DESIGN AND COATING SELECTION CONSIDERATIONS FOR SUCCESSFUL COMPLETION OF A HORIZONTAL DIRECTIONALLY DRILLED (HDD) CROSSING

A.I.(Sandy) Williamson
Shaw Pipe Protection Limited
1200, 630 3rd Ave. S.W.
Calgary, Alberta, Canada T2P 4L4

J.R. Jameson
Entec Consulting Ltd.
250, 6125 11th St. S.E.
Calgary, Alberta, Canada T2H 2L6

ABSTRACT

Since the 1970s, horizontal directionally drilled (HDD) crossings have become increasingly used for pipeline crossings of rivers and other obstacles. HDD crossings are now being undertaken in most soil and rock types with crossings up to 2000m in length and pipe diameters up to 48”. Whilst HDD crossings have a predictable and short construction schedule and in most cases are the least expensive crossing method, proper planning and design are of primary importance to the success of the crossing. The design requirements and considerations for a successful HDD crossing are examined and put into perspective based on the economics involved. Secondary factors such as selection of plant-applied and field-applied external protective coatings also play an important role. Common types of plant-applied anti-abrasion coatings used to protect the anti-corrosion coating and results from the various test methods used to relatively rank these coatings are discussed.

Keywords: directional drilling, pipeline, coating, anti-abrasion, corrosion

INTRODUCTION

HDD crossings and conventional slip bore crossings are a critical part of most pipeline projects. In order to ensure that the crossing is completed with the anti-corrosion coating intact, a number of factors need to be considered that not only involve proper coating selection, but also the actual design of the drilling activity and the subsequent pullback of the pipe through the drill bore. [Figure 1] Some of these factors although relatively low in cost have a disproportionate effect on the outcome of the crossing. Unfortunately, in many cases these same low cost factors are not properly addressed during the design phase and the consequence is the high cost of a “failed” crossing. For that reason, the economics of these factors and their respective impact on the success of the crossing will be discussed.

One of the factors that pipeline engineers have to consider is the choice of anti-abrasion coating system for the HDD crossing. There are currently a number of plant-applied coating systems that can be used for this purpose. Several of the more popular systems have been tested using a number of recognized test methods. The coating systems have subsequently been ranked on a relative scale based on these test results in order to assist the pipeline engineer in recognizing the relative strengths and weaknesses of the different coatings.

DESIGN REQUIREMENTS AND CONSIDERATIONS FOR A HDD CROSSING

Geotechnical Study

The most important aspect of a HDD crossing is the degree of effort taken to study the geotechnical aspects of the planned crossing. A comprehensive assessment of the underground conditions such as soil type, rock type, and their location relative to the planned drill crossing is required in order to properly design the crossing and ensure its success. Air photos, topographical maps, geological maps, previous job histories (road cuts, bridges, and other crossings), hydrology, and geological analysis are some of the tools used to study the intended crossing. Typically vertical exploration holes are made to retrieve core samples which are used to assess the extent and depth of varying underground conditions.[1] It is important that the depth of the exploration holes is at least 10-15m below the intended drill path and that a sufficient number of holes are made to adequately define the underground conditions.

Engineering Design

With a complete geotechnical study report in hand, a cross-sectional profile and plan view is made for the intended crossing. The next step is to choose the intended drill path with entry, exit, and pipe laydown areas compatible with the surface layout. Emergency plans should also be made at this stage for situations such as loss of drilling fluid circulation.[2,3]

Line Pipe

In most cases, the line pipe required for a crossing has a heavier wall thickness than the main line. The reason for this is that there are significant forces and stresses exerted on the pipe during the pulling/installation of the pipeline into the crossing. The rule of thumb for designing the pipeline is to ensure that the diameter to thickness ratio is less than 50.[1,4] The consequences of having too thin a pipeline is an increased risk of pipe collapse and the subsequent cost of removal of the installed pipe and its replacement.

In addition to reviewing the diameter to thickness ratio, one should also conduct a stress analysis to assess the forces on the pipeline to ensure that the proper grade of material is used. Many engineering companies have developed their own in-house computer design programs to conduct these analyses.

Anti-Corrosion Coating

An anti-corrosion coating is applied to the pipeline, including any sections to be used for a HDD crossing. The anti-corrosion coating is used in conjunction with cathodic protection to provide a corrosion protection system for the steel line pipe. In most cases the anti-corrosion coating has been designed to have some degree of flexibility, impact resistance, good adhesion to the steel substrate, some degree of moisture permeation resistance, and compatibility with the cathodic protection system.[5] The anti-corrosion coating system is applied in a coating plant using an industry standard such as CSA Z245.20-98.[6] Whereas a number of coatings will meet the necessary requirements to provide external corrosion protection for the pipeline, they do not necessarily have the mechanical properties to withstand the rigors of a HDD crossing.

Anti-Abrasion Coating

A variety of anti-abrasion coatings have been developed specifically to protect the anti-corrosion coating from mechanical damage. In addition to gouge and wear resistance, it is important to have good adhesion between the anti-corrosion coating and the anti-abrasion coating. Flexibility and impact resistance are less of a concern as the pipe is not bent to any significant degree and the coating is not subjected to the same degree of potential impact damage as that encountered by the main line in an open ditch installation. These coating systems and methods for testing their properties will be discussed in more detail later in this paper.

