



Cathodic protection shielding of coated buried pipeline

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Abstract During the 2000s, the concept of cathodic protection (CP) shielding was first raised in open literature and remains debated between coatings professionals. The mechanism of CP shielding, and its understanding continue to be studied for different coatings with different approaches and using various techniques. From the CP shielding factors to the assessment methods, the published literature merits a deep analysis to capture the established knowledge and identify the research gaps to further tackle the issue for reliable coated buried structures. A holistic approach to this topic seems necessary where coatings ageing, cathodic protection, electrochemistry, and transport processes should be considered. In the first part of the present review, the recent works related to the understanding of CP shielding, coatings properties were considered before discussing the mechanisms involved underneath coatings. Transport phenomena and their relationship with cathodic protection performance in the presence of chemical and microbiological processes are discussed in the second part. Finally, CP shielding assessment methods and modeling works are presented and discussed from different perspectives.

Keywords Coatings, Cathodic protection, Shielding, Modeling, Disbondment

Introduction

A major part of strategic fluids (oil and gas, water) is transported through underground pipelines crossing thousands of kilometers and facing various internal and external corrosion challenges including corrosion due to the surrounding soils. The mitigation of this

challenge starts with a proper material selection associated with efficient protection methods. All international standards recommend combining cost-effective external coatings with well-designed cathodic protection (CP). However, both protection methods may suffer from loss of effectiveness together or separately. Moreover, compatibility between these two methods was mostly discussed from one perspective which is the effect of CP on coating adhesion, i.e., cathodic disbondment. The other perspective is the effect of coating characteristics on the ability of the CP current to reach the metal substrate and favorize the passive layer formation reducing the corrosion rate.¹ However, this concern is mostly raised in the case of coating defect or disbondment.

The coatings market offers a wide spectrum of choices to the end-user who is always asking the question of CP compatibility. The performance of the different coatings continues to feed technical articles published in international journals and conferences. Desired technical coating characteristics are well accepted between corrosion and coatings professionals. This includes excellent barrier properties and adhesion, ease of application, mechanical and biodegradation resistances, etc. However, when it comes to their use with cathodic protection, there remains some nonconclusive aspects. This includes the cathodic disbonding (CD) rate and cathodic protection shielding in the case of disbonded coating. While CD assessment method is defined by a variety of international standards,^{2–4} testing factors and the complete understanding of the mechanisms continue to be discussed between specialists.^{5, 6} In parallel, CP shielding by coatings remains less understood in terms of mechanisms and influencing factors which explain the absence of standard testing procedure accepted and practiced by coatings and CP specialists. Regardless of this issue, pipeline industry focus is paid more to the detection of buried coating defect and CP performance

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assessment through the development of accurate (qualitative and/or quantitative) inspection techniques.

CP shielding by coatings involves several research areas (coatings, cathodic protection, corrosion mechanisms under disbonded coating). Thus, the present review aims to discuss the outcomes and main findings of the most relevant research works in these directions. Special focus is made on the most adopted and recommended coatings for buried pipelines. Some recent discussion on CP theory is presented to clarify confusion around CP shielding. An additional section is dedicated to the mathematical efforts focused on the environment under disbonded coatings. Finally, a holistic approach is proposed to cover the most relevant pending research questions.

Cathodic protection shielding

CP shielding is a concept which has been mentioned in different applications including structures covered by (low porosity and low water saturation) concrete, and underground pipelines buried in contact with rocks, tree roots, etc.^{7, 8} However, in the present review, the discussion will be limited to the case of disbonded coating on buried pipeline in different soils. CP shielding is a term used to define the prevention or diversion of the cathodic protection current from its intended path. It was proposed as the main cause for field observed corrosion failures of buried pipelines under disbonded coating. Then, coating manufacturers started to distinguish between shielding and nonshielding coating qualifying the latter as fail-safe coatings.^{9, 10} Some coating manufacturers claim that this concept is limited to the situation of coating adhesion loss only.

