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PIPELINE COATING FAILURE –

NOT ALWAYS WHAT YOU THINK IT IS

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ABSTRACT

Corrosion coating failure has traditionally been defined by the changes which occur in coatings exposed above ground. Blistering and loss of bond are considered to be examples of failure. Their significance with regard to pipeline coatings (underground or sub sea) is different because pipelines are cathodically protected. Coatings and cathodic protection together form a system designed to protect the pipeline from corrosion and cathodic protection itself causes or accelerates some of the changes.

Fusion bonded epoxy is the most commonly used underground corrosion control coating in North America. Because it is thin, the effects of aging are visible earlier than with other coatings and include cathodic disbonding, moisture penetration, loss of bond and occasional blistering. This paper explains why and how these physical and chemical changes takes place.

Many of the observations are similar to those found in above ground coatings. However, for FBE, they are not coating failure for two reasons: FBE is an excellent oxygen barrier and the coating is part of a corrosion control system, coating and cathodic protection. A new definition for corrosion coating failure is proposed: "An underground coating has failed when it is no longer economical to maintain cathodic protection."

INTRODUCTION

There is a great deal of information on FBE coatings available in published literature. Much of it concerns laboratory evaluation and, at times, specific tests. There is, however, little mention of performance in the ground, even though FBE coatings have been used for corrosion control below ground for thirty years. There has been some discussion in recent years on the occurrence of blisters and loss of bond on FBE coatings, particularly after long term exposure, often wrongly characterized as coating "failure". This is discussed below.

Recently published studies on cathodic disbonding and information from bellhole inspections show that FBE coatings undergo characteristic changes in the ground. This information along with an understanding of fundamental electrochemical processes explains why the changes occur. Today's coatings combine flexibility with improved water and cathodic disbonding resistance. Some properties, important to in ground performance, are shared by all epoxies. Of most significance is the fact they are an excellent oxygen barrier.

This paper defines coating failure and covers basic corrosion, electrochemical processes and field observations.

BACKGROUND

Peabody [1] states coating alone can control pipeline corrosion only if the coating is an effective insulator, there are no holidays once the backfill is completed and, it is a perfect coating that does not deteriorate; but, as he describes, coatings absorb moisture, the electrical resistance drops and they conduct some current. There are always holidays after installation and the application of cathodic protection causes or accelerates these changes.

Cathodic protection by itself can prevent underground pipelines from corroding. Although effective, cathodic protection alone is expensive and no longer allowed by the Department of Transportation for new construction. Anti corrosion coatings are used to reduce the cost and a complete system would include a coating and cathodic protection designed to work together.

All pipeline coatings change with age. The changes include cathodic disbonding, water absorption, general loss of bond and blistering. Some also show deterioration due to leaching of components, cold flow, damage from soil stress and bacterial attack. FBE typically exhibits only cathodic disbonding, water absorption, blistering and occasional loss of bond. These conditions are either due to or accelerated by cathodic protection because of the phenomena of electroosmosis, electrophoresis and the highly alkaline conditions at a holiday. The changes are not unique to FBE but become obvious sooner because an FBE coating is relatively thin compared to other pipeline coatings, 16 vs. 140 mils (0.4 vs. 3.56 mm) and they are related to moisture vapor transmission which increases at high temperature. Also, the absolute rate of absorption is proportional to the inverse of the square of the thickness. It will take moisture four times longer to penetrate a film that is twice as thick.

DEFINITION OF FAILURE

Coating failure on a steel structure above ground is considered to have occurred when blistering or disbonding takes place. Invariably, underfilm corrosion is visible. Failure of a coating on a buried line under cathodic protection is not so easy to define. If the coating is blistered and disbonded and there is no corrosion then is has not failed. If there is corrosion due to the coating shielding the cathodic current, it has failed.

NACE RP169-83 [2] states: "Satisfactory service is indicated if no significant current increase attributable to deterioration of the coating has been required to maintain adequate cathodic protection."

Werner [3] defines failure as follows: "A buried pipeline coating has exceeded its useful life when adequate CP can no longer be economically maintained.

These definitions are based on the concept of coatings and cathodic protection working together as a corrosion control system. As such, the physical condition of the coating is less important than its electrical and electrochemical performance. End users report FBE coated lines show low and often declining current requirements and only occasional small amounts of corrosion. FBE performs well after more than twenty five years. Research discussed below shows why.