Joint Coating

The selection of joint coating is probably the most overlooked aspect of the total coating system. The major factor involved with the joint coating is the fact that it is applied in the field and therefore is subjected to additional challenges not seen in a plant application such as climate, degree of surface preparation/cleanliness, and level of quality control required to ensure proper application. Liquid-applied, spray-applied and heat-shrinkable sleeves are commonly used to protect the joint area.[7] In the latter case, a sacrificial sleeve can be incorporated into the design to protect the underlying primary sleeve.

Drilling/Installation

The first step prior to drilling the crossing is to develop a detailed execution plan. The plan should include methodology for each phase of the drilling: pilot hole, reaming, cleaning, buoyancy control, and pullback. Contingency plans for unexpected conditions should be made. Emergency response plans, environmental response plans, and safety should also be included in the execution plan.

Secondly, one must ensure that the equipment is properly designed for the scope of the job and is in good working condition. The drilling contractor's records should be checked for equipment maintenance and also for job histories, experience of personnel, and training records.

Following the pullback stage where the pipe is installed in the crossing, an assessment of the coating integrity should be made. One of the most common methods used for assessing the nature of the drill bore is to pull a couple of sacrificial joints through the bore prior to pullback. In this way one can assess any damage to the sacrificial joints and take remedial steps such as additional reaming and/or cleaning passes. If the drill bore is determined to be acceptable then pullback can proceed. Once the pipeline is installed in the crossing, it is very difficult if not impossible to remove, depending on the soil/rock type. This further underlines the importance of proper planning and design.

Some more recent work has been conducted to assess the integrity of the coating after installation in a HDD crossing. Common electrical techniques used by cathodic protection technicians are used to estimate the amount of bare area on the pipe.[8,9]

ECONOMICS OF A HDD CROSSING

Table 1 shows typical cost factors for a HDD crossing job and puts the above requirements for a successful HDD crossing into economic perspective. The cost factors illustrate that important requirements such as geotechnical studies, engineering design, and coating selection are small costs relative to the actual drilling and installation. These same requirements however play a critical role in determining the success of the actual job.

ANTI-ABRASION COATINGS FOR HDD CROSSINGS

There are several different types of coatings that can be used for the purpose of protecting the integrity of the anti-corrosion coating. In most cases the design engineer has time to specify the type of coating such that it can be plant-applied in conjunction with the remainder of the pipeline. In some cases the pipe is already coated prior to knowing the full extent of HDD crossings or road bore crossings and therefore the quantity of anti-abrasion coating required. In the latter case, there are fewer coating options and usually more expense due to the extra handling of the pipe. Where the anti-abrasion coating is to be applied in the field, extra measures need to be taken to ensure proper surface preparation prior to coating and adequate control of environmental parameters such as humidity and temperature during the coating process.

The following anti-abrasion coatings will be discussed, as they are the most common generic types used at the plant site and were therefore chosen for evaluation in the test program.

Fusion Bonded Epoxy (Thick)

Fusion bonded epoxy (FBE) coating is a thermosetting epoxy powder generally recommended for use as an anti-corrosion coating for larger diameter pipe. FBE has been used since the mid-1970s. FBE is normally specified for the main portion of the pipeline as 350 microns nominal thickness.[6] For the portion of the pipeline to be used for HDD crossings, the end user has the option to specify a thicker coating such as 700 microns nominal thickness of FBE. The extra thickness of coating is used as extra protection to minimize the occurrence of holidays or bare steel being exposed during pipeline installation.

Fusion Bonded Epoxy (Dual Powder System)

The dual powder FBE system is a more recent development by the FBE powder manufacturers to improve the anti-abrasion property of the outer coating surface. The dual powder FBE system is comprised of two thermosetting epoxy powders. The first coat is applied at a standard nominal thickness of 350 microns, while the second outer coat is applied at a nominal thickness of 500 to 750 microns giving a total system thickness of 850 to 1100 microns. The second coat has been designed by the FBE powder manufacturer specifically for its anti-abrasion properties and therefore to have an improved resistance to abrasion or gouging compared to the single component FBE discussed above. The two coats can be applied within the same powder booth or in separate powder booths. In either case there is some mixing at the boundary of the two coats yielding a system with an inherently good bond. Another economic advantage of this system is that it only takes one pass through the coating plant to apply the coating system. In some of the systems discussed below, the anti-abrasion coating must be applied in a separate process step, using a different plant configuration with the associated additional handling and set-up costs.

Urethane Overcoat

Urethane coatings were developed as an anti-abrasion overcoating to an existing anti-corrosion coating such as FBE, however in some cases they have been specified as a stand-alone coating. Urethanes are typically a 100% solids content, two component urethane polymer system applied in liquid form. They are usually applied at a nominal thickness of 500 to 750 microns giving a total system thickness of 850 to 1100 microns. Urethane coatings can be applied inline or on a pipe spinning system in the pipe yard. In either case the pipe must first be coated with the anti-corrosion coating and the plant configuration changed to accommodate a spray booth and the associated liquids handling systems. Prior to the application of the urethane overcoating, the anti-corrosion coating is preheated to remove moisture and then lightly blasted in order to provide a surface profile for mechanical adhesion of the urethane to the anti-corrosion coating.

