DAMAGE RESISTANT HIGH TEMPERATURE SYSTEMS

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ABSTRACT

The operating temperature needs of today’s pipelines are beginning to exceed the limits of technology for which standard pipeline coating systems have been developed over the years. Coupling these operating temperature needs with the demands for damage resistance is requiring improvements in technology that are beginning to challenge the pipeline industry. Utilizing two layers of fusion bonded epoxy (FBE) provides great versatility in coatings used for pipeline protection. The first layer has the properties of a standalone FBE coatings developed for higher operating temperatures, including excellent resistance to long term cathodic disbondment at elevated temperatures. The top layer provides mechanical damage resistance from impact or gouging during handling, transportation, and construction. The combination provides the contractor faster, more reliable installations and the pipeline owner with improved underground elevated temperature coating performance.

Key Words: fusion-bonded epoxy, FBE, pipecoating, semi-interpenetrating network, semi-ipn, high temperature, glass transition, cathodic disbondment, adhesives, damage resistant coatings, damage resistance, 3LPO

INTRODUCTION

Pipelines are being operated at temperatures far above the limits of previous standard FBE technologies. The motivating factors for these increased operating temperature demands are high-temperature materials coming out of the ground and materials that must maintain a high
temperature. The trends in the industry that have helped drive these opportunities include tar-sand hydrocarbons and gas with hydrates and the advent for deeper drilling both onshore and offshore. Single layer fusion bonded epoxy and three layer polyolefins (both polyethylene and polypropylene) are the most commonly used pipeline coating systems in the world. The corrosion coating must have a glass transition temperature, Tg, above the operating temperature of the pipeline to prevent damage from pipe movement. In the case of systems with a thick polymer overcoat, the FBE is protected from damage and may be serviceable on pipelines operating above the Tg of the corrosion coating.

Still another option includes the use of compatible Dual-layer FBE (DLFBE) coatings over the primer FBE. These DLFBE’s combine coatings that are non-shielding to cathodic protection and low-cost economics to deliver damage resistance which is now approaching that of 3LPP and 3LPE. Dual-layer FBE coatings have the added advantage of compatible girthweld coating systems. Historically, one disadvantage of DLFBE has been reduced flexibility in extreme-bend cases such as offshore installation by reel barge or installation in the cold arctic. New technology is now available to provide improved flexibility for those environments with an even more damage resistant DLFBE. Utilization of primer FBE’s with the ability to adhere at higher temperatures and these DLFBE’s with improved flexural properties combine to form systems that are viable to perform at increased operating temperatures while still providing excellent damage resistance in adverse conditions.

This paper reviews various options for pipelines operating at elevated temperatures and requiring damage resistance including:

- Single-layer FBE’s for high operating temperature,
- Three-layer polyolefin (3LPO) (polyethylene and polypropylene) coatings,
- Semi-IPN’s over FBE’s
- Dual-layer FBE with the ability to operate at temperatures above standard epoxy coatings.

It also demonstrates the performance characteristics of dual-layer FBE pipeline coating systems through test results and case histories for entire pipeline projects.

**HIGH TEMPERATURE TECHNOLOGY REVIEW**

An ideal high temperature FBE would differ from a standard FBE only in its performance properties. It could be applied in existing coating plants using current application conditions. The high temperature FBE would also be sufficiently resistant to damage so that no special handling during transport and installation would be necessary. The damage resistant properties would be particularly important for single layer systems and less important in multilayer systems where those properties are primarily provided by the topcoat.

Due to the severity of new anticorrosion coating service temperatures, new materials must be developed to survive these more difficult environments. Common fusion bonded epoxies, customarily utilized for oil and gas pipeline protection, encounter problems because of their relatively low glass transition temperatures, which lead to issues of maintaining adhesion to steel substrates. Multifunctional epoxy resins have commonly been used to produce coatings with highly crosslinked and high glass transition temperatures. FBE coatings formulated with these resins exhibit poor flexibility, poor impact resistance, and reduced adhesion to steel.
However recent advances in epoxy technology have made the formulation of FBE coatings with high glass transition temperatures, good adhesion, and good mechanical properties possible.

