CHAPTER B10

FUSION-BONDED EPOXY INTERNAL LININGS AND EXTERNAL COATINGS FOR PIPELINE CORROSION PROTECTION

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INTRODUCTION

Corrosion is a global problem, consuming 3 to 4 percent of gross national product in the developed countries of the world.[1] Selecting economical and effective techniques for minimizing the effects of corrosion is a critical design decision in pipelines as well as in other technologies. Protecting pipeline systems from corrosion is essential to prevent leaks and consequent possible environmental disasters, fire and explosion, personal injury, service disruption, and costly maintenance. Protective measures are critical, yet they represent only a small fraction of the long-term overall cost of a pipeline system. The effectiveness of the corrosion-prevention system has a direct bearing on the design life of the pipeline and significantly influences operational costs such as general maintenance, pumping energy, and capacity upgrades.

This chapter reviews fusion-bonded epoxy (FBE) coatings, three-layer polyolefin coatings which utilize FBE as the primary corrosion coating, and FBE linings as solutions for mitigating external and internal pipeline corrosion.

Higher operating temperatures in modern pipeline systems and a host of hostile environmental conditions during transportation, installation, and use require a new generation of FBE-based world-class coatings to protect the pipe exterior.[2] The FBE primary coating controls the steel/coating interface where corrosion begins. Advanced field application technology provides comparable-quality same-system coatings for the girth weld.

Higher levels of hydrogen sulfide (H_2S), carbon dioxide (CO_2), salt water, and higher operating temperatures aggravate internal pipe corrosion. Corrosion-resistant alloys, inhibitors, and linings provide solutions for internal corrosion problems. FBEs have been formulated to operate in these very harsh service environments. These internal linings provide additional advantages besides corrosion prevention for the pipeline system. For example, they[3]:

- Improve fluid flow for higher throughput and reduced energy requirements
- Improve pipe inspection prior to installation
- Prevent corrosion during storage
- Facilitate pipeline cleaning and water disposal after hydrostatic testing

BACKGROUND, HISTORY, AND ADVANTAGES OF FBE LININGS AND COATINGS

Fusion-bonded epoxy is a one-part, heat-curable, thermosetting epoxy resin powder. The application of heat causes this material to melt and adhere to a metal substrate. The resulting coating contains no trapped solvents, exhibits excellent adhesion qualities, and provides a tough, smooth finish that is resistant to abrasion and chemicals. FBEs have been in use since 1960 to protect pipelines from corrosion. It is estimated that over 50,000 miles (80,000 kilometers) of FBE-coated pipelines are installed around the world.

FBE is the favored primary coating for three-layer polyolefin corrosion coatings. In this technology, it has been in use since 1979.

FBE is currently specified in the oil, gas, and water pipeline industries. It has been used as an internal lining in desalination plants in Australia and the Middle East, and on gas transmission pipelines.[5] It has been in use to protect downhole tubing for over 20 years.[14] More recently, it has been used in sour crude pipelines.[4]

In the water industry, FBE provides a thinner coating compared to concrete, enabling smaller pipe sizes and reduced bulk and weight during handling and installation of pipe. The smooth, hard coating provides reduced friction compared to uncoated or concrete-lined pipe. This results in more efficient flow, reduced energy costs, and lower installed pump or compressor investment. It has been used on valves, pumps, and fittings in water districts for both water and sewer systems in California for nearly 30 years. It is in use protecting brine-pit piping systems, solving erosion corrosion problems as well as general corrosion.[5] FBE has been used in high-sand-content seawater cooling pipework for 10 years and these installations are still in excellent condition. It has been applied to valves and pipework handling seawater for the U.S. Trident submarine program and has a 20-year history in the pump manufacturing industry, effectively protecting against cavitation and slurry damage. In the United Kingdom, FBE has protected drinking water pipework since 1978, with coatings on over 2,153,000 ft^2 (200,000 m^2) of piping.[6] Specific formulations meet the drinking-water requirements of many countries.

There are reports of 6 to 18 percent flow efficiency improvements in gas transportation when using FBE internally-lined pipe as opposed to bare steel pipe. Using the 6 percent figure on an 800-mile (1300-kilometer) NPS 30 (DN 750) pipeline with a discharge pressure of 960 psig (6600 kPa) and a compressor station every 80 miles (130 kilometers), the potential savings are over \$4 million in compressor equipment cost, plus an annual energy savings of about \$1 million.

TERMINOLOGY

Cathodic Disbondment. Loss of coating adhesion around a holiday (hole in the coating) when the coated pipe is provided with cathodic protection. The phenomenon of cathodic disbondment happens with all organic coatings.[7]

Cathodic Protection. When external pipeline corrosion takes place, there are anodic and cathodic areas on the surface. In the anodic areas (the corroding sites), current flows from the pipeline steel into the surrounding electrolyte (water in the soil). Where the current flows from the electrolyte to the pipeline, the area is cathodic and does not corrode. An external source of current flowing to the pipe will make it cathodic and will prevent corrosion. This method of corrosion prevention is called cathodic protection.[8,9]

Cathodic Shielding. Cathodic shielding can take place when an electrically insulating barrier prevents current flow from reaching the pipe. An example is disbonded coating that allows water to come in contact with the pipe, but does not allow cathodic protection current to passivate the pipe surface. Current flow under the coating will depend on the resistance of the water there and, after a short distance, will be insufficient to protect the pipe from corrosion.[8]

Coating. Application of FBE on the internal or external surface of a pipe or other metallic equipment. When applied on the internal surface, it is referred to as a *lining*, and, when applied to an external surface, it is called an *external coating*.

Cure Time. The time required to complete the heat-induced crosslinking reaction to the point where the coating provides the acceptable level of performance.[10]

DGEBA. Diglycidyl ether of bisphenol A, a widely used solid epoxy resin employed in the manufacture of fusion-bonded epoxy pipe coatings.[20]

FBE. Fusion-bonded epoxy.

Fusion-Bonded Epoxy. A one-part, heat-curable, thermosetting epoxy-resin powdered-coating material normally comprised of an epoxy and a curing agent, plus other materials to provide a tough, well-adhered coating. The powder is sprayed onto a hot pipe where it melts, flows, and cures.

Gel Time. The time interval during which the coating material converts from a molten liquid to a solid.

Holiday. A discontinuity, or hole, in the coating that allows an electric charge to pass at a specific voltage.[32]

Joint. 1. A length of pipe. 2. The welded area connecting two pieces of pipe (i.e., field joint).

Nested. Rows of pipe that rest directly on each other in storage.

NSF. National Sanitation Foundation (U.S. certification agency for potable drinking water systems).

Powder Coating. See fusion-bonded epoxy.

Soil Stress. Damage to a pipeline coating caused by wet/dry cycling of the soil and/or pipe movement caused by temperature change.

Stacked. Rows of pipe placed on each other in storage, but with intervening layers of stripping (normally wood).

Stress-Corrosion Cracking. In the presence of stress, corrosion cracks can initiate.[9] The incidence of failures on pipelines have been in cathodically protected areas of disbonded coatings where liquids at a pH of 9 to 11 and carbonate/bicarbonate solutions have collected[11] between the coating and the surface of the steel.