Epoxy Polymer Concrete Overcoat

Epoxy polymer concrete coatings are 100% solids content coatings that have been designed for overcoating of anti-corrosion coatings such as FBE and as stand-alone coatings. They are applied at thicknesses between 500 microns and 3175 microns. They are typically applied by spraying successive coats onto the pipe in the pipe yard. The pipe surface must be free of moisture and contamination, and requires blasting when the coating has been exposed to ultraviolet rays for more than a week.

Powder coated Multicomponent Coating

Powder coated multicomponent coatings are a recent development where the good adhesive properties of an inner FBE layer are married with the good mechanical properties of an outer polyolefin layer through the use of an intermediate polyolefin adhesive layer. These coatings were developed as stand alone anti-corrosion coatings. All three components are applied in powder form sequentially onto the pipe surface leading to some mixing at the boundaries and therefore good intercomponent adhesion. Whilst the thickness of the FBE and adhesive remains fixed at about 125 microns, the outer polyolefin can be applied up to 1525 microns for the purposes of increased mechanical and anti-abrasion properties. Similar to FBE, this coating system has the advantage of making only one pass through the coating applicator’s facility.

Extruded Polyethylene (Overcoat or Thick)

Extruded polyethylene coatings are commonly used for pipelines with diameters under 406mm. The polyethylene is used for its mechanical properties over a liquid adhesive layer bonded to the steel (2-layer system), or over a polyethylene adhesive and epoxy primer layer (3-layer system). All components are applied inline with the outer polyethylene coating being applied by crosshead or side extrusion. The 3-layer system is more commonly used for HDD crossings due to its superior shear resistance properties provided by the polyethylene adhesive layer. To give the coating additional protection for a HDD crossing, either additional thickness of outer polyethylene layer is extruded onto the pipe or the pipe is run through the coating plant for a second coating application. In either event, approximately 2000 microns are applied to the pipeline.

TEST METHODS FOR SELECTING ANTI-ABRASION COATINGS

A number of test methods exist for understanding the behavior and characteristics of anti-abrasion coatings. In most instances, the anti-abrasion coating is applied in order to protect an underlying anti-corrosion coating. The anti-abrasion coating is not therefore considered as a corrosion barrier, but rather as a sacrificial coating. It is therefore tested primarily for its ability to withstand damage during handling, construction and installation.

The test methods discussed below include shear scratch resistance (gouge), Taber abrasion (wear), flexibility, impact resistance, and adhesion. These test methods have been previously discussed[10] so after a brief description of the test method, the discussion here will concentrate on results obtained from these tests.

Coatings Tested

Table 2 describes the generic types of coatings that underwent testing at Shaw Pipe Protection Limited's Technology and Development laboratory. The thicknesses tested were typical of those specified by the industry and in all cases samples were cut from plant-applied production test rings.

Shear Scratch Resistance Test

The shear scratch resistance test sometimes referred to as the "gouge test" is designed to simulate a coated pipe being dragged across a sharp gouging force such as a rock protruding into the drill bore hole. Whilst this test method can be effective in giving a relative ranking of coatings for their resistance to penetration, the actual point loads existing from a protruding rock in a HDD bore can be an order of magnitude higher than the point loads used in the test. This further stresses the need for a properly designed HDD where hole size and buoyancy are properly designed.

The test procedure calls for a test panel to be fixed to a rolling cart that is pulled at a controlled rate by a tensile test machine under a weighted point. (See Figure 2) The gouged area is then checked for depth of penetration. The gouged area can also be checked for holidays using a holiday tester set at 5 volts per micron of coating thickness. (See Figure 3) The test is repeated with additional weight until the weighted point has penetrated the full thickness of the coating or the gouged area jeeps. The weight causing holiday(s) is then recorded. In addition, X-Y plots are generated for weight vs. depth of penetration. These plots can be used to give a feel for how the coating resists the gouge force.

Abrasion Test

This test method is effective in relatively ranking coatings for their ability to resist abrasion or wear. Coatings may be exposed to continual abrasive action when the drill hole has consistent morphology, and rock/soil type, and the pipe surface comes into contact with the drill hole wall as the pipe is being pulled into the hole.

The abrasion test used most commonly is the ASTM D4060-95 Taber Abrasion test.[11] A coating is applied at uniform thickness to a plane, rigid panel and after curing the surface is abraded by rotating the panel under weighted abrasive wheels. The test measures the abrasion resistance as loss in weight of coating from a test panel subjected to a specified number of abrasion or as number of cycles require to remove a given amount of coating thickness.

Flexibility Test

During the installation of a pipeline in a HDD crossing, the pipeline is subject to some bending, however, considerably less than field bending used for the main line. Anti-abrasion coatings will seldom see more than 1 degree of deflection per pipe diameter.