In addition to epoxy resins, other materials may be suitable for use in high temperature pipecoating applications. One approach to making high glass transition temperature thermosetting materials has been the use of acrylonitrile-butadiene rubber toughened vinyl ester resins. Vinyl ester precursors ranging in number average molecular weight from 3600 to 3800 have been made into toughened coatings having glass transition temperatures a few degrees above 140°C. ¹

Another approach to making high temperature polymeric resins for protective coatings is to graft amino groups on polyetherimides.² Coatings with glass transition temperatures ranging from 150 to 210°C were produced by this method. A 5% maximum degree of grafting was attained. The glass transition temperature showed a linearly decreasing trend with degree of grafting. Yet another approach has been the modification of bismaleimides to yield materials with glass transition temperatures of 210°C, providing good thermo-oxidative stability up to 350°C.³ These materials were prepared by reacting 4-(N-maleimidophenyl) glycidylether with bisphenols and silanediols. Polycyanurates, as products of a cyclotrimerization reaction of cyanate ester monomers, are another route to high glass transition temperatures. Studies of polycyanurate networks modified with polyethers have shown that blends with polyisocyanurate as the rich phase, can reach glass transition temperatures that range from 160 to 280°C.⁴

DUAL LAYER FBE REVIEW

The first dual-layer FBE (DLFBE), introduced in 1991, was for high-operating temperature pipelines. That was followed in 1998 by the first abrasion resistant outer (ARO) coating for directional drill pipeline installation. In 2002, the first major pipeline was coated with a dual layer coating system from end to end, including the girthwelds. DLFBE maintains the excellent performance and installation characteristics of single-layer FBE, but provides even better damage resistance, with a slight reduction in flexibility that can negatively influence use in reel barge or cold-weather installation.

CASE HISTORY - Koyali-Ratlam Pipeline Project, India, 2006 – 2007

While DLFBE is well known and often used for directional drill installation, it is equally accepted as the mainline. The applicator reported holidays on two to three percent of of the joints during each day’s production, with normally one to two holidays in each case.⁵ Those holidays were repaired and the pipe transported to holding areas. At that point, the contractor found holidays on three to five percent of the pipe, usually from one to three in number.⁶ Those were repaired. The pipe was in storage for several months through the rainy season, transported to the right of way, welded and ready for installation. Another holiday measurement was taken. Two to three percent of the pipe joints had holidays usually two to three in number. Reasons given for utilizing DLFBE included ⁷

- Improved handling capabilities
- In-ground performance, including freedom from cathodic shielding.
- Lower cost of materials and higher application output, which reduces the potential for construction delays and increased costs.

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Another factor in the low level of damage, in addition to the robustness of the coating itself, was the use of well defined guidelines for handling the coated pipe.

**CASE HISTORY - Kern River Expansion Project, USA, 2003**
This project looped an existing pipeline and was connected to the same rectifier system. While anecdotal evidence suggested that there was significantly less coating damage than normally expected for FBE during installation, statistical records are not available. However, a pipe-to-soil potential survey after the new pipe was in the ground showed that it was not necessary to adjust the output of the rectifiers to compensate for essentially doubling the size of the cathodically protected area. This shows that little damage to the coating occurred. Details regarding the project show that the terrain was rugged and there was a significant amount of required bending.

There have been several attempts to make FBE coatings more resistant to mechanical damage. Typically, the thickness of the overall coating is increased to provide added impact and abrasion resistance. However, as the thickness of the coating increases, the flexibility of the coating decreases. Another conventional approach to increasing the damage resistance of coatings is to increase the filler loading. However, similar to the problem with thicker coatings, higher filler loadings can dramatically decrease the flexibility of the FBE coating.

As previously mentioned, the cold temperature flexibility of the coating is very important during arctic installation, and the coating must be tolerant to bending. The damage resistant dual layer coatings currently available require a compromise between toughness and flexibility. A new concept addresses this compromise between damage resistance and flexibility with nanotechnology. This improved dual-layer coating has cold temperature flexibility close to that of a single-layer FBE even at high thickness without sacrificing impact and gouge resistance or reduced filler loading.

**Installation and handling Requirements**
In special circumstances, it is possible to engineer around coating limitations. For example, for a rigid coating, pipe bends are fabricated in a shop and coated in a custom application process. However, that adds difficulties to logistics, which can introduce delays and substantially increase the cost of a project.