CATHODIC PROTECTION

The basics of corrosion and the use of cathodic protection are well known and frequently described.

Peabody describes the following. Corrosion takes place when there is an anode and a cathode, a potential difference between them, a metallic connection between them, and they must be immersed in an electrolyte that contains hydrogen and hydroxyl ions. When these conditions exist, current will flow and the metal will dissolve (corrode) at the anode. Here, electrons are lost and Fe^{++} combines with OH^{1} in the electrode to form $Fe(OH)_2$.

At the cathode, electrons are gained and they react with H^{+} from the electrolyte to form hydrogen gas. Hydrogen is the "polarization" film. This reaction also creates a surplus of hydroxyl ions which becomes the alkaline environment.

Conventional current flows from the cathode to the anode in the metal and from the anode to the cathode in the electrolyte. Metal receiving current from the electrolyte (cathode) does not corrode. The film of hydrogen formed on the surface of the cathode may be thought of as an insulating layer. As it develops, there is a voltage drop across the film. This polarization potential is in opposition to the corrosion cell potential and, in theory, could balance out so that corrosion does not occur. Unfortunately, there are "depolarizing" effects including oxygen and bacteria which deplete the hydrogen film. Cathodic protection is designed to ensure the polarization film remains intact by a remote anode which corrodes making the entire line a cathode.

Water is electrolyzed by cathodic protection current

$H_2O \rightarrow H^+ + OH^-$

The hydrogen ion, H^+, is discharged at the cathode to form nascent hydrogen which forms the polarization film

$H^+ + e^- \rightarrow H$

Parkins [4] shows that OH^- is also formed from dissolved oxygen

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

The alkaline conditions that occur at a holiday are due to the hydroxyl groups and are the primary cause of cathodic disbonding.

CATHODIC DISBONDING

Disbonding mechanisms have been extremely studied for some time. Many of the studies were funded by the American Gas Association and the Gas Research Institute. Early studies [5] determined critical factors such as cathodic current level and interface cleanliness as it related to disbonding under cathodic conditions. A more recent study [6] concentrated on investigating the electrochemical reactions that cause disbonding. The author says cathodic disbonding is a relatively common mode of failure of organic coatings on metal, regardless of whether cathodic protection is used. Applied current accelerates the process.

There are four mechanisms for disbonding at a holiday: chemical attack of the polymer by the eletrcochemically produced alkali, chemical attack of the oxide interface by the alkali, unfavorable surface energetics for maintenance of the adhesive bond and combined effects, (see Figure 1).

Fusion bonded epoxy polymers have exceptional alkali resistance and, therefore, do not disbond from chemical attack on the coating. The oxide layer present on all steel surfaces to which coatings adhere was found to be relatively thick beneath FBE. Kendig [7, 8] confirmed work which shows chemical breakdown of the oxide layer at high pH is the predominant mechanism for disbonding. Subsequently, surface energetics change due to reduced cathodic potential in the disbond crevice and coating disbonds directly from the oxide layer. This is also due to high pH at the disbond front, a result of diffusion of cathodic products from the holiday.

An important result of this work confirms that alkali induced degradation of adhesion is the key to disbonding in the absence of hydrogen over voltage potential, usually 1.2V or higher. Oxide reduction is less important as disbonding continues. This work also confirmed the growth of a magnetite layer on steel under cathodic conditions, often observed in the field and in laboratory testing.

Enough research has been done to indicate disbonding at holidays on all pipeline coatings in the ground or in laboratory testing is due to alkaline conditions caused by cathodic protection. Cathodic disbonding is one of the primary changes observed in buried pipeline coatings.

TRANSPORTATION OF WATER AND SALTS

Buried FBE coatings are known to absorb moisture relatively easily. Three processes by which water and salts enter and penetrate a coating film are osmosis, electroosmosis and electrophoresis.

Osmosis

When water flows from a dilute to a concentrated solution through a membrane it is said to be semi-permeable. The mechanism by which water flows through the membrane is called osmosis and is a result of differential pressure between the solutions. Organic coatings are semi-permeable membranes. When water passes through a coating film, salts that may be present on the pipe surface dissolve. An osmotic pressure can now exist between the soil and the pipe surface and further water transportation occurs.