The flexibility of a coating is measured by bending a coated test bar around a mandrel having a set radius and examining the bent test bar for evidence of surface cracks. The test method commonly used is that outlined within Section 12.11 of CSA Z245.20-98.[6] Whilst this standard was designed for anti-corrosion coatings where the coating is required to withstand 3 degrees of deflection per pipe diameter, the anti-abrasion coated test bars are inherently not as flexible due to the nature of the coating and the total coating system thickness. The test bars are therefore tested at smaller bend radii until they fail. Failure is defined as the point where surface cracks are visually apparent. Different test temperatures (room temperature, 0C, -30C) may be used depending on the anticipated geographical location of the pipeline installation.

Impact Resistance Test

The impact resistance test will give one an idea for the coating's resistance to damage from falling rock while in the hole or on the jobsite, and resistance to handling damage.

Impact resistance of the coating is commonly measured using the drop weight test referenced in Section 12.12 of CSA Z245.20-98.[6] By dropping a known weight from a known height one can subject the test panel to an impact load. The test panel is then examined for evidence of cracks or holidays and is considered to have failed when a holiday is detected. Different test temperatures (room temperature, 0C, -30C) may be used depending on the anticipated geographical location of the pipeline installation.

Adhesion Test

In the case of any of the anti-abrasion coatings, one must ensure that there is adequate bond strength of the coating system to the steel substrate to withstand the shear stresses existing during a crossing installation. In the case of anti-abrasion coatings that are applied as a distinct second (or third) layer over an anti-corrosion coating, one must also ensure that there is sufficient bond strength between the different layers for the same reasons.

The Elcometer pull-off adhesion test defined in ASTM D4541-95 [12] whereby a metal dolly is glued to the coating, allowed to set, and subsequently pulled off the coating with a known force (e.g. 14Mpa) is commonly used to assess the adhesive strength of the various coating systems.

DISCUSSION OF RESULTS OF ANTI-ABRASION COATING TEST METHODS

The results from the five different test methods described above are reported in Table 3. Whilst actual values were obtained in the different tests and are shown on the respective figures for each test, Table 3 gives a relative ranking from 1(highest) to 6(lowest) for each coating system. In some cases, where a number of coatings showed the same level of performance, they were grouped. This method of presentation allows the pipeline engineer to assess the relative strengths and weaknesses of each coating system.

Shear Scratch Resistance Test

Figure 4 shows the results achieved with the shear scratch resistance test apparatus using a SL-1 smooth carbide bit at four different load settings. The SL-1 bit was chosen for its uniform shape as opposed to the #1 Phillips screwdriver bit, which has often been used in this apparatus. The depth of the gouge was measured using a dial gauge whose base bridged the actual gouge. The use of the bridge allowed for a more consistent zeroing of the gauge as the bit tends to leave a ridge on either side of the gouge. The gouge depth was then reported as a percentage of the total coating thickness, as some of the coatings are thicker than others as shown in Table 2. Holiday testing was not carried out on any of the samples as it was found to be too difficult to use a conventional holiday tester in conjunction with the narrow spacing of the gouges.

The conventional FBE sample showed a large depth of penetration (85%) leaving little coating left for corrosion protection. The coatings with a polyethylene outer surface also showed a large degree of penetration (up to 85%), however these coatings are typically applied thicker allowing them to still afford protection to the underlying epoxy primer layer. The 3 layer polyethylene sample performed marginally better than the powder coated multicomponent sample, most likely due to the higher density polyethylene used in the former. The epoxy polymer concrete, dual powder FBE, and urethane were all significantly better performers with respect to gouge depth as a percentage of their coating thickness. These three coatings gave excellent protection to the underlying FBE layer.

At this point there is a large variation in the results from the shear scratch resistance test reported by the various coating manufacturers, as there is no industry standard for this test. Some of the test variables include the weighted point’s shape and hardness, the design of the apparatus itself, how it imparts weight to the weighted bit, when to replace the weighted point, the speed with which the weighted point is pulled across the coating, the shape of the coating coupon (pipe vs. flat plate), and the nature of the holiday test equipment. At the time of writing this paper, a NACE technical practice committee, T-10D-13, formed a task group in September 1999, and has started work on a test method standard so that coatings can be compared more consistently.

Abrasion Test

The results of the Taber abrasion test are shown in Figure 5. In this test the polyethylene coatings showed better performance than the other coatings. As the test proceeds, coating particles are worn away from the coating surface and some of these particles remain between the wheel and the test panel surface. The polyethylene coatings appear to better resist wear due to the lubricity of the polyethylene particles compared to the harder nature of the particles from the other coatings. For the same reason, the harder nature of the particles from the epoxy polymer concrete and urethane coatings tend to cause a higher degree of wear.

Flexibility Test

The flexibility test results are shown in Figure 6. The tests were run at room temperature (21C), 0C, and –29C. The coatings were subjected to increasingly higher degrees of bend until they exhibited cracks detectable to unaided visual examination. As one might expect the harder, more brittle nature of the epoxy polymer concrete, urethane and dual powder

FBE coatings behaved significantly differently than the polyethylene coatings. The standalone FBE coating showed a higher degree of flexibility than the dual powder FBE, as it was approximately half as thick.

