preparation, and inspection are also addressed. This challenge implies various requirements on a pipeline rehabilitation coating system in terms of coating formulating properties including environmental and safety issues, surface preparation, field-application properties, performance and overall cost. Over the years, many field-applied coatings systems have been developed and utilized for pipeline rehabilitation in China. These systems include: field-applied single or dual-layer fusion bonded epoxies, liquid applied coal-tar or non-coal tar epoxies (either solvent based or 100% solids), elastomeric polyurethanes, cold-applied or hot-applied tapes, cementitious materials, wax and composite systems. None of these coating systems provides a good solution to the challenge and requirements for all temperature field applications. As a result, for a long time the Chinese oil/gas pipeline industry has been searching for a coating system that can not only provide high performance for field oil/gas pipeline rehabilitation but is also enable to be applied during winter times in Northern China due to cold weather conditions.

One of the main pipelines that supply natural gas to northeastern Chinese cities, the 100 km x 21-inch (529 mm) 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, PetroChina Dagang Oilfield Natural Gas Company decided to completely refurbish the pipeline. A 100% solids, rigid and structural aromatic polyurethane coating technology, was selected for a river crossing and some underground/aboveground portions. For the river crossing and aboveground pipe segments, a thin film (3-5 mils or 75-125 microns) of a 1:4 mixing ratio, high solids, aliphatic polyurethane, was applied to coat over the 100% solids aromatic polyurethane coating for protection against ultra-violet (UV) light. The total application coating film thickness ranged from 35 to 40 mils (850 to 1000 microns). The application of the Madison's advanced polyurethanes was conducted between November 2001 and May 2002, with field application temperature ranging from 5°F to 86°F (-15°C to 30°C). Extensive tests on lab and field samples were then conducted. In November 2001, PetroChina Dagang Oilfield formed a special technical committee and officially appraised the rehabilitation project based on both testing results and field performance.

This paper outlines the challenges and requirements for a coating system for pipeline rehabilitation at all environmental temperatures and discusses the advanced 100% solids structural and rigid polyurethane coatings technology. It chronicles the case history of the Dagang-Cangzhou gas pipeline rehabilitation project with the polyurethane technology and details the performance testing results achieved during this project on both lab and field prepared samples.

THE CHALLENGE AND REQUIREMENTS FOR A COATING SYSTEM FOR PIPELINE REHABILITATION AT ALL ENVIRONMENTAL TEMPERATURES

Corrosion protection by pipeline rehabilitation coatings is the implementation of a well-balanced cycle of the four equally-important elements: a) specifying and using a proper rehabilitation coating system; b) proper surface preparation for the coating system; c) proper application of the coating system; and d) quality inspection of the coating system. For years, the pipeline industry has required an effective rehabilitation coating system with excellent application and performance properties and the ability to withstand corrosive environments. In order to meet these requirements, a pipe rehabilitation coating system has to be able to meet five challenges: environmental and safety regulations, economics, field application conditions, effectiveness, and high performance. Engineers must strike a balance between these five areas. The ideal pipeline rehabilitation 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 during application, handling, burial or insulation. 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 pipeline rehabilitation coating system 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 pipeline rehabilitation 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.

Field application and repair attributes determine the construction contractor's ability to achieve the proper results for pipeline rehabilitation. The quality of field application is very much limited by the number of coats, curing temperature, and cure time required by the 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 the pipe substrate and the existing 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, burial or insulation without losing effectiveness. It is therefore very important to understand the surface preparation requirements of the coating system to be selected. Surface preparation often becomes a bottleneck for pipeline rehabilitation. Abrasive blasting to an often recommended SSPC-SP10 (NACE 2) near-white or SSPC-SP5 (NACE No.1) white metal surface can be slow. However, 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. Surface preparation often requires special procedures at transitions between the existing coating and the rehabilitation coating, such as, feathering the abrasive blasting edge for several inches into the existing coating to improve adhesion. The extent of surface preparation for the transitions depends on how compatible the rehabilitation coating is with the existing coating. The choice of a type of blasting machinery to use for surface preparation during a pipeline rehabilitation project is related to the total length of the pipeline, production daily rate, and whether the pipeline can be taken out of service and cut into long sections.