Ideally, a high temperature stand alone pipe coating should perform as well as or better than today's commercially available pipcoating materials. For installation purposes, that means that a new coating should resist damage to impact, gouge, and abrasion. It should also have sufficient flexibility to meet field bending requirements or those for offshore installation through J-lay, S-lay, or reel barge.

In the case of three layer coatings, the corrosion-coating layer does not require the same damage resistance properties, but does require sufficient adhesion to resist delamination due to stress in the polyolefin top coat.

**Gouge Testing**
With a normal force of 37.5 kg, a gouge test was performed on several DLFBE offerings and PP and PE. The results ranged from an average of 0.16 mm to 0.35 mm, depending on coating source. PE ranged from an average of 1 mm to 2.2 mm and PP from 0.73 to 1.25. To assess which system has better gouge resistance, a DLFBE and a 3-layer polyethylene were tested at the same thickness of 0.762 mm. The DLFBE had a gouge depth of 0.177 mm.
leaving 78% of the initial coating while the 3-layer polyethylene coating penetrated all the way to the steel. The gouge results can be seen below in Figure 1.

The results indicated above for a typical DLFBE coatings are similar to those reported by Edmundson et al which are summarized below:

- The dual powder system has a much greater resistance to damage by gouging than polyethylene three layer. Therefore it can give good resistance to damage at a much lower film thickness than a three layer polyethylene system.
- Since HDPE shows a significant decrease in strength above 50 °C, its ability to withstand damage will decrease significantly over 50 °C. If it is being considered for use at an elevated temperature, its strength at that temperature needs to be determined.
- Polypropylene will be much better at withstand damage in the range 50 to 100 °C than polyethylene.
- Indentation testing confirms that systems with a higher modulus give better resistance to damage by penetration. Specifically, the dual powder system has greater resistance to damage by penetration than polypropylene at both 25 °C and 130 °C. 10

High Temperature Pipe Coatings – Thermal Analysis Discussion

As new technologies develop or old technologies are applied to new uses, the industry must adjust or improve its standards. For example, most people in the pipeline industry recognize that the glass transition temperature of a thermoset material is important. But what Tg should be used and which methodology best applies for a given condition?

With a differential scanning calorimeter (DSC), a commonly acceptable methodology for acquiring Tg values, there are several protocols that affect the result. These include:

- Scan rate
- Tg selection method
- On-set,
- Inflection point,
- Mid-point,
- End point.
In one case, the reported result varies depending on the selection point. The other case illustrates the fact that some chemistries are not amenable to Tg measurement by the DSC method as commonly used in the pipeline industry.

There are also several recognized analytical methods for determining Tg, with dynamic mechanical analysis, DMA, being an example. Figure 2 illustrates the point with Tg values ranging from 110ºC to 155ºC on the same cured FBE. Which value should be used when predicting the useful pipeline operating temperature for this coating?

![Figure 2. The charts shows the Tg of an example high-temperature FBE as measured using different DMA techniques and DSC onset. These represent a small subset of available methods and results. Charts courtesy of 3M.](image)

An oversimplified description of Tg is that it is the point where a plastic goes from being a brittle, glassy material to one that is softer and rubbery. Measuring hardness vs. temperature can illustrate the effect of going through the Tg. There are other effects as well. For example, above the Tg, a polymer picks up moisture at a higher rate and has a higher permeation rate. It is also more susceptible to damage.

A final concern about the Tg of a pipe coating is that FBE is plasticized when it absorbs water. That results in a drop in the Tg. Sourant-Moynot, et al, demonstrated a typical drop of about 20ºC for many FBE pipeline coatings after exposure of a free film to 60ºC deionized water for three months. Would the same effect occur with a pipeline operating at a temperature above the boiling point of water? 4,11