Three-layer Coating. External pipe coating composed of an epoxy primary corrosion-protection layer, a tie-layer of modified-polyolefin adhesive, and an overcoating of polyolefin.

TYPES OF ORGANIC PIPELINE PROTECTION LININGS AND COATINGS

Internal Linings

Internal pipeline linings are commonly divided into three categories: concrete, rubber, and plastics.

Concrete Linings. There are several factors to consider beside the initial cost per unit area of coating application.[12] Of particular interest are the effects of the concrete liner on the pipe diameter, and its roughness. A concrete lining is thicker than FBE lining, and consequently the concrete-lined pipe has a smaller inside diameter than FBE-lined pipe (Refer to Chapter B9 for a detailed discussion of concrete-lined pipe.) Plastic linings generally reduce the diameter by 40 mils (1000 microns) or less. Thus, the use of plastic linings can result in utilizing a smaller pipe size while retaining the same throughput. Refer to Chapter B12 for details on plastic lining. Another major advantage of using plastic linings instead of concrete is the reduction of roughness.

Rubber Linings. Refer to Chapter B11 for detailed discussion of rubber lined piping.

Plastic Linings. Internal plastic linings have been used in oil well downhole tubulars for almost 50 years. See Table B10.1 for material comparisons.[13]

Phenolic resins, formed by the chemical reaction between phenol and formaldehyde, have the longest history.[14] They provide good performance at high service temperatures and high pressures. Phenolic-based linings have low permeability to water vapor, and good carbon dioxide, solvent, and abrasion resistance. Low impact resistance, low flexibility, and moderate caustic resistance limit their usage. They are gas-permeable and normally are not applied beyond 5 to 8 mils (125 to 200 microns) in thickness. Phenolic liquids must be layered in multiple coats to achieve the necessary thickness and to facilitate solvent removal.

Urethane linings have experienced some usage over the last few years because of improved abrasion resistance and flexibility. However, recent improvements in other systems, such as FBE, have limited urethane's growth in the marketplace.

Nylon powder linings provide good flexibility, abrasion, saltwater, and impact resistance, but suffer from limited temperature resistance, hydrogen sulfide sensitivity, and acid resistance.

Modified epoxy-phenolic lining systems provide improved flexibility and caustic resistance compared to phenolics but exhibit reduced operating temperature ranges and acid resistance. They also tend to be permeable to water.

TABLE B10.1 Types of Organic Internal Linings

Type	Advantages	Disadvantages	Upper temperature	Single coat	Type
Phenolic	• Low water vapor permeability • Good carbon dioxide, solvent, and abrasion resistance	• Low impact • Low flexibility • Moderate caustic resistance	392°F (200°C)	N	TS L
Urethane	• Good abrasion • Flexible • Smooth, resists paraffin build-up		220°F (105°C)	Y	TS L
Nylon	• Good abrasion • Flexible • Good salt-water resistance • Resists installation handling damage	• Low hydrogen sulfide and acid resistance	220°F (105°C)	Y	TP P
Epoxy-phenolic	• Improved flexibility and caustic resistance compared to phenolic • Resists depressurization	• Increased water-vapor permeability • Reduced acid resistance compared to phenolic	250°F (120°C)	N	TS L
Epoxy-novolac—FBE	• Improved flexibility and caustic resistance compared to phenolic • Resists depressurization	• Increased water-vapor permeability • Reduced acid resistance compared to phenolic	300°F (150°C)	Y	TS P
Epoxy—FBE	• Flexible • Good salt-water resistance • Resists installation handling damage	• Increased water-vapor permeability • Reduced acid resistance compared to phenolic	250°F (120°C)	Y	TS

Abbreviation definitions:

Single Coat: Y = yes, the coating can be applied in a single pass. For example, FBE coatings are frequently applied at a coating thickness of 25 mils (625 microns). N = No, materials like phenolics are applied in several layers of 25 to 50 microns (1 to 2 mils).

Type: TS = thermoset coating system (there is a chemical reaction which causes the coating to cure and take on final properties). TP = thermoplastic. L = liquid. P = powder.

FBEs show improved flexibility and are saltwater, carbon dioxide, and caustic resistant. Like modified epoxy-phenolic liquid systems, they are generally limited to an operating temperature of 250°F (120°C). New chemistry is improving the operating-temperature and chemical-resistance windows for FBE linings. For best performance, the thickness is normally 16 mils (400 microns) and above. The coating is applied in one operation; FBEs have no volatile organic compounds (VOCs). In many cases FBE coatings are displacing other lining types.

External Coating

There are a number of factors to consider when selecting an external pipeline coating.[15,16] These include:

- Physical and chemical stability
- Resistance to soil stress
- Adhesion and resistance to impact
- Resistance to cathodic disbonding

Types of External Pipe Coatings. This subsection reviews the available external pipe coatings and their capabilities on the just-noted factors:

Polyethylene tapes usually consist of a primer followed by adhesive backed polyethylene tape spiral-wound around the pipe. Alternatives include two separate tape layers. Tape is often applied over the ditch over a wire-brush-cleaned surface. Tapes provide economy of materials but have poor resistance to installation damage. Tape-coated pipes are susceptible to soil stress and can insulate the pipe from cathodic protection[15] current, thus creating a corrosive environment. They are also vulnerable to corrosion at the weld seam and at the tape overlap.

Extruded polyethylene over mastic has good resistance to installation and handling damage, but can be affected by shrinkage and soil stress. Currently, it is available for only up to NPS 24 (DN 600) diameter pipe[17] because of application-process limitations.

Waxes and vinyl tapes require simple application technology and provide resistance to water permeation, but they are susceptible to damage due to cathodic disbondment and have a very limited operating temperature range.

Asphalt enamels also have the advantage of utilizing simple technology. However, they soften at higher operating temperatures and have poor resistance to moisture and soil stress.[17] Field studies have also shown that they have a tendency to cathodically shield the pipe,[15] which means that corrosion can take place even though the cathodic-protection system appears to be functioning normally. There is evidence that stress-corrosion cracking of the steel pipe can take place under enamel coatings.

Coal-tar enamels show good resistance to cathodic disbondment, which means moderate increases in cathodic-protection current over time. However, impact resistance[18] is poor, which leaves pipes vulnerable to handling damage and storage problems. Soil-stress resistance is poor,[17] resulting in potential coating loss during operation.

Three-layer polyolefins combine the good oxygen barrier properties of FBE with the good moisture-penetration resistance of polyolefin. The thick polyolefin layer also provides superior resistance to mechanical handling damage. Polypropylene has good high-temperature properties. There is a theoretical concern about cathodic shielding, but 20 years of satisfactory field performance belie that concern.