Performance of a pipeline rehabilitation coating depends on many factors. These factors include the adhesion to the pipe substrate and the existing coating, abrasion, impact, and penetration resistance (hardness), chemical and corrosion resistance, dielectric strength and cathodic disbondment resistance, flexibility or bendability, stability at low or elevated temperature service conditions, and water absorption or water vapor permeability. Details of discussion on the requirements of these performance properties were given in the author's recent presentation at NACE Corrosion 2003[4].

Many coating manufacturers are in a rush to develop and launch new pipe rehabilitation coating systems. An example is 100% solids polyurea coating. While the industry should appreciate the variable choices of rehabilitation coatings and coating suppliers, it is very important to select those coating technologies, products and coating suppliers, that are backed by solid case histories in terms of both performance and capability of technical support. Field experience, although it is often expensive to acquire, can demonstrate the ability of a rehabilitation coating to perform under actual operating conditions. Case histories, consistent past performance, as well as capability to provide onsite technical support are a coating manufacturer's reputation for good coating performance, which should be factored into the decision on whose and which rehabilitation coating should be used.

The true cost of any rehabilitation coating system is not the 'cost per bucket' or even the initial 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 the coating material and its field-application, handling and burial, throughout the entire operation period.

Table 1. Additional challenges and requirement with coating systems for pipeline rehabilitation at all environmental temperatures

Area of challenges	Requirements
Formulating, handling, and safety properties	
• Is the coating resin curable at the field ambient temperature? • Is an accelerator needed? • Is heating needed for the coating material? • Will the coating become either too viscous when it is cold in the winter or too thin when hot in the summer? • Any potential health and safety issue due to not so ideal environmental temperatures?	• Cold temperature naturally cured coating systems are desirable than those that require heat-cured. • Less number of coating components is better. • Viscosity of the coating shall be proper for easy application. • For rehabilitation of piping, less than 80 feet, airless spray can be effective. For longer lengths liquid systems application using 1:1 plural component spray equipment is desirable. • 100% solids and solventless systems are desirable.
Surface preparation	
• Is heating or cooling needed for the substrate by the coating? • How sensitive is the prepared substrate surface and coating to ambient temperature and moisture? • Will it be possible to control the pipe surface temperature?	• It is ideal to have a rehabilitation coating that can be applied, as fast as possible, onto the substrate regardless its temperature under the environmental and climate conditions.
Field application properties	
• How easy is the application of the coating at cold or hot temperatures? • Any special equipment requirements due to the ambient temperature? • Is the coating formulated for easy application? • Any potential problem on spray pressure, coating material temperature, and substrate temperature? • For how long does the coating need to be dry to touch, to handle, inspection, backfill, and to service? • What is the maximum coating thickness to hang on the pipe per single coat application at the ambient temperature? • How many coats are required? What is the minimum and maximum recoat or topcoat window between coats? • What and how easy the field inspection tests can be done at the ambient temperatures? Would the time for inspection cause delaying the project? • How easy can repairing be done? • Would the coating application meet the tough schedule due to climate changes?	• Easy application is important. Proven systems are best. • 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. It is recommended to select those systems in which both components have the same or very close values of medium-ranged viscosities. Too high viscosity values of these coatings may cause application and equipment problems in handling. • A fast cure one single coat system is the ultimate goal to meet the work schedule requirements and also to minimize costs.
Performance properties	
• Are any performance properties affected due to exposure to hot ambient temperatures during field application (such as adhesion, resistance to penetration of the back-fill material, etc.)? • Are any performance properties affected due to exposure to cold ambient temperatures during field application (such as brittleness, impact resistance, etc.)?	• A rehabilitation coating system shall perform at all possible environmental conditions that can be encountered during the field application

While dealing with costs, maintenance costs and hidden costs cannot be avoided either. In order to reduce the total life cycle cost of a pipeline, it is also desirable to reduce the rehabilitation/repair to a one-time event or to reduce the maintenance cost of the rehabilitation coating. Maintenance costs of a field-applied 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 back into service almost immediately can mean significant economic and other benefits.

The challenge of field-applying coatings for pipeline rehabilitation at all environmental temperatures, particularly in cold winters, implies additional requirements on the rehabilitation coating systems in terms of coating formulating properties including handling and safety characteristics, surface preparation, field-application flexibility and properties, performance and cost. These requirements are outlined in Table 1.