Impact Resistance Test

Figure 7 shows the results of the impact resistance test. As one might expect the 3-layer polyethylene coating showed the highest resistance to impact due to its thickness and the density of its outer polyethylene layer. All of the anti-abrasion coating systems showed marked improvement over FBE, although the FBE sample still passed the CSA standard requirement of 1.5J.

Adhesion Test

All of the coatings tested using the Elcometer pull-off test showed excellent interlayer adhesion and coating/steel adhesion. Ultimately, a quantitative number for failure of the coating system could not be obtained as the failure always occurred within the epoxy glue used to attach the dolly to the coating. The coatings typically exhibited in excess of 2000psi adhesion strength prior to glue failure.

CONCLUSIONS

After investigating the factors involved with HDD crossings and the cost impact of these factors, it has been shown that the geotechnical study and engineering design of the drilling and pipeline installation are the most important factors for the success of the crossing. Secondly, the selection of the anti-abrasion coating is important in that it plays a role in protecting the anti-corrosion coating of the pipeline. Several test methods were used to relatively rank the various anti-abrasion coating types. Whilst no one coating performs the best in every test, one can use the results to assess the relative strengths and weaknesses of the different coatings. Finally, further work is required to establish an industry practice for the shear scratch resistance test method. This is currently being undertaken by a task group within NACE T-10D-13.

ACKNOWLEDGEMENT

The authors would like to thank the staff of the Technology and Development laboratory at Shaw Pipe Protection Limited for their contribution to this work.

REFERENCES

1. “Guidelines for a Successful Directional Crossing Bid Package” Directional Crossing Contractors Association

2. D. Winckler, “Contractor completes eight crossings for mainline project”, Pipe Line & Gas Industry, July 1999: p. 51-53

3. “Tidy Digging”, Oilweek, May 3 1999;p.19-20

4. R.S. Norman, “Uncased Pipelines at Railroad and Highway Crossings Benefits to the Gas Industry”, American Gas Association Distribution/Transmission Conference, May 1993,Orlando, Florida

5. K.Varughese, ”Mechanical properties critical to pipeline project economics”, Oil and Gas Journal, September 9 and 16,1996

6. CSA-Z245.20-98- External Fusion bond Epoxy Coating for Steel Pipe

7. D.Neal, ”Comparison of Performance of Field Applied Girth Weld Coatings”, Materials Performance, January 1997

8. I.Fotheringham, P.Grace, “Directional Drilling What have they done to my coating?”,Corrosion (Australia), June 1997

9. R.A.Gummow, S.M.Segall, R.G.Wakelin, “Coating Quality Testing of Directionally Drilled Pipe Sections”, to be presented at Corrosion 2000, March 2000, Orlando, Florida

10. A.I.(Sandy) Williamson, “Selection of Anti-abrasion Coatings for Pipelines” NACE-Brazil Corrosion ’99, (Sao Paulo, Brazil, NACE International, 1999)

11. ASTM D4060-95,"Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser"

12. ASTM D4541-95,"Standard Test Method for Pull-off Strength of Coatings using Portable Adhesion Testers"

TABLE 1- Typical economic factors for a HDD crossing

Factor	Contribution (%)
Line Pipe	10
Anti-corrosion coating	1
Anti-abrasion coating	4.5
Joint coating	0.5
Geotechnical study	1
Engineering Design	7
Drilling/Installation	76
Total	100
Cost of Failure	**100-300%**

TABLE 2- Thickness of tested coating systems

Coating Description	Total Coating System Thickness (microns)
Fusion Bonded Epoxy	585
Dual powder Fusion Bonded Epoxy	990
Urethane	1460
Epoxy Polymer Concrete	1475
Powder coated multicomponent	1665
3 Layer Polyethylene	2110

TABLE 3- Relative ranking of anti-abrasion coating systems vs. test method

Coating	Gouge @ 76kg	Taber Abrasion	Flexibility @ -29C	Impact @-29C	Adhesion
Fusion Bonded Epoxy	2	3	2	3	1
Dual powder Fusion Bonded Epoxy	1	4	3	2	1
Urethane	1	6	3	2	1
Epoxy Polymer Concrete	1	5	3	2	1
Powder coated multicomponent	2	2	1	2	1
3 layer Polyethylene	2	1	1	1	1