Fusion-bonded epoxy coatings have good chemical resistance, do not shield the pipe from cathodic protection, and there are no known cases of stress-corrosion cracking of FBE coated pipe. The coating is tough, but when installation damage occurs it is readily detected and repaired. Field application of FBE coating on girth welds provides the same protection as the plant-applied materials. Two-

TABLE B10.2 Types of External Pipe Coating Systems

Material	Advantages	Disadvantages	Temperature ±2°F (5°C)
Polyethylene tapes	Simple application in field.	Cathodic shielding—SCC†. Very poor resistance to soil stress.	95°F (35°C)
Extruded polyethylene	Good resistance to handling and installation damage. Self-healing adhesive.	Limited to NPS 24 (DN 600) or smaller pipe. Limited at elevated temperatures under soil stress.	105°F (40°C)
Wax/vinyl tapes	Simple technology. Low moisture permeation.	Very sensitive to temperature. Prone to cathodic disbondment.	85°F (30°C)
Asphalt enamels	Simple technology.	Poor resistance to moisture and soil stress. Very sensitive to temperature.	95°F (35°C)
Coal-tar enamels	Good corrosion resistance.	Low soil stress resistance. Properties sensitive to temperature.	120°F (50°C)
Fusion bond epoxy	Good corrosion resistance. Does not shield CP* systems. No evidence of SCC†.	Moisture absorption and permeation. Susceptible to cathodic disbondment.	175°F (80°C)
2-layer FBE	Good corrosion resistance. Good resistance to handling and installation damage.	Moisture absorption and permeation.	230°F (110°C)
3-layer polyethylene	Good corrosion resistance. Good resistance to handling and installation damage.	Cathodic shielding concern	175°F (80°C)
3-layer polypropylene	Good corrosion resistance. Good resistance to handling and installation damage.	Cathodic shielding concern	250°F+ (120°C+)

* CP: Cathodic Protection
† SCC: Stress-Corrosion Cracking

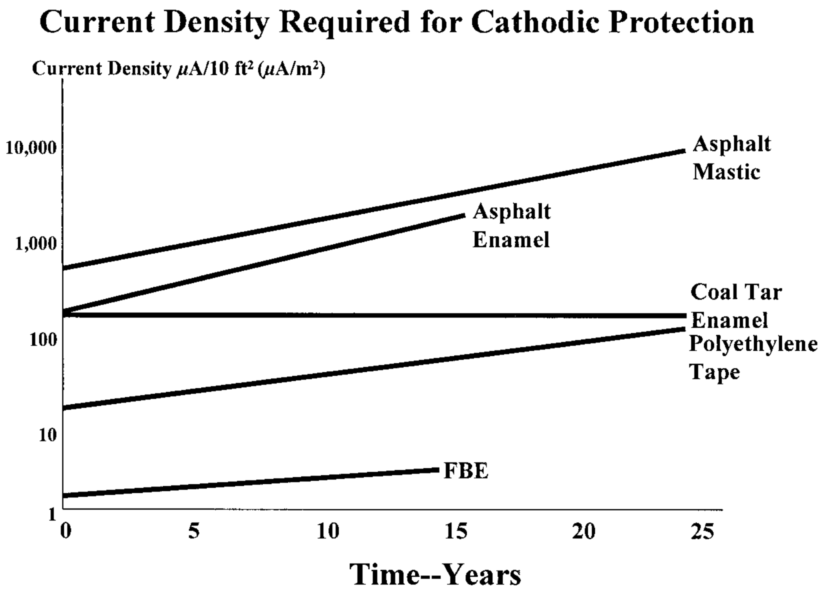


FIGURE B10.1 Lifetime pipeline costs are significantly impacted by the amount of cathodic protection current required to protect the pipe. FBE coatings provide an operational cost savings.[15]

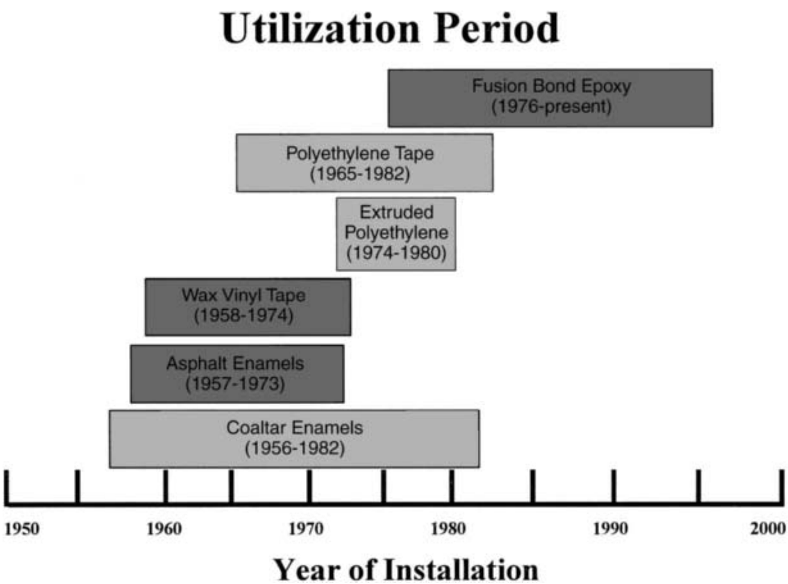


FIGURE B10.2 Progression of coating solutions for external pipeline corrosion mitigation for a major North American gas transmission company.[15]

layer FBE systems have recently entered the marketplace. They allow combining specific performance properties of the two layers to meet pipeline requirements. For example, the chemistry of the primary coating can be designed for minimal cathodic disbondment, and the topcoat can be designed to enhance impact resistance and high-temperature operating performance.

See Table B10.2 for more comparison information; also see Fig. B10.1 for cathodic protection current density requirements for coating types. See Fig. B10.2 for the coating-systems technology migration of a major Canadian gas-transmission company.[15]

FBE CHEMISTRY

During the development of coating and lining formulations and manufacturing processes, two key factors must be balanced:

- Requirements of the application plant that will apply the internal lining or external coating material
- Performance requirements of the end user, the owner of the pipeline system

If the world's best lining or coating cannot be applied efficiently, economically, and consistently, it has little value. The opposite is also true.[19]

To assist the ''understanding'' component of the selection process, this section provides a brief overview of fusion-bonded epoxy chemistry to illustrate the performance properties available and the tradeoffs required. It reviews raw materials used, and their effects on properties important to the applicator and the end user.

FBE Raw Materials

From a chemist's viewpoint, epoxies are exciting to work with because of the wide range of properties that can be derived from the selection of available materials. Materials selection and chemistry significantly affect product performance:

- Resins
- Curing agents or hardeners
- Catalysts and accelerators
- Fillers and pigments
- Additives

Resins. The term epoxy[20] comes from the three-member ring available for reaction (see Fig. B10.3). While there are several different types of epoxy resins, the two most frequently used in FBE linings and coatings are based on either diglycidyl ether of bisphenol A (DGEBA) or novolac chemistry. DGEBA resins provide excellent adherence, good mechanical and electrical properties, and good

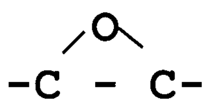


FIGURE B10.3 Epoxy ring.

resistance to chemicals. Novolacs provide a highly crosslinked coating that means improved elevated temperature performance and chemical resistance with reduced flexibility.