**Coupling Analytical Test Methods.**

Others have found that coupling multiple analytical techniques might render a more meaningful understanding of thermal degradation and thermal degradation mechanisms. These coupled techniques provide structural information and enhance the understanding of the decomposition processes. The TG/DTA–GC/MS couple system is a powerful technique that is a direct measurement of weight loss, a function of temperature, the separation of products by gas chromatography coupled with a sensitive spectroscopic detector. The identification of volatile products arising from thermal decomposition can be determined by TG/DTA–GC/MS.12
Kinetic analysis of polymer degradation can be determined using TGA data by applying Ozawa’s method. It is based on the determination of the activation energy of the decomposition process by the slope of plots of log of heating rate versus 1/T. The goal of the article authored by Parra and others is to propose the advantages of the thermal analytical techniques to better understand the degradation of powder coatings using a TG/DTA–GC/MS coupled system in the identification of the toxicological degradation products. This study also reports kinetic parameters, for example, the activation energy of thermal decomposition for the epoxy and polyester-based powder coatings. It also suggests the application of a TG/DTA–GC/MS coupled system as a potential methodology in the investigation of the powder coatings. The system provides analysis and identification of the toxic decomposition products of powder coatings arising from their degradation.

**Other Methods**. Although not included in this review, there are methods used by other industries for thermally rating the performance of polymer composites and coatings. One such method tests the flexural strength of a coated helical coil at varying elevated temperatures. The length of the exposure period and the number of coils tested per cycle will depend on the deterioration rate at each exposure temperature. The logarithms of the time in hours to reach predetermined bond strengths are plotted as a function of the reciprocal temperature (1/K) to give an Arrhenius plot. Thermal ratings are estimated by taking the intersection of the plotted graphs with the specified time.

**RESULTS AND DISCUSSION**

**Single Layer High Temperature Coating Evaluations**

In order to function as a protective coating at temperatures of 120°C and above, either as a single layer coating or as a primer in a multilayer coating system, an FBE coating must be able to maintain adhesion under hot and wet conditions. Industry standard testing includes evaluation of the ability of a coating to retain adhesion to steel after immersion in hot water for an extended time period.

Since cathodic protection is applied to the pipeline, the cathodic disbondment test important in the evaluation of pipe coatings. A coated test specimen with a holiday is subjected to conditions of cathodic protection while exposed to a sodium chloride solution at an elevated temperature. At the end of the specified test duration, the extent of the resulting disbondment of the coating around the holiday is measured.

These two tests have traditionally been used to evaluate standard pipe coatings intended for use at temperatures below 110°C. In order to evaluate the suitability of pipe coatings for use at higher temperatures, the same tests can be carried out at higher temperatures for longer times. In addition a high temperature cathodic disbondment test, capable of producing test temperatures greater than 100°C, has been developed and used to evaluate high temperature coatings.

Results of performance testing of a standard FBE coating and two high temperature FBE coatings are presented in Table 1. The results of the hot water adhesion tests carried out at 75°C and 95°C indicated that high temperature FBE coating B retained adhesion to the steel substrate somewhat better than did the standard FBE coating. In testing performed at 23°C and 65°C, the CD test results for the standard coating and the two high-temperature coatings were similar. However in CD testing at 95°C for 28 days the disbondment radius of the two high temperature FBE coatings was less than 6 mm, while that of the standard FBE coating was greater than 27 mm. Results of the high temperature CD tests showed a disbondment radius of 6.2 mm for the high temperature coating A even after 28 days at 120°C.
### TABLE 1
**PERFORMANCE PROPERTIES**