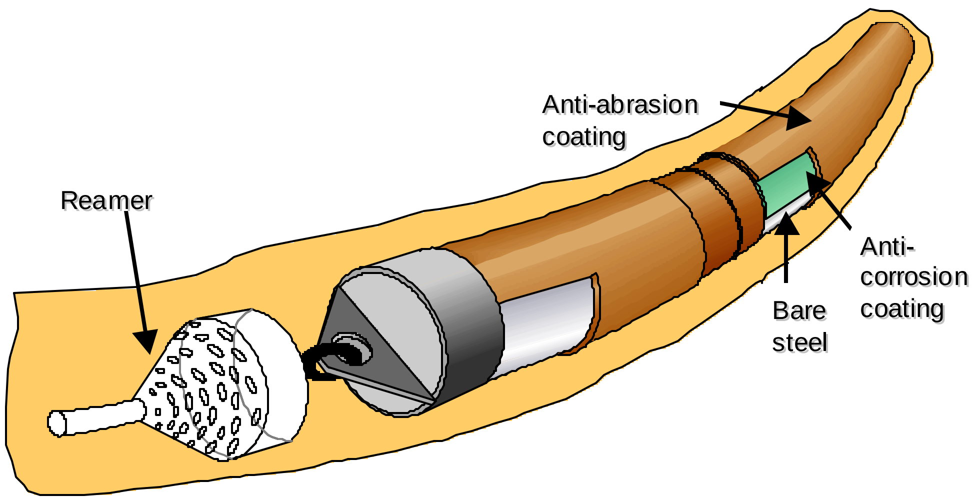

FIGURE 1- Schematic of pullback of pipeline in a HDD crossing

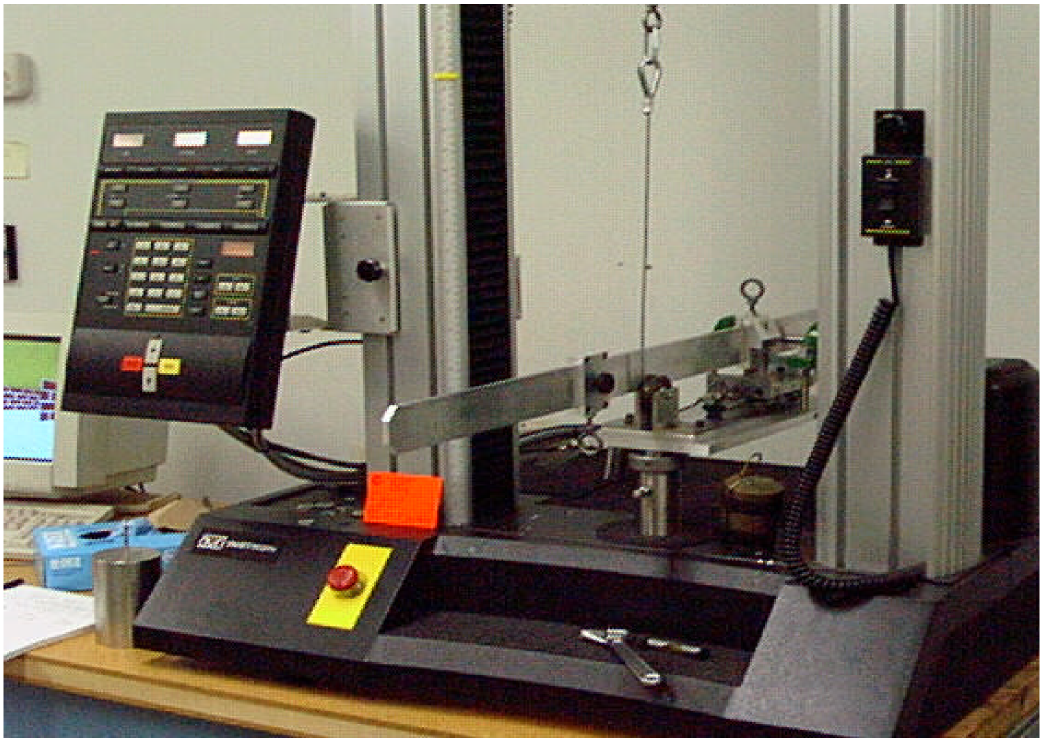

FIGURE 2- Shear scratch resistance test apparatus

FIGURE 3- Shear scratch resistance test panels

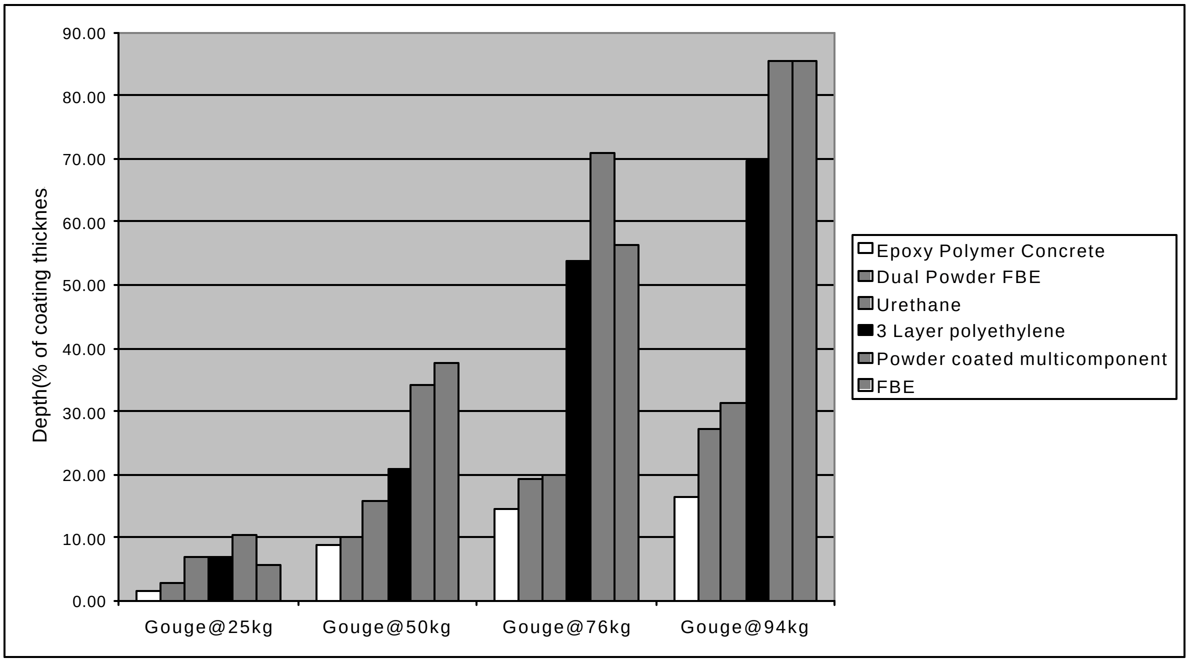

FIGURE 4- Shear scratch resistance results using SL-1 smooth carbide burr for anti-abrasion coatings

