FBE, a Foundation for Pipeline Corrosion Coatings

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ABSTRACT

The key to a successful pipeline anti-corrosion program is an effective protective coating system comprised of proven, high-quality coating materials, consistently applied to exacting specifications. Mill applied fusion-bonded epoxy (FBE) has been, and continues to be, the coating of choice for many pipeline operating companies since the 1960s. As the use of such coatings has expanded, much research has been conducted in an effort to improve the physical, chemical, and economic aspects of these coatings. New advancements in FBE coating technology have led to the availability of dramatically improved coating materials and systems to address specific pipeline construction needs and to enable the coating to function under a wide variety of corrosive conditions. In this paper, a review of FBE pipe coatings will be presented, progressing from their early years to the next-generation materials under development today. FBE coating solutions for the corrosion mitigation of pipeline systems will be discussed, ranging from its use as a stand-alone external coating, to the foundation layer of a three-layer coating, to a stand alone internal lining.

Keywords: Fusion Bonded Epoxy, FBE, Pipe coating, Corrosion, Two-layer, Three-layer, internal lining, self-healing coating

INTRODUCTION

"FBE is dead. Long live FBE."[1] FBE coatings have been in use for 40 years and, as such, are often mistakenly viewed as an established, unchanging technology. This couldn't be farther from the truth. FBE formulations of today are substantially different from their predecessors of even 5 years ago. Environmental conditions into which coated pipelines are placed and performance expectations have changed with time, often increasing in severity—however, FBE coatings have continuously evolved to meet these new challenges. The following sections will address the many applications of FBE in today's pipeline industry (Figure 1), review its history as a corrosion mitigation coating, and explore new developments on the horizon.

FBE YESTERDAY

A fusion-bonded epoxy is a one part, heat curable, thermosetting epoxy resin powder that utilizes heat to melt and adhere to a metal substrate. It provides a coating with excellent adhesion, a tough, smooth finish resistant to abrasion and chemical degradation, and with the absence of entrapped solvents.[2] This combination of properties—particularly the ease of use and chemical durability—make FBE an ideal choice as a protective coating under a wide variety of environmental conditions. As a result, it is no coincidence that FBE coatings have been used for pipeline corrosion mitigation since 1960 on over one hundred thousand kilometers (sixty thousand miles) of coated pipe installed around the world (Figure 1). FBE is not only used on pipelines. Though not the focus of this paper, FBE coated reinforcing steel for concrete structures has been utilized since 1972 in over one hundred thousand concrete structures in North America alone.[3]

Corrosion costs an estimated three to four percent of gross national product for direct and indirect costs (Figure 2) in the developed countries of the world.[4] In order to minimize such costs, selection of the most economically effective technique for mitigating the effects of corrosion is a critical design decision.

The protection of pipelines, valves, and fittings from corrosion is necessary to ensure long-term operation, minimize maintenance, and to prevent costly service disruption, loss of life, and injury. Protective measures are extremely important; yet, they represent a small fraction of the overall cost of a pipeline system. FBE coatings offer a solution to the protection of a wide variety of components in numerous applications. This is why they are the cornerstone corrosion protection defense in many gas and oil companies around the world. As will be seen FBE coatings possess many properties, such as the ability to optimize the benefits of cathodic protection (CP) at a defect site. This makes them a better choice than competitive systems such as 3-layer polyolefin tape coatings for numerous applications.

External Pipe Coating:

There are a number of performance factors to consider when selecting an external pipeline coating[5,6] including:

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

FBE coatings possess all of the aforementioned traits, a fact that leads to their frequent use for pipeline protection. Fusion-bonded epoxy was first introduced by 3M Company for pipeline corrosion protection in 1960. Typically, coatings have been single-coat materials applied in a thickness range of 300 µm to 450 µm (12 mils to 18 mils). To enhance specific properties, pipeline owners occasionally specify increased coating thickness—as much as 1000 µm (40 mils). This thickness increase improves both high-temperature cathodic disbondment and damage resistance. Significant performance improvements have also been made over the years through advancements in formulation technology (Figure 3).

In general, FBE standalone coatings are an excellent choice when good construction and installation practices are in use, the backfill aggregate is controlled, and the operating temperature is below 65°C (150°F). When the environmental requirements are demanding—higher temperature or more extreme installation circumstances—dual and multilayer FBE systems are available. In other situations, a three-layer system consisting of an FBE base layer, an adhesive, and a thick polyolefin layer are sometimes specified. Although these systems possess increased damage tolerance and an extended high-temperature operating range, some researchers are concerned about their ability to interact effectively with cathodic protection. This will be discussed later.