To be useful in powder coatings, an epoxy resin must be of sufficient molecular weight to be a brittle solid at ambient temperature, but low enough in molecular weight to melt, flow, and wet out the substrate at application temperatures.

Curing Agents. To achieve desired properties, the epoxy resin must react with a curing agent or hardener. Curing agents can be divided into three classifications:

- Bases
- Acids
- Catalytics

Basic curing agents include materials such as aromatic amines, aliphatic amines, amides, and dihydrazides. Acidic hardeners include organic anhydrides, organic acids, and phenolics. Catalytic hardeners cause the homopolymerization of the epoxy resin and include such materials as Lewis acids and tertiary amines.

Each curing system provides unique properties and is chosen carefully with requirements of both the pipeline owner and the applicator in mind. Crosslink density significantly affects flexibility and chemical resistance. Acidic cures typically result in materials with improved resistance to low pH environments. Conversely, basic cure coating systems are more resistant to high-pH, caustic environments. The selected curing agent should be latent at room temperature and highly reactive at application temperature.

Catalysts. Catalysts, or accelerators, can be divided into two categories—Lewis acids and Lewis bases. Many of the curing agents previously listed will act as catalysts for other curing systems. Others include imidazoles, BF_3 complexes, quaternary ammonium compounds, inorganic metal salts, phenols, and sulfones.

Catalysts serve two functions. First, they direct the curing mechanism of the lining or coating system. For example, the final properties of an anhydride-cured FBE system catalyzed with a base, such as an amine, will be significantly different from the same system catalyzed with a metal salt. Second, they control the speed of the curing reaction. Selection of the catalyst system is critical to final performance properties.

Pigments and Fillers. Normally pigments are employed to impart a specific color, but they can also be reactive. Fillers provide both functional and economic improvements to lining and coating systems. They can impart improved flow control, chemical resistance, and hot-water resistance, but usually at the expense of flexibility. Examples include carbonates, sulfates, and silicas frequently seen in paint formulations.

While optimization of these materials is critical to coating performance, the formulator is most often able to provide unique properties through the development and use of additives. These additives are used to control the melt and flow characteristics of the lining or coating, improve adhesion performance, water permeation, and handling characteristics of the powder material and resulting coating.

Three-Layer Systems

Three-layer external pipe-coating systems utilize FBE as the primary corrosion coating. Polyolefins possess good mechanical properties but have no polarity to

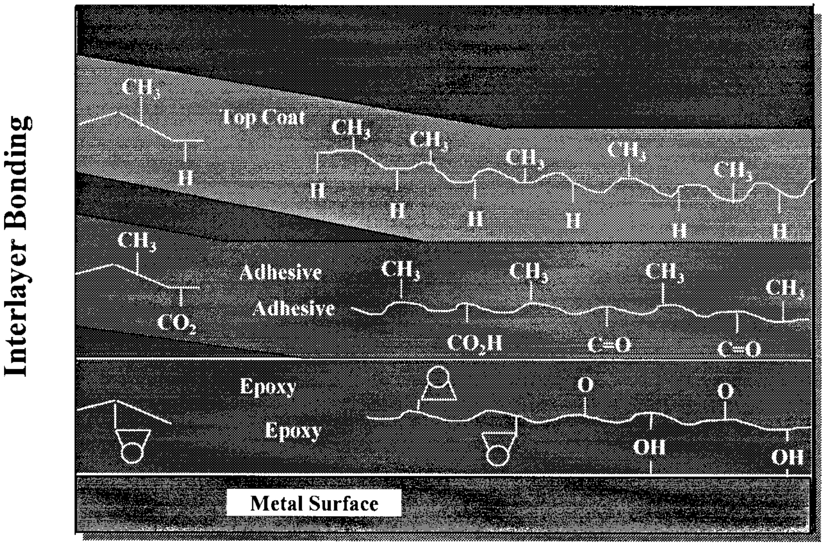


FIGURE B10.4 FBE is the primary corrosion coating for the three-layer pipe coating system and provides adhesion to the steel. The modified polyolefin tie-layer adhesive reacts with the epoxy to provide a bond. The topcoat provides a moisture barrier and impact resistance and adheres well to the tie layer.

''wet'' and adhere to steel. Combining the ''polar'' epoxy with the ''nonpolar'' polyolefin combines the positive properties of both materials. An intermediate adhesive layer of modified polyolefin achieves the bonding of the epoxy to the polyolefin. This adhesive contains polar groups grafted onto the carbon-bond spine of the polyolefin. The polar groups react with the epoxy. The polyolefin is compatible and bonds to the unmodified topcoat of polyolefin. See Fig. B10.4.

CHOOSING A FUSION-BONDED EPOXY COATING OR LINING

Application Properties

Powder Handling Characteristics are critical and must be compatible with the application process, whether it is electrostatic spray, flocking, or fluidized bed. Key elements affecting these properties are particle size distribution, electrostatic charging susceptibility, and softening point of the powder.

Cure, gel, and flow characteristics must be designed to fit the applicator's plant, or, conversely, the plant must be designed to fit the application characteristics of the powder coating. Gel and cure times can normally be adjusted without adversely affecting the performance properties of the lining or coating.[21] A lengthy gel time may cause the coating to sag, and the cure time may be too long. Undercure results in an insufficiently crosslinked coating that is brittle, easily damaged, and has poor chemical resistance. If the gel time is too short, there will be inadequate wet-out and flow, resulting in a rough coating with increased probability of holidays. Some powders cure quickly using the residual heat of the steel. Others take longer to cure and require postbaking.

Stability of the powder can affect costs from the standpoint of storage environmental control. While FBE curing systems are normally latent, a chemical reaction slowly occurs at room temperature. This chemical reaction is called *advancing*. If the powder advances too far before usage, lining and coating application and performance will suffer.[22]

Environmental Conditions and Field Performance

Internal Lining. Proper selection of a lining system means balancing chemical resistance and flexibility characteristics of the lining so that it can perform satisfactorily in adverse chemical, pressure, and temperature environments, yet meet the installation requirements.[13]

Judicial selection means gathering the facts and systematically evaluating the lining choices. All coating formulations are compromises, having clear advantages and distinct limitations. The biggest tradeoffs are normally between flexibility,

TABLE B10.3 Autoclave Testing (Internal Lining Selection Depends on Environment)

Temperature	200°F (93°C)	200°F (93°C)	275°F (135°C)
Duration (hours)	16	24	24
Liquid phase	5% NaCl Brine	15% HCl	34% Brine 33% Kerosene 33% Toluene
Gas phase	5% CO_2 95% Methane	Air	25% CO_2 75% Methane
Discharge	Cool for 4 hours then rapidly release pressure	Force-cool to ambient, release pressure over 5-minute period	Release pressure over 5-minute period at test temperautre
Results			
Lining A	Use	Don't use	Don't use
Lining B	Use	Use	Don't use
Lining C	Use	Use	Use
Lining D	Use	Use	Use

Lining A: Bisphenol-A type epoxy with NSF listing for potable drinking water
Lining B: Modified bisphenol-A type epoxy for harsh environment
Lining C: Novolac epoxy
Lining D: Novolac epoxy designed for girth-weld field application. Requires no primer or post cure.

application speed, and chemical/temperature resistance. The key is to find the most flexible system that can be economically applied in the application plant that gives optimum performance in the required operating environment.