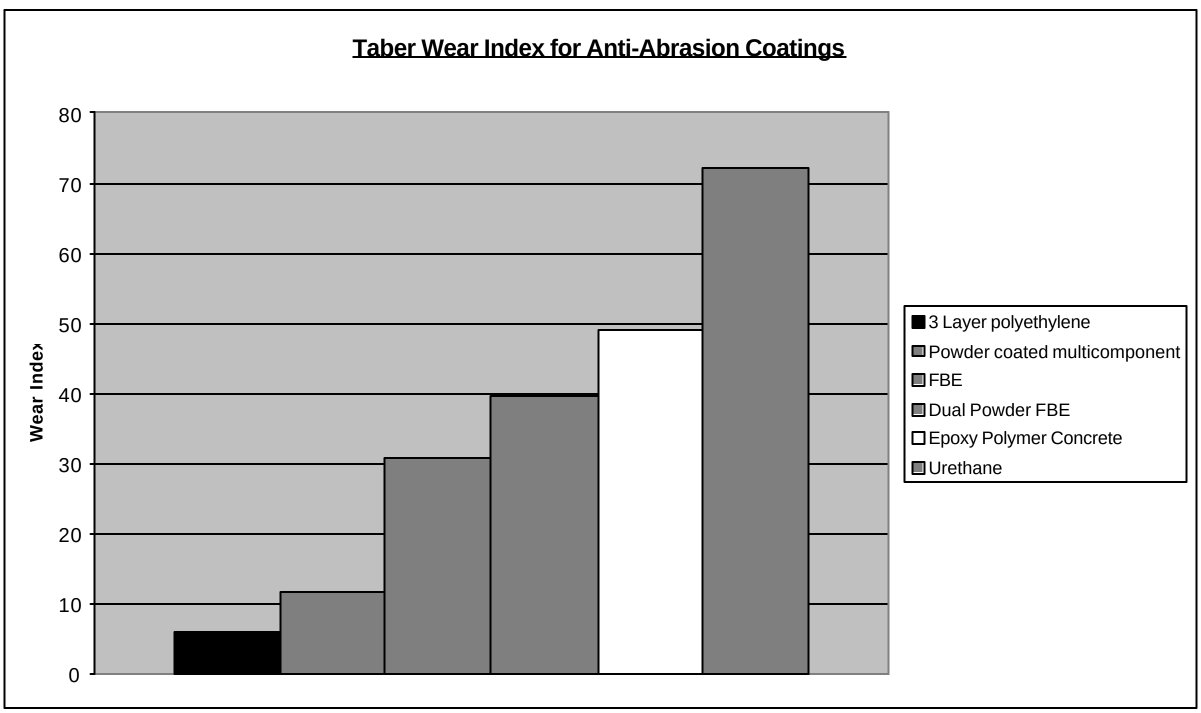

FIGURE 5- Taber Wear results for anti-abrasion coatings

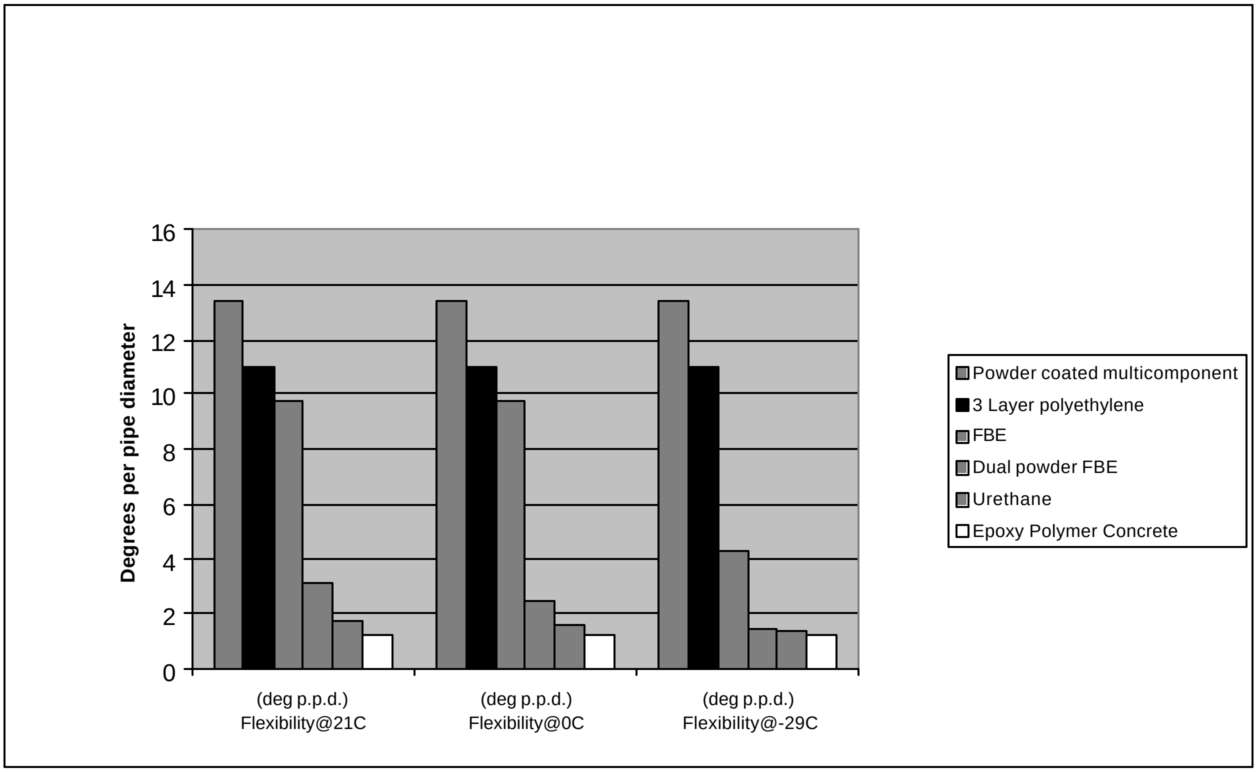