Electroosmosis

As the name suggests, this is a phenomenon similar to osmosis but electroosmosis is related to electrical current flow. When two containers of water are separated by a membrane and a potential difference is maintained between them there will be a flow of water from one side to the other. The flow rate is proportional to the applied voltage and the direction of flow depends on the charge carried by the water.

Pipe coatings function as permeable membranes. When cathodic protection is applied, hydrogen ions are generated at the anode. They dissolve in water and become solvated protons * which pass through the coating to the steel. There, the electrons combine with the hydrogen ion to form a polarization film and water remains on the surface. The rate of transfer is proportional to the applied cathodic protection potential and, inversely proportional to the coating thickness. The higher the pipe to soil potential, the faster the transportation of water. Conversely, the thicker the coating film, the slower the rate of transfer.

Electrophoresis

Electrically charged ions in an aqueous solution will flow towards the electrode of opposite charge when a potential difference exists. This is known as electrophoresis which occurs across membranes. Since the transport of particles is involved, electrophoresis may actually take place through micro fissures in the coating under the influence of pipe to soil potential.

Overall Effects

The three phenomena have been known for some time. Osmosis was first investigated in 1748, electroosmosis and electrophoresis during the nineteenth century. All occur with pipeline coatings under cathodic protection and have been discussed in the literature. A good summary is given on the American Gas Association study on pipeline coatings [5]. Theoretical considerations and equations relating to the transportation of water and ions are given in any physical chemistry book [9]. Osmosis and electroosmosis, the transportation of water through the coating to the steel directly affect the bond. Under cathodic protection it is believed to be approximately 95% electroosmosis, 5% osmosis [10].

The initial stage of water absorption takes place because of moisture vapor penetration followed by electroosmosis. Later, when saturation occurs, small amounts of current will flow and the rate of transfer increases. Thick coatings with low transmission rates allow moisture to pass slowly at ambient temperature. For example, polyethylene is an excellent moisture barrier and moisture penetrates the film very slowly. At high temperature, transmission rates are much increased and the flow rate through the film is greater. Disbonding of polyethylene film usually occurs for reasons other than moisture penetration and electroosmosis. Electrical shielding of the cathodic current can occur with the potential for severe corrosion. After long term exposure, FBE coatings are often found with disbonding around a holiday and at times there is reduced bond. In almost all instances, there is no under film corrosion. If the coating is removed the steel is usually clean. At times there is moisture on the surface with a high pH which indicates the cathodic protection system is doing its job.

THE FLOW OF ELECTRICAL CURRENT

FBE coatings are known to absorb moisture and pass current. This is widely reported in published literature, [6, 11-16]. Authors report FBE allows current to pass, or that it exhibits a reduced electrical resistance under cathodic protection. This FBE property was identified as early as 1978 in a report prepared by the American Gas Association [5].

Leeds [17, 18] states FBE is transparent to cathodic current and describes changes that occur when FBE is cathodically protected in the ground. The most important from a corrosion standpoint is the formation of a protective magnetite film, Fe_3O_4, on the steel surface. Usually, there is no significant corrosion beneath the coating which confirms the cathodic protection is working.

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* $H^+ + H_2O \rightarrow H_3O^+$

The magnetite layer described by Leeds and others is an important component in the overall protection of pipelines. It is chemically inert, anodic to the steel and bonded to the surface.

Because FBE is a good oxygen barrier, any oxide that forms is reduced to magnetite which provides a protective layer. This layer has a significant iR drop which means the current requirement is reduced. The formation of a protective layer is the reason cathodic current remains stable, or declines, as FBE coated pipelines age. This is not true with many other coatings. When they disbond or suffer reduction of electrical resistance the current increases. A magnetite layer is visible on the surface after the coating is removed in disbonding tests, (Figure 2). Clearly, disbonding extends beyond this layer because the primary mechanism is the dissolution of the original oxide. The magnetite forms later on a clean steel surface. Magnetite observed on pipelines below ground can be mistaken for mill scale which is chemically identical.