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 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.[5] 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°C (-40°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 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 pipeline 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. Differing from the linear polymeric structures of a 100% solids elastomeric polyurethane or polyurea 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 film, similar in feel and appearance to the casing on a laptop computer and having structural rigidity. In North America, 100% solids rigid polyurethane coatings were first developed specifically for underground storage tanks in the early 1970s. In 1975, ULC (Underwriters Laboratories of Canada) issued the first listing for cathodically protected steel tanks with a rigid polyurethane coating system. In 1981, the same technology was approved for use in the STI-P_3 ® tank by the Steel Tank Institute (STI). By the late 1980s, 100% solids rigid or structural polyurethane technology had almost completely replaced coal tar epoxy and other coatings technologies in the North American underground storage tank industry. By January of 1998, the Steel Tank Institute reported that over 250,000 STI-P_3 underground steel fuel storage tanks had been registered and installed in the U.S. In addition, the Steel Tank Association of Canada estimated that 100,000 steel tanks had been installed in Canada. In total, these tanks involved approximately 200 million square feet of steel, and over 80% of the area was coated with 100% solids rigid polyurethane coatings. The technology's performance has been nearly flawless, according to a 1993 report by a U.S. based risk-management consulting firm[6]. A tank can be basically viewed as a pipe with two closed ends. If such an underground tank could be installed to eliminate corrosion, why not coat an underground pipe with that very same coatings technology? This idea has resulted in the use of the 100% solids rigid coatings in pipelines. In water/wastewater transmission pipeline applications, the 100% solids structural polyurethane coatings have been demonstrated to be by far the most successful protective coating systems used for both exterior and interior applications.[7] 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.[8] Currently, NACE Task Group (TG) 281, administered by NACE Specific Technology Group (STG) 03, is developing a NACE standard recommended practice for the use of polyurethane coatings for field repair, rehabilitation, and girth weld joints on pipelines. This standard is applicable to underground steel pipelines in the oil and gas gathering, distribution, and transmission industries.

Since 1998, PetroChina Tianjin Dagang Oilfield in the People's Republic of China and Madison Chemical Industries Inc. has partnered together to develop advanced pipeline rehabilitation coating technologies for the Chinese oil and gas pipeline industry, based on the 100% solids rigid and structural polyurethane chemistry. One of the development projects is to develop and utilize the 100% solids rigid and structural polyurethane coating technology to the Chinese oil/gas pipeline industry in order to resolve the industry's long term problem of searching for a coating system that can not only provide high performance for field oil/gas pipeline rehabilitation but is also able to be applied during winter times in Northern China due to cold weather conditions.

The 100% solids rigid polyurethane rehabilitation coating technology resulted from this joint partnership currently offers a sprayable, aromatic polyurethane resin version. A "mix, pour, and cast" castable, aromatic polyurethane resin version is also under development and field testing in order to be used only for field joint applications with a pipe diameter size of less than 36 inches (914 mm). The sprayable, aromatic polyurethane 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. Special setting times are often made 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 formulations, 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 brought back into service within hours.

Table 2 highlights the product handling and safety characteristics of the 100% solids rigid sprayable, aromatic polyurethane resin version, together with some other typical liquid-applied field coatings that are used today in the market for pipeline rehabilitation. Examples of these typical coatings include a coal tar epoxy, a 100% solids epoxy, and a 100% solids elastomeric, aromatic polyurethane, and a Fusion Bonded Epoxy (FBE) coating.

Table 2. Product handling and safety characteristics of various pipe rehabilitation coating systems

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

As to the field rehabilitation application, both 100% solids elastomeric polyurethane and 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. Table 3 outlines the field application and repair attributes of the 100% solids, rigid, aromatic polyurethane technology, comparing with other rehabilitation coating systems.

The performance properties of the advanced 100% solids rigid sprayable, rigid, aromatic polyurethane resin version were carried out both in-house and through independent laboratories on samples prepared under laboratory conditions.[9, 10, 11, 12] 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 100% solids rigid, aromatic polyurethane outperform liquid applied epoxies and the 100% solids elastomeric polyurethane, with properties comparable with those of the typical FBE system.