FBE TODAY

FBE as Single Layer Coating:

FBE coatings are most commonly utilized as a monolithic corrosion protection coating. Fusion-bonded-epoxy coatings exhibit excellent adhesion to steel, have good chemical resistance, do not shield the pipe from cathodic protection, and there are no known cases of stress-corrosion cracking (SCC) of pipe coated with FBE.[7] FBE has been installed under harsh conditions under the sea , through rolling plains, in rocky, mountainous areas, in the desert, and the arctic. Although the coating is tough, when installation damage occurs, it is readily detected and repaired. FBE coating systems have a good track record of installation with a minimum of damage. When total damage and cost of repair are taken into account, FBE may provide the best economic answer to field and construction damage (Figure 4). [8]

Application of an FBE coating is straight forward, which is one of its greatest strengths. [9] As with most other coating technologies, the surface to be coated is first cleaned, then grit blasted to provide an appropriate anchor pattern to enhance adhesion. Next, pipe being coated is heated to the application temperature required to begin the coating process. Heating may be done in any number of ways, including induction, direct-flame impingement, and soaking ovens. Once at temperature, the FBE is deposited via an electrostatic spray process. The deposited powder then melts, and flows out over the metal surface—resulting in a smooth, tough finish. The coating cures rapidly and is capable of supporting the weight of the pipe within seconds of application. Once cured, the pipe is cooled for safe handling, inspected, and, if necessary, repaired (Figure 5). The resulting coated pipe is then ready for installation and use. Some of the advantages of this application method include the elimination of VOCs and the near elimination of waste (i.e., overspray is readily recovered and recycled). In addition, this application technique is readily adapted for use in the field, through the use of portable heating/application equipment.

Field application of FBE coating on girth welds (Figure 6) provides the same level of performance quality as plant-applied materials—the pipeline can be protected with the same coating from end to end. FBE coating systems are also compatible with other girthweld repair systems—2-part liquid epoxies, shrinksleeves, and tape.

FBE as Dual Coating:

Two-layer FBE systems utilize the application of a second coating on top of the base coating. The top layer typically is deposited during the melt (pre-gelation) stage of the primary layer. The result is an intimate chemical bond between the two layers. A significant advantage of multilayer technology is that unique characteristics can be developed by selection of different coating layers. Each layer can be designed to impart specific characteristics that combine to produce performance results that significantly exceed those of a single coating. Examples are presented below:

IMPACT RESISTANCE: A topcoat incorporating a closed-cell structure (Figure 7) that acts as an impact-energy absorber and imparts damage resistance to protect the primary corrosion coating from penetration and ensuing cathodic disbondment has been designed. Flexibility for field bending is also maintained. This system passes 3-layer specification requirements for impact resistance.

GOUGE RESISTANCE: Abrasion resistant dual-layer FBE systems make good choices when pipe will be installed via directional boring, or if there is likelihood of rough construction practices or installation in rugged terrain. These coatings are hard and employed to resist gouging, cutting and penetration from sharp backfill. Although flexibility is reduced, specific formulations enable the coating to remain undamaged even when bent to a radius more severe than that permitted for the underlying steel itself (Figure 8).[10,11]

HIGH-FRICTION SURFACE COATING: A friction-enhancing rough coating can reduce slippage between concrete and coating for applications where concrete weight coating provides negative buoyancy. End users have claimed slippage resistance increased by as much as 20%. These coatings also improve traction for offshore application of small diameter pipe where there is no concrete overcoating. Finally, they are specified for personnel safety during installation (Figure 9).

HIGH-TEMPERATURE PERFORMANCE: Dual-coating systems can be used to enhance operating temperature performance, enabling the FBE coating to operate at temperatures as high as 110°C (230°F). Use of specifically designed coating layers and increased coating thickness dramatically improve cathodic-disbondment performance at elevated temperatures. A combination of an adhesion-enhanced basecoat with a thick-layer topcoat provides high temperature performance with significantly improved cathodic-disbondment resistance and adhesion retention (Figure 10).

UV RESISTANCE (WEATHERING):[12] FBE coatings develop a natural ‘chalk’ layer when exposed to sunlight and humidity. The chalk layer is protective and prevents significant change in properties. However, under some climate or physical conditions, the chalk layer is removed. The newly exposed coating chalks again—the process can result in loss of 10 microns to 40 microns (½ mil to 1 ½ mil) per year. To prevent coating thickness loss during atmospheric exposure or to provide a specific color, a weatherable powder coating can be used as a topcoat (Figures 11 and 12).