Temperature and pressure combine to degrade lining performance and survival. Most coatings are permeated to some degree by hydrogen sulfide and carbon dioxide, which can cause blistering when pressure is released. This can also lead to premature failure of the internal lining.[23]

While field experience data is the most useful basis for decision making, it is often not available. To solve this dilemma, chemical resistance tests, such as autoclave testing, can be used. For example, in Table B10.3, for a high or variable carbon dioxide content environment, Lining A, a Bisphenol-A type epoxy with certification for potable water use in the United States, will work well in mild environments and relatively low temperatures. However, for more aggressive environments, such as higher temperatures and high levels of CO_2 or H_2S, a highly crosslinked novolac epoxy such as Lining C will be required.

Table B10.4 also shows examples of the compromises that must be considered. These compromises include the amount of flexibility required for pipeline installation and the equipment and facilities availability in the applicator's plant. For example, Lining A is relatively easy to apply since it requires neither a postcure nor a priming station. It is suitable for installation in a terrain that requires field bending. Lining B requires more extensive application facilities when used in a high-CO_2 environment, since proper application includes both the use of a primer and a postcure to achieve optimum properties.

TABLE B10.4 Application and Handling Characteristics of Different Types of Lining (Internal Lining Selection Depends on the Environment, Required Handling Characteristics, and Application Characteristics of the Material)

Lining	Elongation %	Primer required	Post cure	Wire line*	NSF†	Test‡
Lining A	6	No	No	+	Yes	Water
Lining E	4	No	Yes	++	Yes	Hot water
Lining E	4	Yes	Yes	++	No	3% CO_2
Lining B	6	No	Yes	++	No	3% CO_2
Lining B	6	Yes	Yes	++	No	100% CO_2
Lining F	1.5	No	No	+++++	No	100% CO_2

Lining A: Bisphenol-A type epoxy with NSF listing for potable drinking water (See Table B10.3)
Lining E: Modified Bisphenol-A type epoxy with NSF listing for potable drinking water
Lining B: Modified Bisphenol-A type epoxy for harsh environment (See Table B10.3)
Lining F: Novolac epoxy designed for wire-line damage resistance

* Wire Line: For downhole tubing, equipment is moved via a cable, or wire line. Resistance to damage by the wire line is based on a 1-to-5 scale with +++++ being the best rating.

† NSF: National Sanitation Foundation. U.S. certification agency for potable drinking water systems.

‡ Testing: An increase in either the temperature or level of CO_2 creates a more hostile environment for internal linings.

Primers. Phenolic based primers have been used for years with excellent performance. However, they have three significant drawbacks:

- Requirement of closely controlled cure before topcoat application
- Postcure
- Emissions from the volatile organic content of the formulations.

Water-based primer systems eliminate these problems and are suitable for less severe internal-pipe environments. One such system has been in use in brine and saltwater source-injection wells for over a year.[24]

FBE APPLICATION PROCESSES

Single-Layer Process

While the FBE application process is straightforward, attention to details is important. The steps are:

- Clean
- Apply primer or surface treatment (if specified)
- Heat
- Apply FBE
- Cure
- Cool
- Inspect

Cleaning. For most applications, blast cleaning of the metal substrate surface using hardened steel grit to a near-white-metal blast according to NACE No.2/ SSPC-SP10,[25] free of visible contamination and no more than 5 percent staining is sufficient. For internal linings in severe environments such as downhole tubing, the pipe must first be thermally pickled at a temperature of 725°F (385°C) followed by a NACE No. 1/SSPC-SP 5 blast cleaning with hardened steel grit or suitable mineral abrasive.[13]

For external coatings, the blast-cleaned surface is often washed with a phosphoric acid cleaner to remove blast debris and contaminants, such as salt, from the substrate. A chromate treatment is sometimes used to remedy coating deficiencies or to allow a wider window for the pipe-coating application temperature.

Priming. In highly corrosive internal-pipeline conditions with high pressure, high temperature, and carbon dioxide or hydrogen sulfide, a primer is required[26] for the lining. For both phenolic- and water-based systems, the primer is applied prior to the heating step. In the case of a phenolic primer, the preheat drives out the volatile organic solvents and causes a partial cure before FBE application. Control of the prime-cure step is important to coating system performance. If applied too hot or allowed to fully cure before application of the FBE, there will not be proper adhesion between the two.

Water-based primers require an application temperature lower than the boiling point of water. Flash rusting can be avoided by preheating the pipe to about

150°F (66°C) and/or using an oil-free, compressed-air drying step immediately after application. If induction coils are used for heating, the primer should be nearly dry before entering coil.

Heating. The pipe is then heated to the application temperature range specified by the coating material supplier—usually approximately 350°F (177°C) for internal linings; 400°F (204°C) for three-layer external coatings; and 450°F (232°C) for standalone FBE external coating.

Applying. Depending on the configuration of the component to be coated, all commonly used application techniques are applicable:

- Fluidized bed—the powder is aerated in a chamber via air flow; the hot component is dipped into the "fluidized" powder.
- Flocking—powder is sprayed onto the component via compressed air.
- Electrostatic spray—powder is sprayed onto the preheated component with compressed air. An electrostatic charge is imparted to increase powder-usage efficiency.

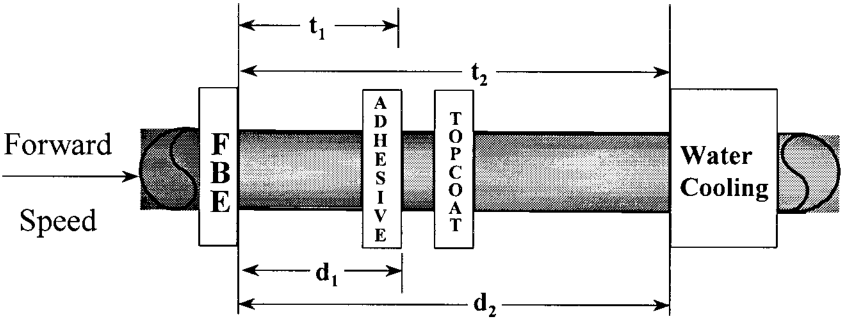
Curing. When some FBE systems are applied to sufficiently heavy-walled articles [usually ⅛ in (3.2 mm) wall thickness or heavier], the heat retention of the metal provides the thermal energy required to achieve cure—the thermosetting chemical reaction that provides the required properties of the coating or lining. In that case, facilities for postcure are not necessary. Systems utilizing a phenolic primer generally require a postcure heating step to complete the chemical reaction of the primer.