Additional tests were conducted to evaluate the compatibility of the 100% solids rigid, aromatic polyurethane system with various pipe samples coated with the plant-applied mainline FBE or polyethylene. Two sets of samples were produced. The testing set of samples was made by spraying the 100% solids rigid, aromatic polyurethane coating onto a 2 month-old FBE and 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.

For aboveground application, high solids or 100% solids, aliphatic polyurethane coatings technologies were also developed in order to provide UV stability. An example is a 1:4 plural component, mix-and-apply, 70 % solids, fast chemically-cure, UV and color stable, direct-to-metal, aliphatic polyurethane. The mix-and-apply polyurethane is applied with a single component spray gun. Because it involves premixing two ingredients prior to application, the per-coat film build is higher. The pot life of the polyurethane is about two hours, and the coating has an initial cure time of approximately 1 hour. A 1:1 plural component, 100% solids, aliphatic polyurethane has also been developed and is under field testing for pipeline rehabilitation applications. Table

6 outlines some properties of the 1:4 plural component, mix-and-apply, high solids, direct-to-metal, aliphatic polyurethane.

Table 3. Field application and repair characteristics of various pipe rehabilitation coating systems

	Coal-tar epoxy	100% solids epoxy	Elastomeric PU	Rigid and aromatic PU	Fusion bonded epoxy
Application methods	Brush, roller, conventional spray	Brush and conventional spray	Plural component spray	Plural component spray	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	16 mils (12 mils minimum)
Surface preparation	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 +	2.0 mils +
Ambient temperature	50 to 110°F	>41°F	50 to 140°F	-40 to 150°F	Not applicable
Substrate surface temperature	50 to 110°F and 5°F above dew point	>41°F and 5°F above dew point	50 to 140°F and 5°F above dew point	-40 to 150°F and 5°F above dew point	425 to 488°F
Materials temperature	50 to 90°F both A and B	150°F (A) 120°F (B) (spray grade)	120 to 140°F both A and B	32 to 150°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
Spray pressure	2100-2500 psi	About 2200 psi	4260 psi	1800-2500 psi	Not applicable
DFT per coat	Up to 24 mils	Up to 45 mils	Unlimited @ multiple passes	Unlimited @ multiple passes	25 mils maximum
# of coats required	1 to 2	1	1	1	1
Dry to touch	4 hours @75°F	1 hr 45 min. @75°F	<10 min. @75°F	1-10 min. @75°F	Up to 90 sec. @ 450°F
Dry to handle	12-24 hrs @75°F	3 hrs @75°F	6-8 hrs @75°F	5-60 min. @75°F	Upon completion of coating
Holiday testing	24-48 hrs @75°F	3 hrs @75°F	2 hrs @75°F	5-60 min. @75°F	Upon completion of coating
Backfilling	24-48 hrs @75°F	3 hrs @75°F	6-8 hrs @75°F	30-180 min. @75°F	After holiday testing
Ultimate cure	7days @75°F	7 days @75°F	7 days @75°F	7 days @75°F	Not applicable
Recoat time	6 hrs (Min) 24 hrs (Max) @75°F	Within 3 hrs @75°F	2-6 hrs @75°F	0.5-1.5 hrs @75°F	No recoat allowed
Repair material	Brush grade	Brush grade or patch compound	Self or brush grade	Self or brush grade	Patch component or liquid epoxy

Table 4. Performance properties of various pipeline rehabilitation coating systems on samples prepared under laboratory conditions

	Coal-tar epoxy	100% solids epoxy	Elastomeric PU	Rigid and aromatic PU	Fusion bonded epoxy
Average coating film thickness	20 mils	27 mils	53 mils	30 mils	18 mils
Adhesion to steel ASTM D4541	750 psi	1850 psi	1000 psi	2000 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)	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	Failed at 180^o 1" mandrel
Elongation ASTM D638	3.2%	2.8%	59%	4.8%	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	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	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	85 Shore D @75^{o}F
Impact resistance ASTM G14	28 in-lbs	29 in-lbs	76 in-lbs	50 in-lbs	160 in-lbs
Penetration resistance ASTM G17	13%	NIL	6.6%	5.0%	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	-100^{o}F-230^{o}F
Water absorption ASTM D570	1.2%	2.0%	2.0%	1.4%	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	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	1.3x10^{15} ohm.cm
Salt spray ASTM B117, 2000 hours	<3/8" undercutting	<3/8" undercutting	Pass	Pass	Pass
Chemical resistance CSA245.20M (10% HCl, 10% NaOH, 5% NaCl)	Pass	Pass	Pass	Pass	Pass