BLISTERS AND HOLIDAYS

Blistering on FBE coating in the ground is not unusual. It occurs when the pipe is under cathodic protection and often found near a holiday. Blisters are frequently observed in elevated temperature cathodic disbonding tests and are a result of cathodic conditions at the intentional holiday, (Figure 3). Two samples are exposed in the same container for 60 days at 150°F, (65°C). The sample on the right was under 1.5V SCE, it shows blistering. The other sample had no applied voltage, it shows no blisters.

FBE coated pipe examined on bellhole inspections show blisters usually form near a holiday. A series of bellholes on one line showed holidays associated with blisters over 99% of the time. Research indicates the frequency is directly proportional to the protective voltage [19]. This is not unexpected given that electroosmosis is also directly proportional to the voltage. Current will not flow evenly over a pipe surface. It will flow preferentially to a bare areas such as a holiday. When this occurs, the current density gradient will be highest at the holiday and will drop to a base level on the surrounding coating, (Figure 4). Near the holiday, electroosmosis and pH will be higher than on the bulk of the coating and blisters would not be unexpected. Unpublished data show blistering is aggravated by phosphoric acid treatment.

SHIELDING AND CORROSION

When disbonded coatings have a high electrical resistance they may shield the pipe from cathodic current. If this occurs, corrosion can ultimately lead to pipe replacement or repair. The two types most often encountered are stress corrosion cracking where operating conditions favor its development, and pitting. Stress corrosion cracking has been studied extensively and has never been observed on FBE coated pipelines in over thirty years. Industry surveys show pitting is also a rare occurrence [16].

SUMMARY

Research, field observations and industry experience show fusion bonded epoxy coatings perform well below ground. They change with the cumulative effects of water absorption and cathodic protection. Pipelines are buried, or submerged, in many different locations. Clearly, the rate of change depends on the environment and the operating conditions. At any bellhole inspection the following conditions may be observed on an FBE coating:

excellent coating
disbonding around a holiday
blistering near associated holidays
highly alkaline surface
reduction or loss of bond
magnetite film
no significant corrosion.

It is obvious from the above discussion that it is beneficial to repair a coating before backfilling and to exercise care to minimize damage in the ditch. It is equally obvious, while cathodic protection is essential, the rate of change in an FBE coating can be slowed significantly if the cathodic protection system is designed to preclude excessive voltage. FBE coatings enjoy a unique balance of properties. They absorb moisture, are transparent to current and, of prime importance, they are an oxygen barrier. These combined properties allow the formation of a protective magnetite layer. The outcome is a stable current demand and an economical cathodic protection system.

What is failure? “A buried pipeline coating has exceeded its useful life when adequate cathodic protection can no longer be economically maintained” [3].

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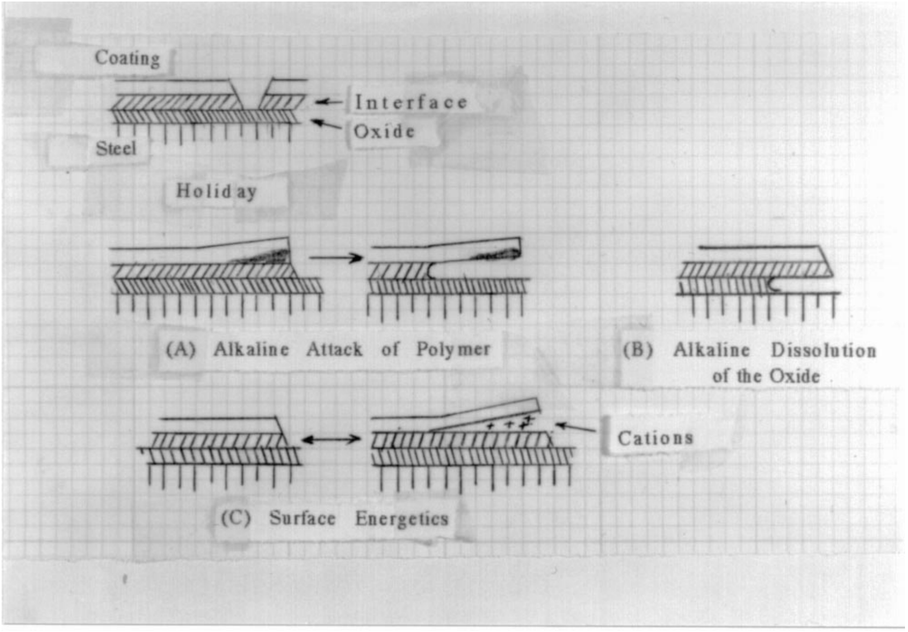

Figure 1 – Proposed mechanisms for cathodic disbonding (after Kendig).