For water-based primer systems, postcure conditions are determined solely by the fusion-bonded epoxy. The temperature of the postcure step is determined by the lining system requirements and is usually in the same range as the application temperature. For metal that is likely to outgas, such as cast-iron, it is important to postcure at a temperature well below the application temperature. For example, the component may be lined at 400°F (204°C) and postcured at 350°F (177°C). In extreme cases, a preheating outgassing step may be needed—several hours at 660 to 725°F (350 to 385°C) before cooling to application temperature and applying the lining.

Cooling and Inspecting. Cooling is achieved either by spraying the outside and/or inside of the pipe with water or by simply allowing it to dissipate the heat in ambient air. Appearance, holiday inspection,[27,28] and thickness[29] checks usually follow.

Three-Layer Application

The plant application of three layers of external coating material is obviously more complicated than a single coating, but is not fundamentally different in approach. The goal is to get three layers which are well-adhered to each other and to the steel substrate. Time management is the key to the coating process. The adhesive needs to be applied while the epoxy still has free polar sites available to bond with



t_1 = Gel Time of FBE (Sec)
t_2 = Cure Time of FBE (Sec)
d_1 = Forward Speed x t_1
d_2 = Forward Speed x t_2

FIGURE B10.5 Effective time management during the application process is critical to coating performance.

the adhesive layer, but sufficient gel strength to maintain damage-free continuity (see t_1, the gel time, in Fig. B10.5).

The FBE must be cured by the time the water cooling reduces the pipe temperature below the point where the chemical reaction effectively stops. The overriding performance consideration is the full cure of the epoxy. It is the epoxy primary coating that is elemental to the long-term corrosion protection of the coating system.

QUALITY ASSURANCE

Quality assurance requires systems, processes, and monitoring to ensure successful production. Each coating system, internal lining, FBE external coating, or three-layer external coating has many similar requirements and a few unique unto itself. All require careful inspection of the in-bound pipe for determination of fitness for use and suitability for lining or coating. This includes detection of oil or salt contamination that can be spread during the cleaning process to affect otherwise coatable pipe. It also includes searching for metal defects that will be covered by the coating. One of the advantages of FBE linings or coatings is that they are relatively thin and readily show surface defects in the steel that may cause future problems.

All processes require careful attention to and monitoring of surface preparation and surface treatment or priming steps. The preheating system must bring the pipe to the proper uniform application temperature without contaminating the surface. Proper attention must be paid to the time management aspects of the application process to ensure adhesion to the steel and/or between primer and layers of the lining or coating system.[30]

For internal linings, final inspection is mainly visual, and blisters, sags, runs, or drips are identified. Also, film thickness and holiday inspections are made. For severe service, the lining must be holiday-free.[13]

FBE external-coating inspections are extensive and include destructive tests as well as evaluation of the coating on the pipe.[31,32] Nondestructive tests include visual examination, anchor profile measurements, measurement of thickness, and holiday inspection. Destructive tests require cutting a ring sample and performing bend, cathodic disbondment, cross-sectional porosity, impact, interface contamination, thermal characteristics (differential calorimetry evaluation for cure), hot water immersion, and adhesion. A recent survey[33] showed that the tests most important to the pipeline owner companies were pipe-surface cleanliness, holiday detection, coating thickness, and pipe-surface anchor profile.

For three-layer external coating systems, there are provisions for many of the same tests as in the quality assurance testing for FBE,[34] such as cathodic disbondment. Most reliance beyond visual inspection and process control is based on a peel-adhesion test to ensure bonding between the coating layers and to the steel substrate.

JOINT SYSTEMS COATINGS AND LININGS

To ensure corrosion protection, it is essential to provide quality lining or coating on the girth welds and joints that is equal to that on the main pipe body. Girth welds require special systems because of the potential for heat damage to the lining by the welding process. Several systems are available for coating the girth-weld area. Coupling systems are also available that either eliminate the welding process or protect the internal lining from heat damage.

The ideal system allows the use of the same lining or coating on the girth welds as on the remainder of the pipe. The process[5] is essentially the same as the plant lining or coating process, except that it is done in the field. The rest of this section describes the various systems and processes available for protection of the joint area.

Internal FBE Lining

The development of primerless linings that do not require postcure, yet provide the required chemical, temperature, and pressure resistance properties, has been a significant improvement in the process. Robots are available to do the operations inside the pipe.

Cleaning. The cutback area is left bare by the coating plant. Sand- or grit-blast the surface to white metal prior to welding.

Welding. Weld, X-ray (if specified), and accept for lining.

Postweld cleaning. Blast-clean to remove flux. All blast media must be removed before beginning the internal lining process.

Heating. Use an induction coil placed on the pipe exterior to bring the weld area up to lining temperature—normally in the 450°F (232°C) range.

Lining. Center the spray head of the application robot on the weld bead and apply the coating. Frequently, both the internal lining and external girth-weld coatings are applied at the same time.

Curing. Select a properly formulated girth-weld FBE that will cure through the residual heat in the pipe.

Inspecting. For final assurance, use robotic video-inspection equipment to check the quality of the coating.

Welded Internal Coupling Systems

Couplings are available to isolate the welded area of the pipe from the corrosive effects of long-term fluid transmission. An attachment system acts as a welding guide for joining the two sections of pipe and becomes an integral part of the weld. The coupling allows pigging for cleaning and inspection of the pipeline.

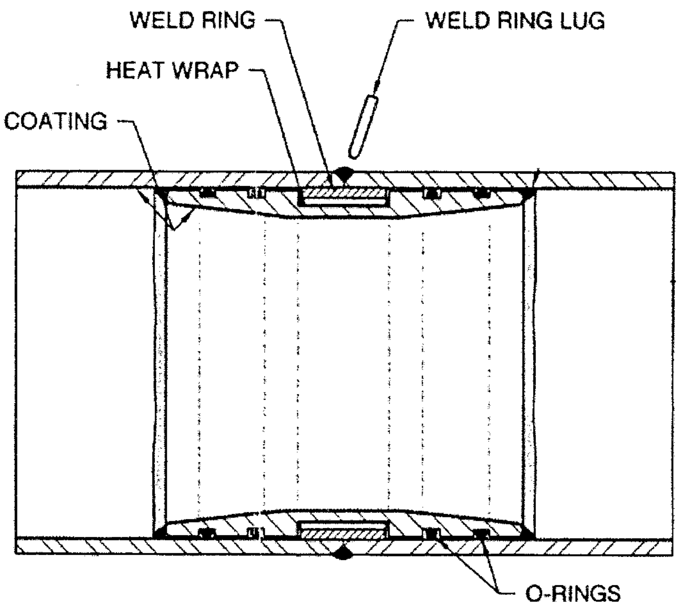


FIGURE B10.6 Welded internal coupling system. The coupling is internally coated with FBE and externally coated to include the o-rings.

The coupling (see Fig. B10.6) is inserted into the end of an internally lined pipe to the weld guide. The second internally lined pipe is slipped over the protruding half to the weld nubs. The center portion of the outer coupling circumference has a machined recess holding heat-resistant material and a steel band with the attached weld nubs. The heat-resistant material acts as an insulator to protect the lining on the inside of the coupling from weld-induced heat damage. O-rings isolate the weld from corrosive attack. The welding process unifies the two pipes and the coupling.