FBE as Primary Coating for 3-Layer System:

Fusion-bonded epoxy coating is well established as a cost-effective solution to pipeline corrosion protection. High internal strength and excellent adhesion to steel ensure good cathodic-disbondment resistance. Because it is thin in comparison to other coating materials, a concern may be that excessive damage during installation could result in higher repair and cathodic-protection costs Figures 4 and 13).

In that case, either a dual layer FBE system or a three-layer polyolefin, with FBE as the primary coating should be considered.

The basic construction of three-layer coatings [13] is illustrated in Figure 14. The three layers include an FBE base layer, an adhesive tie layer, and a polyolefin top layer. The FBE represents the foundation for the system, providing a primary layer, which is well adhered to the underlying steel substrate. This layer is essential, because polyolefin does not bond well to a metal surface. FBE also has the advantage of a slower oxygen permeation rate compared to polyolefin. The middle, or "tie" layer, is an adhesive which serves as a bridge between the low-surface-energy polyolefin and the FBE base layer. Adhesives are typically polyolefins modified with polar end groups grafted onto the carbon backbone. These polar groups in turn react with, and chemically bond to, the FBE. The polyolefin adhesive is also compatible with, and bonds to, the unmodified polyolefin topcoat. Finally, the top layer of the structure is the polyolefin, which provides a high degree of damage tolerance or impact resistance. In addition, polyolefins exhibit low moisture permeability. This trait is useful at elevated operating temperatures. Polypropylene, with its high softening point, is especially suited for high-temperature pipeline applications and has been used in these conditions for over 10 years. [14]

Three-layer polyolefin based coating systems are an effective solution in situations[15] where extraordinary coating damage is probable (due to the impact resistance of the polyolefin) or when elevated temperature service is likely (due to the insulating ability of the coating). Unfortunately, the same properties, which make the three-layer system appealing in these conditions, also have drawbacks. These are the coating of field joints (e.g., weldments), and the prevention of corrosion once the coating has been compromised.

To effectively protect a pipeline, any area where two pipes are joined must be coated with a material offering a similar level of protection to the factory applied coating on the bulk of the pipe. Unlike FBE coatings, there is no universally accepted solution for the coating of three-layer field joints. A variety of solutions are available, ranging from shrinksleeves to flame-sprayed powders. Unfortunately, each have inherent disadvantages including complexity of application, reduced quality and poor performance under hot, wet conditions.[14, 16]

Typically, the protection system utilized to mitigate corrosion of a pipeline consists of two components—the coating (as described in this paper) and a secondary protection mechanism, cathodic protection. In the case of FBE coatings, the combination of a CP source with the coating results in a cost effective, high performance system. The coating protects the bulk of the metal surface, while the CP system addresses areas where the coating has been breached. Due to the conductive nature of the FBE coating, it is possible to throw cathodic protection current through the coating. As a result, it is possible to prevent underfilm corrosion from developing at a damage site. Unfortunately, in the case of a three layer system, the polyolefin layer is highly resistive. As a result, it is not possible to pass cathodic protection current through the coating—in effect, it shields the metal surface. Thus, if the coating is penetrated and corrosion initiates at the damage site, the effectiveness of the cathodic protection system is significantly reduced. This phenomenon is known as cathodic shielding, and is well documented in the field.[17,18,19]

Three-layer systems grew out of the European philosophy that high electrical resistance coatings, combined with good mechanical properties were necessary to withstand handling and construction damage.[20] The track record of these systems in Europe has been good. Three-layer systems have a wide usage-temperature window during construction—as such, they can be used effectively during both high-and low-temperature construction. [21] Possibly the greatest value for three-layer systems comes in high-temperature environments. The high-melting point and low water-permeability of polypropylene, combined with a highly crosslinked novolac-epoxy primary coating, provides a system with superior performance characteristics at operating temperatures in excess of 120°C (250°F).[22]

FBE as Internal Pipe Coating:

Internal plastic coatings have been used successfully in downhole tubulars for nearly fifty years.[23] In recent times, new technology has improved the operating-temperature range and widened the chemical-resistance window of FBE coatings. For most such applications, optimal coating performance is achieved with thicknesses of 400 microns (16 mils) and above. A considerable advantage of FBE over other coating systems is that this thickness level can be achieved in a single operation—repeat application of multiple layers are not required. Another benefit of FBE as an internal pipe coating is that they are applied as a 100% solids material—they have no carrier solvents (VOCs) that must be dealt with.