Table 5. Adhesion and cathodic disbondment tests for testing the compatibility of the 100% solids structural and rigid polyurethane with FBE and polyethylene

Type of Surface Preparation	Adhesion (ASTM D4541)	Cathodic disbondment resistance (CSA245.20M, -1.5 V, 80^{o}C, 72 hours)
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
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

Table 6. Laboratory Performance Properties of a mix-and-apply, 1:4 plural component, 70% solids, rigid, aliphatic polyurethane coating for aboveground pipeline rehabilitation

Properties	Mix-and-apply aliphatic polyurethane
Application temperature	0^oC to 50^oC (32^oF to 120^oF)
Initial setting time @ 20^oC /70^oF	1 hour
Curing time before handling @ 20^oC /70^oF	4 hours
Solids content by volume	72%
Adhesion direct-to-steel (ASTM D4541)	1000 psi
Hardness (ASTM D2240)	50 Shore D
Impact resistance (ASTM G14)	80 in.lbs
Abrasion resistance (ASTM D4060, Taber CS17 wheels, 1kg, 1000 cycels)	60 mg loss
Initial gloss 60^o and Gloss retention (ASTM G154, 5000 hours QUV 313B)	86 (initial) 92 (retention)
Chemical resistance after 96 hour immersion exposure	No color change, slightly softened in 10% H_2SO_4 and 25% NaOH

DAGANG – CANGZHOU NATUAL GAS PIPELINE REHABILITATION

One of the main pipelines that supply natural gas to northeastern Chinese cities, the 100 km x 21-inch (529 mm) 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, PetroChina Dagang Oilfield Natural Gas Company decided to completely refurbish the pipeline. A 100% solids, rigid and structural aromatic polyurethane coating technology, was selected for a river crossing and some underground/aboveground portions. For the river crossing and aboveground pipe segments, a thin film (3-5 mils or 75-125 microns) of a 1:4 mixing ratio, high solids, aliphatic polyurethane, was applied to coat over the 100% solids aromatic polyurethane coating for protection against ultra-violet (UV) light. The total application coating film thickness ranged from 35 to 40 mils (850 to 1000 microns). The application of the Madison's advanced polyurethanes was conducted between November 2001 and May 2002, with field application temperature ranging from 5^oF to 86^oF (-15^oC to 30^oC). Extensive tests on lab and field samples were then conducted. In November 2001, PetroChina Dagang Oilfield formed a special technical committee and officially appraised the rehabilitation project based on both testing results and field performance (Figure 1, 2, and 3).

Figure 1. Comparison between a coated and uncoated pipe after 5 minutes of the polyurethane coating application at -15^oC (9^oF)

Figure 2. Application of the 100% solids, rigid, aromatic polyurethane coating for river crossing on top of an iced river

Figure 3. A river-crossing section of the DaGang-CangZhou gas pipeline after being re-coated with a 100% solids, rigid, aromatic polyurethane coating and then top coated with a high solids, UV stable, aliphatic polyurethane coating

Prior to the coating application, the pipe section to be coated was surface cleaned to remove contaminations such as oil and dirt, and then abrasive blasted, using medium grade coal slag abrasives, to a near-white metal blasting (SSPC-SP 10 / Sa 2.5) with a surface profile of 40-60 microns. Coating application was done within 4 hours of blasting.

The field inspection included two elements: in-situ adhesion and holiday inspection and field sample preparation for third-party lab testing. At -15^{o}C, the field-applied coating cured in about 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 packed and sealed on-site, and then were sent out immediately to the Pipeline Coating Testing Centre of the Research Institute of Engineering Technology of China National Petroleum Corporation.

Table 7 and 8 show typical field inspection results of the rehabilitation using the polyurethane coatings at cold and hot ambient temperatures.