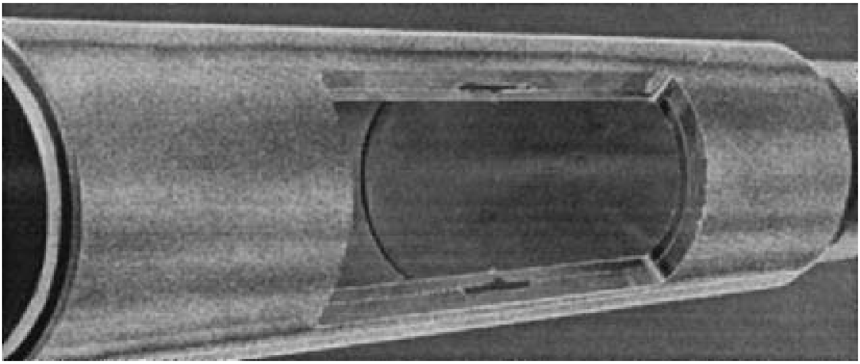


FIGURE B10.7 Weldless coupling system for internal and/or external FBE coating

Weldless Coupling System

This system consists of a coupling that slips over the outside of the coated pipeline (see Fig. B10.7). The coupling is machined with serrated grooves and is smaller than the outside of the line pipe to provide a compression fitting.

A two-part epoxy is applied to the inside of the coupling and to the outside of the lined pipe. It acts as a lubricant during the compression-fit installation and as a seal at the pipe ends, where it forms a bead to provide a continously lined internal pipe. Normally, the coupling is installed in one end of each pipe in the coating-plant yard. In the field, a hydraulic ram is used to join the two pieces of pipe together inside the coupling.

The system is available for pipe in the range of NPS 2 to 12 (DN 50 to 300). It has been used in highly corrosive applications including carbon-dioxide injection, brine-water disposal, and produced fluids of hydrogen sulfide and carbon dioxide containing oil, saltwater, and natural gas.[35]

HANDLING, SHIPPING, STORAGE, INSTALLATION, AND REPAIRS OF FBE LINED AND COATED PIPE AND FITTINGS

For protection of the piping material without regard to the lining or coating, follow the guidelines outlined in API Recommended Practices *RP 5L1 Recommended Practice for Railroad Transportation of Line Pipe and 5LW Recommended Practice for Transportation of Line Pipe on Barges and Marine Vessels.* See NACE RP0394-94 *Standard Recommended Practice: Application, Performance, and Quality Control of Plant-Applied, Fusion-Bonded Epoxy External Pipe Coating*[31] for guidelines for handling, storage, and shipping of coated pipe. For rigid internal linings,[13] steps must be taken to prevent pipe flexing during handling and transportation.

FBE coatings are tough and resistant to handling damage. However, any organic material caught between a rock and a hard place (e.g., steel) can be damaged, and care must be taken to properly handle, load, and transport the coated pipe in one example of good practice, NPS 42 (DN 1050) pipe was coated, loaded onto rail cars, shipped 3000 miles (4800 kilometers), unloaded, and stockpiled. It was later strung along the right-of-way and welded—representing a total of nine handling operations on the coated pipe. Final electrical inspection detected less than 1.5 holidays per joint.[36]

Handling and Shipping

Handling Equipment. Do not use forklifts unless dunnage between layers of stacked pipe is at least ¾ in (19 mm) thicker than the forks. Use at least 2-in (50-mm) runners. Do not use with nested pipe. The top of the forks should be padded with at least 3⁄16 in (5 mm) of dense rubber or polyurethane. Torn or worn pads may allow burrs or other protrusions to come in contact with the coating. To protect the lower level of pipe coating, the bottom of the forks should also be padded.

Overhead Loading Equipment. Both sides of the pipe hooks and the first 4 ft (1.3 m) of the cable attached to the pipe hooks must be padded with at least ⅛ in (3 mm) of rubber or urethane. Overhead equipment may be used with either stacked or nested pipe.[37]

Use of dunnage—to wood strips that support and separate the pipe—is important to ensure safe arrival of the load. Care is required in attaching chocks or padding to the dunnage. Nails should be positioned to avoid contact with the pipe coating. This can be accomplished by countersinking the nails ⅛ in (3 mm) or positioning to avoid pipe contact. Dense rubber padding may be used as an alternative to countersinking the nails, but nails or staples used to attach the padding must not come in contact with the pipe surface. Do not use carpet or excelsior-filled kraft paper, since nails can penetrate through this type of padding.[37]

Separators. Pipe that is loaded or stored should have full-encirclement separators located within 3 ft (0.9 m) of the pipe ends, and one or more at approximately equidistant intermediate locations.[31,38]

There are several suitable materials available for separators, including tight-weave polypropylene rope, dense rubber padding, and cardboard sleeves. Material selection and number of separators depends on the compression characteristics of the separator and the weight of the pipe. For example, with pipe weighing 300 lb per ft (450 kg per m), either eleven 3 in (7.6 cm) wide by 0.6 in (1.5 cm) thick dense rubber pads or seven 0.75 in (1.9 cm) diameter tight-weave polypropylene rope separators will provide adequate separation between nested pipes.[39]

Separators at the rear end of the pipe may fall off in transit. They should either be attached by tape or placed in front of the dunnage.

Hold-down strapping, used during shipping, should be either nonmetallic or steel banding with burr-free edges. Steel bands should be at least 1.5 in (38 mm) wide. Padding should not be used with steel bands, because it may compress and allow loosening of the load. Chains can cause damage to both the coating and the pipe. Heavy, dense rubber padding for chains should be used, but even that is not foolproof.[38]

Submerged arc-weld beads, in contact with adjacent pipe or dunnage, may damage the coating. Position the weld seam to avoid such contact. This does not apply to electric-resistance weld (ERW) pipe, which does not have an elevated weld seam.[39]

Storage

Stockpiling of Pipe. The bottom row of pipe should be elevated off the ground on timber skids or earth berms covered with polyethylene, properly spaced and leveled to support the coated pipe without damage. The bottom row should be restrained to prevent joints from rolling. The racks should be level over their entire length, but a slight tilt of the pipe to permit drainage is desirable.

To prevent damage by bevel-shoulder gouging, place the pipe as parallel as possible. Position the weld seam, if present, toward the interstitial gap, not toward the adjacent pipe.[38] Do not intermix short joints with long joints. To avoid bevel-damage to the coating, store short joints on the top or at the end of the pipe stack.

Chalking of FBE—the formation of a light-colored powdery residue on the coating surface caused by exposure to sunlight and moisture—is normal and acceptable, as long as the thickness of the FBE remains above the specified minimum. Chalking protects the coating from further damage, but it can be removed by rain, which allows further chalking and eventual reduction in thickness. For long-term outdoor storage (over two years), protect the sunlight-exposed surfaces with a latex paint[40] or other suitable shading system.

Installation

Off-Loading. Use only nylon slings, rope belts, or other padded equipment as detailed in the handling section.