Clearly, there are a wide variety of areas where FBE has been applied as a corrosion protection coating. In many cases, these applications are to protect the interior surfaces of oil, gas and water pipelines (Figure 15). Some notable examples include: [24, 26]

- Desalination plants and gas transmission lines in Australia and in the Middle East
- High-sand-content seawater cooling pipework (in this application for ten years and still in excellent condition)
- Seawater handling valves and pipework for the US Trident Submarine program
- Protection of downhole tubing from H_2S and CO_2

However, there are also many cases where FBE is specified for reasons other than corrosion performance. These applications include:

- Improved fluid flow characteristics resulting in reduced energy requirements

  An improvement of six to eighteen percent in flow efficiency has been documented when using FBE internal coated pipe as opposed to bare steel pipe. 25 If a lower limit of six percent is considered, then for a thirteen-hundred kilometer, DN 750 pipeline with a discharge pressure of 6.6 million Pascals, and a compressor station every one-hundred-thirty kilometers, the potential savings are in excess of four million US dollars in compressor equipment costs alone. An additional saving of one million dollars in energy costs is probable.
- Improved pipe inspection prior to installation
- Corrosion prevention during storage [26]
- Easy pipeline cleaning and water disposal after hydrostatic testing
- Cavitation protection
- FBE has a twenty-year history of effectively protecting pumps against cavitation
- Wire line damage in downhole tubulars [27]
- National Sanitation Foundation (NSF) rating for potable water [28]

As an example, one industry, which relies heavily on internal pipe coatings, is the water transmission industry. Typically, concrete-based internal coatings are utilized in order to provide the desired corrosion performance level. Unfortunately, these coatings must be quite thick in order to achieve the desired performance characteristics. As a result, pipes coated with such materials need to be sized appropriately—i.e., the diameter of the pipe must be increased to account for the internal concrete coating, resulting in a larger, heavier, and more unwieldy pipe. FBE, on the other hand, provides a thin coating compared to concrete, allowing for the use of smaller pipe sizes, thereby reducing both the bulk and weight during handling and pipe installation. In addition, the FBE coating is smoother than concrete, resulting in reduced internal friction when compared to uncoated or concrete-lined pipe. As discussed above, this translates to more efficient flow, reduced energy costs, and lower installed pump or compressor investment.

To be effective, an internal corrosion-coating system must cover the entire inside of the pipeline, including the girth weld—this is readily achieved with FBE linings. Robots are available to coat the internal-girth-weld area with the same FBE material as used on the rest of the pipe. [25] Novel mechanical couplings are available to provide one-hundred-percent coverage across the joint.[29, 30] One such system utilizes a compression fitting that eliminates the use of welding. The internal lining is applied throughout the length of the pipe, with no cut back required for welding. Two-part liquid epoxy is used as a lubricant for the compression-fitting application and acts as a sealer and corrosion coating for the pipe bevel. Another system utilizes an internally coated coupling that is welded into the pipe. A heat resistant insulated band protects the internal FBE coating from damage during the welding process (Figure 16).

FBE as Custom Coating:

Corrosion coatings on most cross-country pipelines are done in mechanized coating plants with FBE (fusion-bonded epoxy), multilayer polyolefin, or coal-tar coatings. Though cross country pipelines are provided with both a coating system and a cathodic protection system, it is equally important to adequately protect the other pipeline accouterments: valves, pumps, pipe fittings, pipe drains and hydrants. Specific FBE formulations are designed to meet the different nature of the application process as well as the protection requirements (Figure 17). Liquid-epoxy coatings are also used. They are usually two-part, thermosetting materials applied using conventional air, airless spray, plural-component spray equipment, or brush. They are designed to protect metal from corrosion and are particularly useful in coating tanks, valves, piping and special fabrications where a wide range of chemical resistance is required. Liquid coatings are more versatile than powder coatings because they often cure at ambient temperature and can be applied in the field.

FBE TOMORROW

Enhanced FBE Coatings:

Although FBE coatings are corrosion protection systems with demonstrated effectiveness in a wide variety of environments, their overall success is still closely tied to the quality of the applied coating. As with nearly all barrier coatings, defects caused by mishandling, misuse, or abnormal installation of the coated pipe significantly reduce its ability to provide the superior corrosion protection required for many applications. Coating damage frequently occurs during the handling and installation of a pipeline, or is the result of rock damage occurring during backfill.[7] The solution to this problem is deceptively simple: if the FBE coated pipe is treated properly, and the coating remains structurally sound, the pipeline should readily meet or exceed its design life. Unfortunately, the type of damage causing the problems discussed above is nearly impossible to avoid. Policing jobsites and preventing the use of questionable construction practices is problematic at best. Irrespective of construction condition or abuse level, there is heavy reliance on the pipe coating to get the job done, and an expectation that it will continue to perform by providing a lifetime of corrosion protection. It is better to assume that damage to the coating is inevitable and design the coating to survive it with much of its corrosion-preventive properties intact.