Table 7 Field test results of the 100% solids rigid, aromatic polyurethane coating at cold temperatures

Application and test date	December 26, 2001	
Testing location	Hong-Yuan Salt Field, No. 3 Section	
Ambient temperature	Cloudy, application temperature: -15^{o}C	
Field inspection	Surface preparation	Sa 2.5, angular profile: 40-60 microns
	Coating dry-to-touch time	1.5 minutes
	Coating appearance	Smooth, glossy
	DFT Thickness	Average 900-1000 microns based on 12 points
	Adhesion testing (X cut)	Excellent, no disbondment, difficult to cut
	Holiday testing	Passed 12 kv holiday testing

Table 8 Field test results of the 100% solids rigid, aromatic polyurethane coating in summer

Application and test date	April 11, 2001	
Testing location	Cang-Lang River Corssing	
Ambient temperature	Sunny, application temperature: 30^{o}C	
Field inspection	Surface preparation	Sa 2.5, angular profile: 40-60 microns
	Coating dry-to-touch time	40 seconds
	Coating appearance	Smooth, glossy
	DFT Thickness	Average 900-1000 microns based on 24 points
	Adhesion testing (X cut)	Excellent, no disbondment, difficult to cut
	Holiday testing	Passed 10 kv holiday testing

Results of testing on the field samples are shown in Table 9.

Table 9 Performance properties of the polyurethane coating systems on field samples prepared during the DaGang-CangZhou gas pipeline rehabilitation project

Properties	Results	Testing standard
Appearance	Smooth, glossy, no visual defects	Visual examination
Curing time, surface dry	40 seconds	ASTM D1640-95
Curing time, complete dry	4 minutes	ASTM D1640-95
Cathodic disbondment (48 hours)	4.0 mm	CAN/CSA245.20M 98
Adhesion	Rating 1	CAN/CSA245.20M 98
Hardness	Shore D 65	GB/T 1720-89
Abrasion (1 kg/1000 cycles)	60 mg weight loss	ASTM D4060-95
Bendability	Pass with 13 mm diameter mandrel	ASTM D522-93
Water permeability	4.08 mg/cm^2. 24 hours	ASTM E96-95
Chemical resistance	No effect after exposure to 10% HCl, 10% NaOH, and 5% NaCl, at room temperature for 30 days	CAN/CSA245.20M 98
Impact resistance	10 J	ASTM D2794-93
Salt spray testing	No effect after 1000 hours exposure	ASTM B117-97
Cycling (30 times)	Passed	-40 to 70^oC
Heat resistance	No effect after 500 hours at 100^oC	GB/T 1735-89
Dielectric strength	22.5 MV/m	ASTM D149-95
Volume resistivity	5.8×10^{13} Ω.m	ASTM D257-93
QUV UV resistance on the high solids aliphatic polyurethane coating	Rating 1 after 500 hours of UV exposure	ASTM G53-95

Results of both field inspection and lab evaluation showed that the properties of the 100% solids rigid polyurethane coating outperformed all liquid-applied epoxy systems utilized in China, and exceeded or matched the performance of fusion bonded epoxy coating.

SUMMARY

A pipe rehabilitation coating system has to be able to meet five challenges: environmental and safety regulations, economics, field application conditions, effectiveness, and high performance. Engineers must strike a balance between these five areas. The ideal pipeline rehabilitation 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 during application, handling, burial or insulation. 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 pipeline rehabilitation coating system 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.

An advanced 100% solids rigid and or structural polyurethane technology for field-applied coating of pipeline rehabilitation for oil/gas lines has been presented and evaluated both in laboratory and field 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 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. L.P. Zhang, Z. Lin, Q. Zhang, etc., "Research and Application of External Rehabilitation Material for Buried Pipeline", Paper No. 02609, Proceedings of the 2nd China International Corrosion Control Conference (CICC'2002), Beijing, China, November 2002.

4. S. Guan, "Advanced 100% Solids Rigid Polyurethane Coatings Technology for Pipeline Field Joints and Rehabilitation", Paper No. 03043, NACE International Corrosion 2003, San Diego, March, 2003

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

6. W. Geyer, "Handbook of Storage Tank Systems Available Now", Marcel Dekker, Inc., 2000

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

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

10. "A Testing Program for External Pipeline Rehabilitation Coatings", SPIE Report, 1992

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

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