FIGURE 6- Flexibility results for anti-abrasion coatings

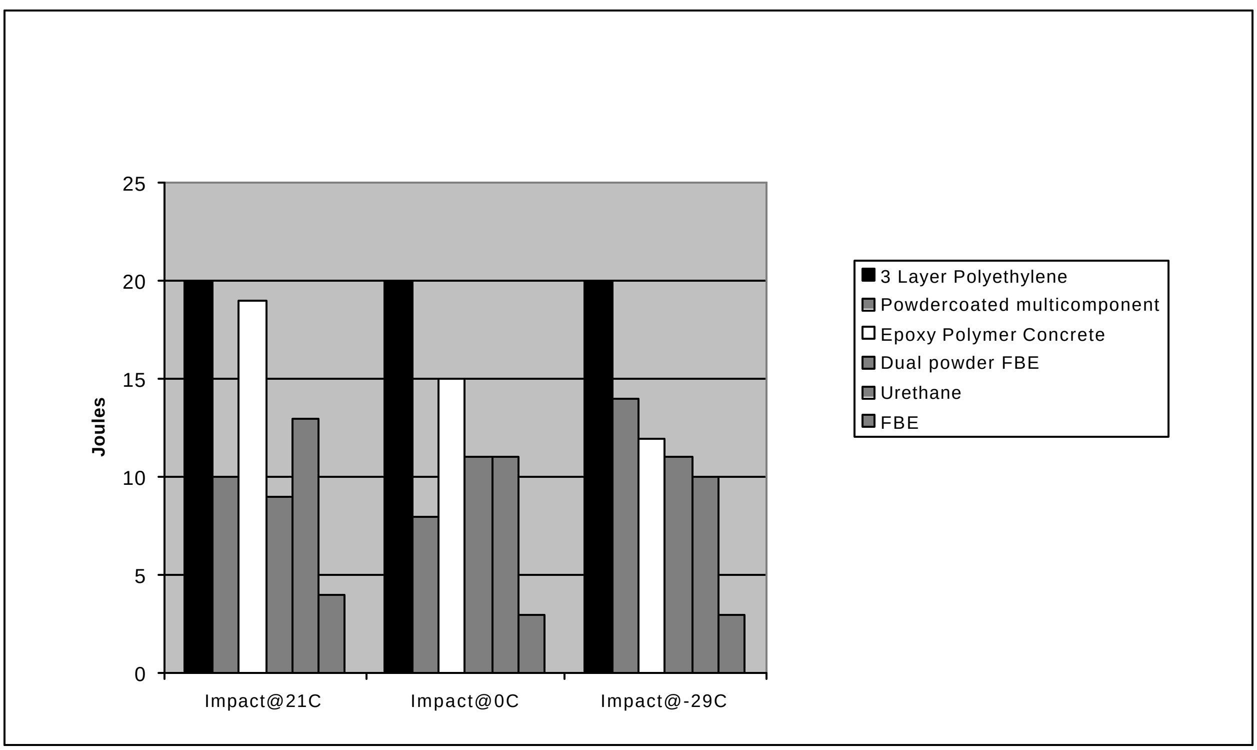

FIGURE 7- Impact Resistance results for anti-abrasion coatings