An example of a damage tolerant FBE coating currently under study[31,32,33] involves the incorporation of microencapsulated additions into the coating (illustrated in Figure 18), which give it self healing properties. . In this example, microcapsules containing a protective fill have been added to a layer of the FBE coating. These capsules provide the self-healing aspect of the coating—in this case, the mechanical damage which weakens conventional coatings, ruptures the microcapsules, which in turn "heal" the FBE coating, preserving its barrier properties.

Microencapsulation is a technique through which liquid materials, such as oils, are encapsulated within a seamless, solid shell. A wide variety of shell-wall materials are available—the appropriate choice is determined by a combination of the application, the material to be encapsulated, and the desired stimulus to rupture the capsule (e.g., impact, pH, or solution chemistry). In general, microcapsules are between 5 µm to 200 µm (0.2 mils to 8 mils) in size with wall thicknesses on the order of 1 µm to 2 µm (0.04 mils to 0.08 mils). Fill materials may be either aqueous or non-aqueous in nature. What is important to note is that, once encapsulated, liquid-based fill materials behave as a solid. As a result, considerably larger quantities of the fill material may be added to a coating without adversely affecting its properties.

As an example, suppose a liquid inhibitor has been demonstrated to effectively halt corrosion of the metal to be coated. The coating formulator then makes the decision that the inhibitor should be added to the current coating formulation. However, in the case of a powder coating such as an FBE, only limited concentrations of a liquid inhibitor may be added before the powder begins to clump and hinder application. If that same liquid is encapsulated prior to addition to the powder, large concentrations of the inhibitor may be added with little or no detrimental effect on the handling or application of the coating material.

Multilayer FBE Coatings

The advent of multiple layers of FBE coatings allows both formulators and end users to create coating systems with the capability of uniquely meeting precise and robust performance requirements. Combining tried and proven coating chemistry with newly developed technologies will provide even better FBE coating systems in the future.

SUMMARY

As a technology, FBE pipeline coatings are alive and well. Their success as a corrosion mitigation system, due in no small part to their excellent chemical resistance and ease of use, has lead to a steadily increasing global market share, which continues to grow. FBE coatings, either as a stand-alone solution or part of a multilayer coating, have consistently met the demands placed upon them in a wide variety of industrial or environmental applications. FBE coatings have a successful track record for protecting pipelines against corrosion all over the world—from the highly aggressive environment of the Middle East region to the extreme conditions in the Arctic. In response to the needs of these industries, novel technologies have led to the development of new FBE coating systems, including self-healing coatings, designed to tolerate abuse on the jobsite, as well as multilayer coatings with user-tailorable physical and chemical properties. The desire for increased service life through corrosion control systems has driven, and will continue to drive, further advancements in FBE technology. As has been illustrated above, FBE is capable of meeting these needs through the use of novel chemistries and intelligent coating design.

FIGURES

Figure 1. FBE pipeline coatings, in use since 1960, have been installed underground from equatorial desert sands to the arctic and in the ocean deeps.

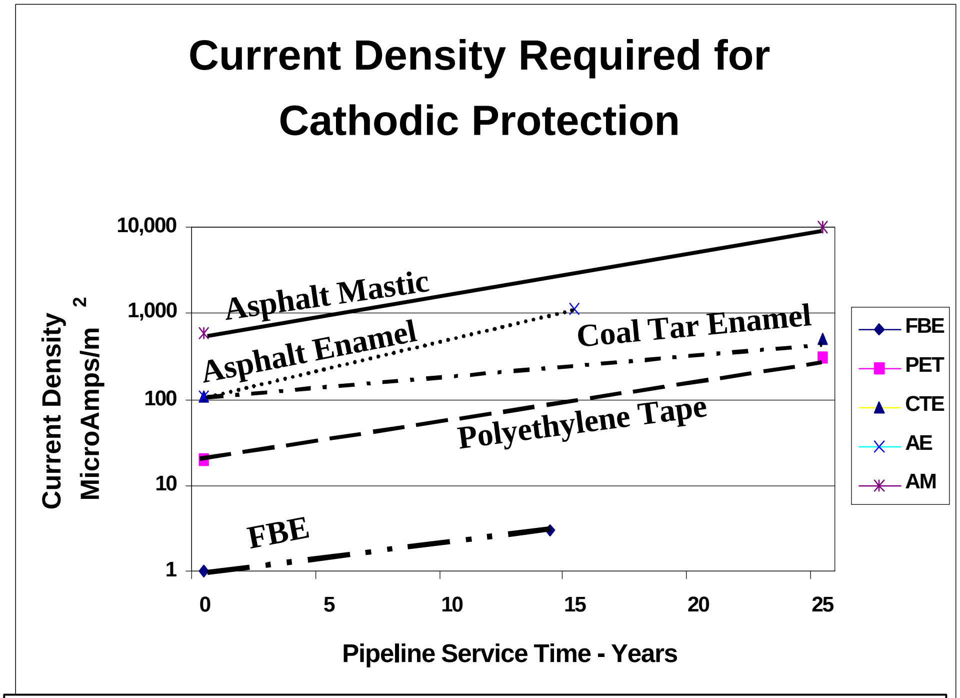


Figure 2. Pipeline owners look at lifetime costs of corrosion protection, not merely initial costs. [7]