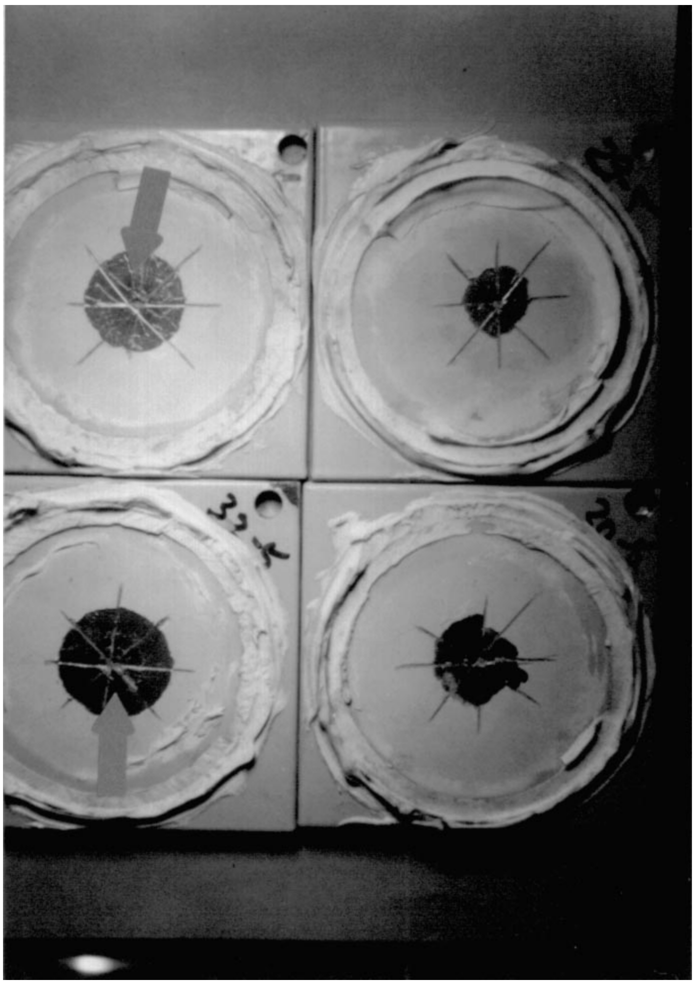

Figure 2 – Magnetite layer after CD testing

Figure 3 – Top sample under –1.5v SCE shows blisters

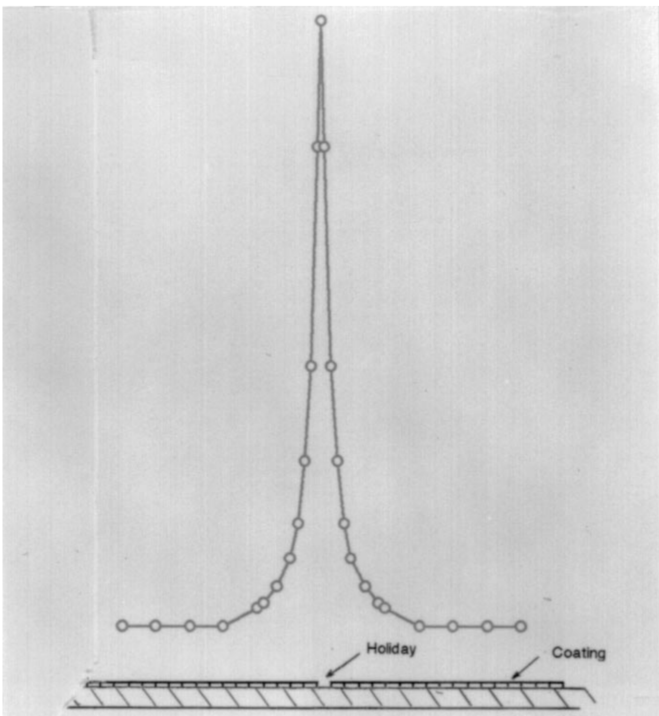

Figure 4 – Current distribution at a holiday.