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Test Method</th>
<th>Description</th>
<th>Standard FBE</th>
<th>High Temperature FBE A</th>
<th>High Temperature FBE B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water adhesion (28 days at 75°C)</td>
<td>Clause 12.14</td>
<td>Immersion in water</td>
<td>2 Rating</td>
<td></td>
<td>1 Rating</td>
</tr>
<tr>
<td>Hot water adhesion (90 days at 75°C)</td>
<td>Clause 12.14</td>
<td>Immersion in water</td>
<td>3 / Rating</td>
<td>4</td>
<td>2 Rating</td>
</tr>
<tr>
<td>Hot water adhesion (24 hours at 95°C)</td>
<td>Clause 12.14</td>
<td>Immersion in water</td>
<td>1 Rating</td>
<td>1 Rating</td>
<td></td>
</tr>
<tr>
<td>Hot water adhesion (28 days at 95°C)</td>
<td>Clause 12.14</td>
<td>Immersion in 95°C water</td>
<td>1 Rating</td>
<td></td>
<td>1 Rating</td>
</tr>
<tr>
<td>Hot water adhesion (90 days at 95°C)</td>
<td>Clause 12.14</td>
<td>Immersion in 95°C water</td>
<td>2 Rating</td>
<td></td>
<td>1 Rating</td>
</tr>
<tr>
<td>CD (28 days at 23°C)</td>
<td>Clause 12.8</td>
<td>1.5 V, 3% NaCl soln.</td>
<td>2.5 mm Radius</td>
<td>5.62 mm radius</td>
<td>27.47 mm Radius</td>
</tr>
<tr>
<td>CD (48 hours at 65°C)</td>
<td>Clause 12.8</td>
<td>1.5 V, 3% NaCl soln</td>
<td>2.3 mm Radius</td>
<td>3.75 mm radius</td>
<td>1.76 mm Radius</td>
</tr>
<tr>
<td>CD (24 hours at 65°C)</td>
<td>Clause 12.8</td>
<td>3.5 V, 3% NaCl soln</td>
<td>1.54 mm radius</td>
<td>3.61 mm radius</td>
<td>1.76 mm Radius</td>
</tr>
<tr>
<td>CD (28 days at 95°C)</td>
<td>Clause 12.8</td>
<td>1.5 V, 3% NaCl soln</td>
<td>5.62 mm radius</td>
<td>3.75 mm radius</td>
<td>27.47 mm Radius</td>
</tr>
<tr>
<td>High temperature CD (14 days at 120°C)</td>
<td>See Figure 3 below.</td>
<td></td>
<td></td>
<td>5.0 mm radius</td>
<td></td>
</tr>
<tr>
<td>High temperature CD (28 days at 120°C)</td>
<td></td>
<td></td>
<td></td>
<td>6.2 mm radius</td>
<td></td>
</tr>
</tbody>
</table>

1 Small blisters appeared along edges of test specimens.

*High Temperature Cathodic disbondment tests.*

The electrical requirements for each cell of the cathodic disbondment test were provided by an Amel Instruments general purpose potentiostat model 2049. Four cells were run simultaneously and wired to a PC. Special glass cells were made for these high temperature tests (3M glass shop, St. Paul, MN). The cells, one of them shown in Figure 3, can be sealed...
against the coated coupon by means of an O-ring/clamp system, no sealant or caulk is needed. The O-ring is capable of continuous use temperatures up to 240 °C. The glass vessel is equipped with coils where a hot/cold liquid circulates to condition the temperature of the electrolyte. There are four ports on top of the glass vessel. They accommodate a water cooled condenser (to reflux the liquid back into the vessel), a Teflon™ coated temperature probe (to measure the temperature of the liquid near the coating’s surface), a platinum and a calomel electrode (rated for 100°C).

Figure 3. 3M’s High Temperature Cathodic Disbondment Cell.

The damage resistant properties of the FBE coatings are listed in Table 2. The damage resistant properties of the high temperature FBE coatings meet the industry requirements for a single layer pipe coating. (CSA, Table 2). Both the standard and high temperature FBE coatings exhibit acceptable impact resistance. The flexibility of the two high temperature FBE coatings is somewhat less than that of the standard FBE coating, but fit-for-purpose for most pipeline installation practices.

**TABLE 2**

<table>
<thead>
<tr>
<th>Test</th>
<th>Test Method</th>
<th>Description</th>
<th>Standard FBE</th>
<th>High Temperature FBE A</th>
<th>High Temperature FBE B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>Clause 12.11</td>
<td>Bending of coated bar over mandrel at -30°C</td>
<td>No cracking</td>
<td>No cracking</td>
<td>No cracking</td>
</tr>
<tr>
<td>2.5°/PD at</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility</td>
<td>Clause 12.11</td>
<td>Bending of coated bar over mandrel at</td>
<td>No cracking</td>
<td>1 crack</td>
<td>1 crack</td>
</tr>
<tr>
<td>3.0°/PD at</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Some thermal and mechanical properties of the FBEs were measured by DSC, DMA, and TGA. The data is summarized in Table 4.

DSC was used to measure thermal properties of the powders. Tg2 is measured after the powder is heated to 250°C and corresponds to the glass transition temperature of the cured coating. The Tg2 values for the high temperature coatings were greater than 140°C, more than 30°C higher than the Tg2 of the standard FBE coating.