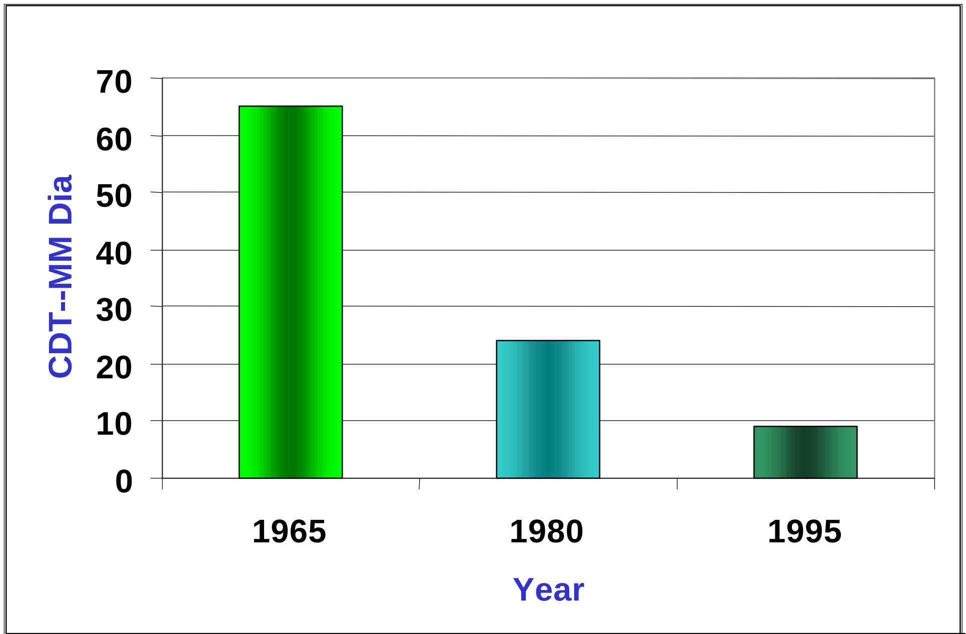


Figure 3. Continuous research and development has resulted in significant product improvements in such characteristics as cathodic disbondment resistance of FBE coating systems.

Cost of Repair:
Coal-Tar Enamel vs. FBE vs. PE

Type of Coating	Damage Index (%)		Cost of Repair (US$/m²)	Cost of Repair for Area (US$/m²)	
	Truck	Ocean		Truck	Ocean
Coal-Tar Enamel	0.05%	0.20%	$206.00	$0.10	$0.41
FBE	0.03%	0.06%	$370.00	$0.11	$0.22
Polyethylene	0.02%	0.04%	$866.00	$0.17	$0.35

Figure 4. When total damage and cost of repair are taken into account, FBE may provide the best economic answer to field and construction damage. [8]