Bending. Bending-machine shoes, calipers, and stiff back should be padded with standard rubber inserts. Burrs and other protrusions around the shoe entry and exit points should be ground smooth.

Welding. The factory-applied coating cutback is normally adequate to prevent burn damage to the coating. Drape a 20 in (0.5 m) strip of fire-retardant matting or cloth over the top and to each side of the weld to prevent spatter from burning through the coatings. Precautions should be taken to ensure adequate ventilation during welding.

Field-Cutting. When field-cutting pipe, the epoxy will carbonize or char about 2 in (5 cm) from the cut. Emissions from the lining or coating are no more toxic than those given off during the welding procedure. However, precautions should be taken to ventilate the area, particularly during tie-ins where there is little air movement at the bottom of the trench.

Girth-Weld Coating. See the section "Joint Systems Coatings and Linings" for details.

Holiday Detection. Make sure that the holiday detector (jeeper) can be set at the proper voltage. A rule of thumb for voltage is 125 V/mil (5 volts per micron). For more precise voltage calculations use the equation[27]:

$$\text{Testing voltage, } V = 525\sqrt{T} \qquad \text{(B10.1)}$$

where V = Peak voltage in volts
T = Minimum specified thickness in mils (1 mil = 25.4 microns)

TABLE B10.5 Reference Codes, Standards, Specifications, and Regulations

American Society of Mechanical Engineers
B31.1: Power Piping B31.11: Slurry Transportation Piping Systems, Special Notice—1990 B31.3 Process Piping B31.4: Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohol B31.8: Gas Transmission and Distribution Piping Systems
American Society for Testing and Materials (ASTM)
G8-96: Test Method for Cathodic Disbonding of Pipeline Coatings G12-83: Method for Nondestructive Measurement of Film Thickness of Pipeline Coatings on Steel G14-88: Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test) G17-88: Test Method for Penetration Resistance of Pipeline Coatings (Blunt Rod) G20-88: Test Method for Chemical Resistance of Pipeline Coatings G80-88: Test Method for Specific Cathodic Disbonding of Pipeline Coatings G95-87: Test Method for Cathodic Disbondment Test of Pipeline Coatings
American Petroleum Institute
RP 5L1 Recommended Practice for Railroad Transportation of Line Pipe RP 5L2-87 Recommended Practice for Internal Coating of Line Pipe for Non-Corrosive Gas Transmission Service; Third Edition RP 5LW Recommended Practice for Transportation of Line Pipe on Barges and Marine Vessels RP 5L7-88 Recommended Practices for Unprimed Internal Fusion Bonded Epoxy Coating of Line Pipe; Second Edition
Manufacturers Standardization Society of the Valve and Fittings Industry
SP-98-87 Protective Epoxy Coatings for the Interior of Valves and Hydrants ES-29-79 Abrasive Blast Cleaning of Ferritic Piping Materials (R 1984)
NACE International
RP0394-94 Standard Recommended Practice: Application, Performance, and Quality Control of Plant-Applied, Fusion-Bonded Epoxy External Pipe Coating NACE Standard Recommended Practice, RP0188, Discontinuity (Holiday) Testing of Protective Coatings RP0490-95 NACE Standard Recommended Practice, Holiday Detection of Fusion-Bonded Epoxy External Pipeline Coatings of 250 to 760 microns (10 to 30 mils)
Steel Structures Painting Council
SSPC-Vis 1 Pictorial Surface Preparation Standard for Painting Steel Surfaces
NACE/SSPC
NACE No. 1/SSPC-SP 5 White Metal Blast Cleaning NACE No. 2/SSPC-SP 10 Near White Metal Blast Cleaning
AWWA Standards for Water Systems Piping
C213-96 Standard for Fusion Bonded Epoxy Coating for the Interior and Exterior of Steel Water Pipelines C550-90 Protective Interior Coatings for Valves and Hydrants

TABLE B10.5 Reference Codes, Standards, Specifications, and Regulations (Continued)

National Standards of Canada
CAN/CSA-Z245.20-M92, External Fusion Bond Epoxy Coating for Steel Pipe CAN/CSA-Z245.21-M92, External Polyethylene Coating for Pipe
ECISS: European Committee of Iron and Steel Standardization* Technical Committee 29: Steel tubes and fittings Subcommittee 4: Coatings
EC 029016 External three-layer, polyethylene-based coating systems EC 029063 External three-layer, polypropylene-based coating systems EC 029062 External thermosetting fusion-bonded epoxy coating systems

* Standards are under development.

An effective electrical connection between the pipe and the holiday detector is required for proper functioning of the equipment. A direct connection to an exposed steel surface on the pipe provides the best connection. An alternative is to use a flexible ground wire, approximately 30 ft (9 m) long, connected to the ground terminal of the detector and trailed along the surface of the earth.

If the pipe lining or coating surface is dry, use a continuous direct-current (DC) voltage holiday detector. If moisture such as dew is present, use a pulse DC voltage holiday detector to prevent false indications of coating discontinuity.[27,40]

Repair. Remove rust or dirt with a cloth or wire brush. Do not remove the FBE pipe lining or coating unless that becomes necessary to remove rust. If undercutting is present, pry or cut away the coating until reaching adhered coating before effecting repair. Roughen the adjacent coating surface with 80 to 120 grit sandpaper to improve adhesion.

For base areas of 1 in (25 mm) diameter or smaller and farther than 8 in (20 cm) from the end of the pipe (the weld-affected zone), use heat-melting sticks. For larger areas, use two-part liquid epoxy.[31,40]

Melt (Patch) Stick. Using any noncontaminating heat source, heat the area to be repaired to approximately 350°F (177°C). Apply the heat in a manner that avoids charring or burning the FBE pipe coating. Continue to heat the cleaned area until the coating is hot enough to melt the patch stick. When the coating is hot enough, the stick will leave residue behind when drawn across the surface. While continuing to heat, apply the patch compound using a circular motion to achieve a smooth, neat-appearing patch having a thickness of no less than 50 mils (1270 microns). Do not apply by melting the stick and allowing it to drip onto the pipe. Allow the patch to cool before handling.

Two-Part Epoxy. Thoroughly mix the separate parts of the coating repair system. Combine the correct ratio of the two parts and mix thoroughly. A uniform color indicates adequate mixing. Apply using a spatula, paint brush, or paint roller. Allow to harden before handling, or protect while wet with a piece of tape. Cure can be speeded by preheating the pipe before application or by using a torch to gently heat the patch after application.

REFERENCE CODES, STANDARDS, SPECIFICATIONS, AND REGULATIONS

Table B10.5 provides a list of various codes, standards, and specifications which are related to piping and FBE lining and coatings. The listed codes cover piping systems, some of which may be lined and/or coated using fusion-bonded epoxy to protect against corrosive flow medium and the environment. The user may seek technical guidance from technical specialists in this field. Manufacturers input and recommendations must be taken into consideration in selecting and specifying suitable lining and coating systems.

Also, the user, owner, designer, and others associated with FBE lining and coatings must ensure compliance with the applicable local, state, and federal regulations.

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