DMA scans on cured films formed from the FBE powders were used for further thermal characterization. As shown in Table 3 the values measured for the high temperature FBEs are 30° to 40°C higher than that of the standard FBE. For each of the FBEs the glass transition temperature, as measured by DMA, is somewhat higher than the value obtained by DSC.

![Image](image-url)

**Figure 4. Comparison of the DMA storage modulus curves for Standard FBE and High Temperature FBE A.**

The change in the storage modulus of the films with temperature is shown by the E' curve. The modulus of each of the films begins to drop at a temperature below the glass transition temperature. The onset of the modulus drop for the high temperature FBEs occurs at approximately 130°C. Figure 4 shows a comparison of the modulus versus temperature curves for the standard FBE and high temperature FBE A.

TGA was used to measure the degradation properties of the FBEs in air. All of the FBEs began to lose weight at around 400°C.
### TABLE 3
**MATERIAL CHARACTERIZATION PROPERTIES**

<table>
<thead>
<tr>
<th>Test</th>
<th>Test Method</th>
<th>Standard FBE</th>
<th>High Temperature FBE A</th>
<th>High Temperature FBE B</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSC</td>
<td>Clause 12.7¹</td>
<td>63°C, 105°C</td>
<td>58°C, 142°C, 97 J/g</td>
<td>51°C, 143°C, 116 J/g</td>
</tr>
<tr>
<td></td>
<td>Tg1</td>
<td>63°C</td>
<td>58°C</td>
<td>51°C</td>
</tr>
<tr>
<td></td>
<td>Tg2</td>
<td>105°C</td>
<td>142°C</td>
<td>143°C</td>
</tr>
<tr>
<td></td>
<td>Delta H</td>
<td>59 J/g</td>
<td>97 J/g</td>
<td>116 J/g</td>
</tr>
<tr>
<td>DMA</td>
<td>Tg</td>
<td>114°C</td>
<td>148°C</td>
<td>154°C</td>
</tr>
<tr>
<td></td>
<td>Onset of modulus drop</td>
<td>99°C</td>
<td>128°C</td>
<td>133°C</td>
</tr>
<tr>
<td>TGA</td>
<td>Onset of weight loss</td>
<td>415°C</td>
<td>405°C</td>
<td>405°C</td>
</tr>
</tbody>
</table>

¹The modified temperature cycles were used. Cycle 1: Powder samples were heated from 25°C to 75°C at a rate of 20°C per minute, then immediately cooled to 25°C. Cycle 2: heated from 25°C to 250°C at a rate of 20°C per minute, then immediately cooled to 25°C. Cycle 3: heated from 25°C to 175°C. Glass transition temperatures are reported as the transition midpoint.

### CONCLUSIONS
This paper provided an overview of performance properties required of a high-temperature pipe coating and a review of test methods designed to predict the functional life of a coating. Using typical industry test methods it also showed a comparison between a commercially available FBE and examples of high-temperature FBE coating materials. It also introduced a new technology for the adhesive tie-layer used in three-layer PP systems for high temperature use. Finally, it introduced new experimental test procedures that may be useful in the development of new generation coatings.

These results indicate that the new high temperature FBE pipe coatings provide acceptable cathodic disbondment resistance and adhesion retention in water as single layer coatings at temperatures where the performance of the standard FBE coating is unacceptable.

The high temperature FBE pipe coatings provided good performance at 95°C to 120°C as a single layer coating. The standard FBE pipe coating exhibited unacceptable cathodic disbondment resistance at 95°C. Evaluation of application and damage resistance properties of the high temperature FBE coatings indicated that they were similar to those of the standard FBE coating.

The poor CD test results for the standard coating at 95°C indicate that the useful operating temperature range for FBE pipe coatings as single layer coatings may be limited to temperatures somewhat below the glass transition temperature of the coating. The change in mechanical properties of the coatings at temperatures below the glass transition temperature in the DMA results is a further indication of the temperature limitations of the coating.
The operating temperature of the high temperature FBE coatings as single layer coatings was not defined in these experiments. Performance as part of a multilayer coating was not investigated. Further work would be necessary to fully define the suitability of the high temperature FBE coatings in either single later or multilayer pipe coating applications.

ACKNOWLEDGMENTS

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REFERENCES


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