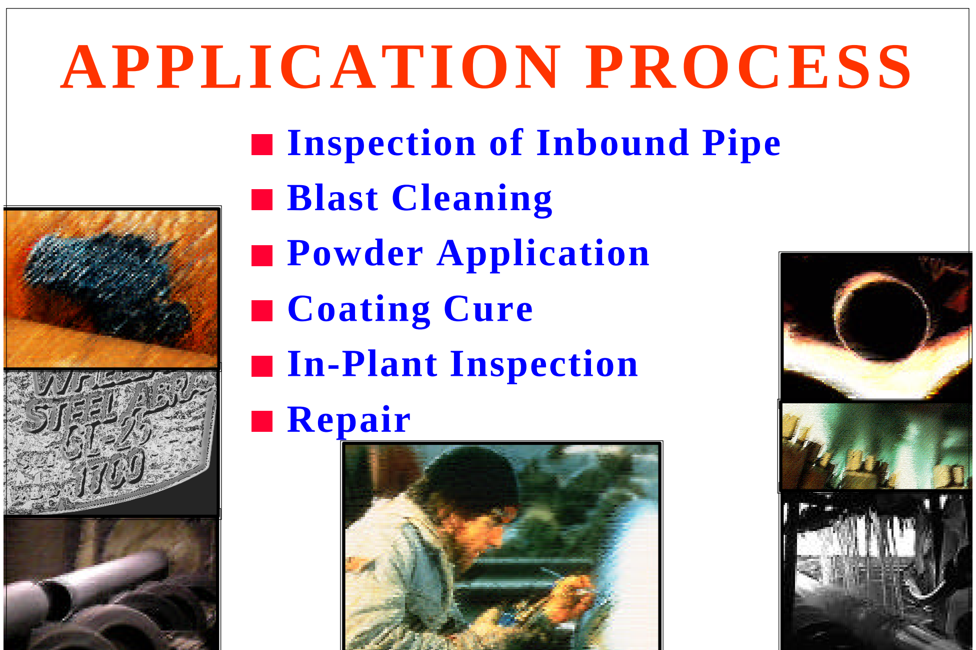


Figure 5. Application of an FBE coating is straight forward, which is one of its greatest strengths. [9]

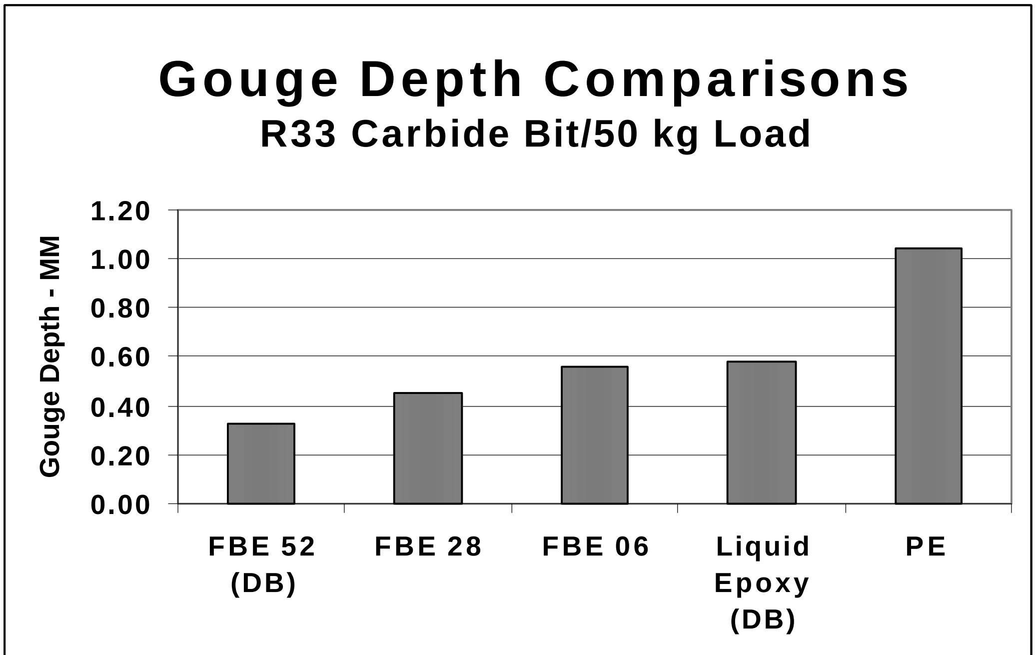


Figure 8. Abrasion resistant dual-layer FBE systems make good choices when pipe will be installed via directional boring, or if there is likelihood of rough construction practices or installation in rugged terrain.

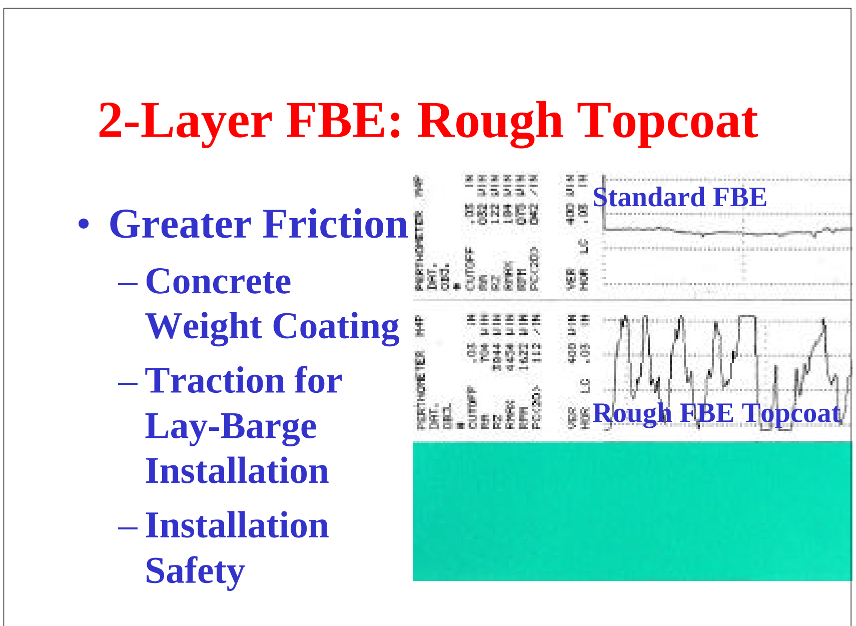


Figure 9. A friction-enhancing rough coating reduces slippage with concrete weight coating, improves traction for lay-barge installation, and provides personnel safety during on-shore installation.

2-Layer FBE - UV Top Coat

Interlayer Adhesion	Salt Spray Resistance	Cathodic Disbondment Resistance

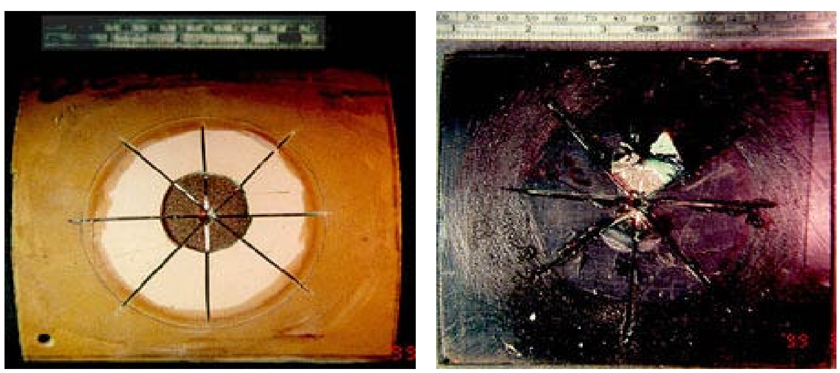
Cross Cut Tape ASTM D3359 (b) No adhesion loss	Salt Fog 800 hours, 35ºC, 5%NaCl, 3mm holiday No Adhesion Loss	7 days, 23ºC, 3 volts, 3%NaCl 1mmr disbondment

Figure 12. A UV-resistant topcoat combined with a functional FBE primary coating provides corrosion performance with a desired color and sunlight resistance. [12]

Comparison: 2-Layer vs. 3-Layer

Same FBE Primary Coating for Both Systems

CDT: 30 Days, 60ºC



Dual Layer FBE - 11mmr   3-Lay PE - 11 mmr

Figure 13. Two-layer FBE systems can meet impact resistance requirements of 3-Layer PE specifications [13] **and provide similar high-temperature performance, for extreme installation or high-operating temperature conditions.**

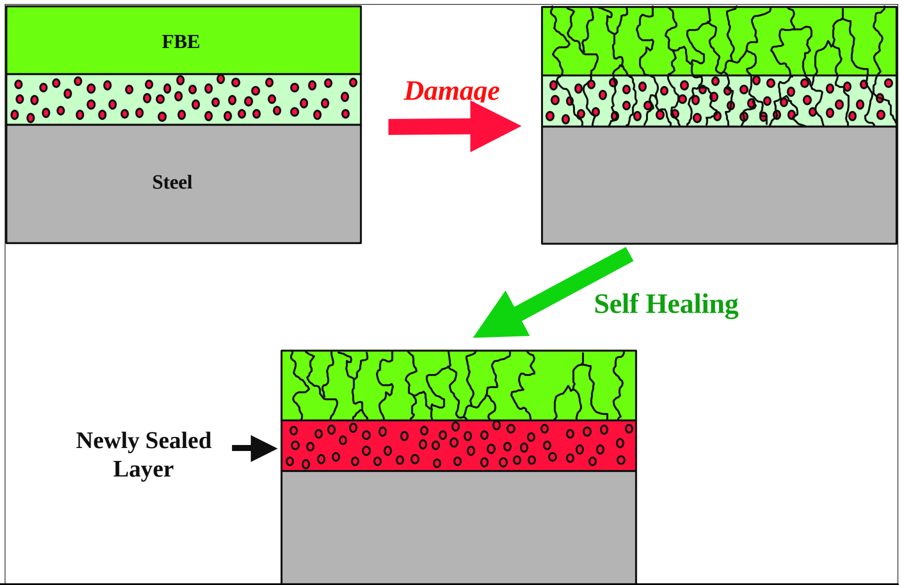


Figure 18. Pipeline coatings of the future will be self-healing and damage tolerant. A possible solution involves microcapsules loaded with film forming and anti-corrosion agents.

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