The relationship between barrier properties and CP shielding is still confusing. The desirable good barrier properties of any coating correspond to high electrical resistance favorable to the CP current shielding. Therefore, an optimal electrical current permeability is needed for CP to continue to protect the underlying steel at a coating disbondment. In this sense, Kehr¹¹ proposes that the coating electrical resistance must be high enough to minimize current flow through it and low enough to allow CP current flow to protect the steel if disbondment or blistering occurs. However, this description remains vague and poorly defined when it comes to the variety of coatings and penetrating electrolytes.¹² In fact, corrosion professionals are unable to determine this optimal value of electrical conductivity. The pipeline industry continues to debate the relatively thin fusion bonded epoxy (FBE) coatings as the benchmark of non-CP shielding coatings. This is based on its field performance where mostly no corrosion is reported in case of its disbondment. The performance is based on the absence of localized corrosion and the basic pH beneath FBE.¹³ However, Norsworthy et al.¹⁴ reported the presence of corrosion initiation at holidays of FBE after 10 years of service in

salty soil near the coast. Such a case study remains qualitatively described in the literature which makes it difficult to determine the full mechanism. On the other hand, other coatings such as the thick and highly electrical resistant polyethylene coating systems (3LPE) showed relatively good anticorrosion performance except in special conditions. While Büchler¹⁵ reported successful performance by European users (for more than 40 years) even in case of adhesion loss, Roche et al.¹⁶ reported corrosion and stress corrosion cracking (SCC) under disbonded PE on CP protected steel buried pipelines. The author explained this failure by the thermal ageing of the coating (inducing its cracking) and the important gap between disbonded coating and steel pipe which allow the renewal of the electrolyte. As reported in DIN 30670, it seems that practically, 3LPE disbondment is unavoidable regardless of the manufacturing method and depending on soil characteristics (salinity and water content) and cathodic protection extent.¹⁷ Also, Fernandez-Lagos et al.¹⁸ reported a general corrosion around 3LPE coating defect with severe adhesion loss after only 5 years of service. A pH of 9 was observed around the holiday while it was near neutral (6–7) under the coating. This situation represents a pH cell with an expected oxidation on the low pH zone depending on typical galvanic corrosion factors (electrolyte conductivity, circulation, etc). Such findings support the theoretical considerations, laboratory experiments and field experience reported by Heim and Schwenk¹⁹ reported that no danger of corrosion would be expected at the defect region. Moreover, the investigators¹⁸ noticed the absence of chlorides and microbial activity. However, soil data were missing to explain fully the occurring mechanisms. Together with these cases, Tan et al.²⁰ reported recently that based on industrial survey conducted by gas pipeline industry, 90% of corrosion damages occurred under CP shielding coatings or heat shrink sleeves. In the absence of detailed information on these case studies, it is difficult to conclude on the corrosion occurrence in case of disbondment of CP shielding coating. What can be mentioned here is that any disbonded coating on buried pipeline represents a risky zone with different possible scenarios (GC*, PC**, SCC†, MIC‡) considering the corrosivity of the surrounding soil, its variation (or renewal) and pipe age.

The actual classification of coatings in terms of CP shielding was summarized by Latino et al.²¹ based on the literature as shown in Table 1.

It appears that comparing or assigning CP shielding characteristics to coatings in this manner is unfair until there is an understanding of the three acting systems and their interactions, i.e., the coating, the CP process

* General corrosion

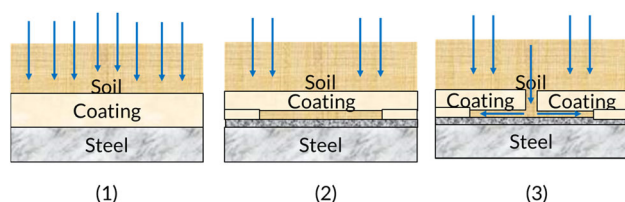
** Pitting corrosion

† Stress corrosion cracking

‡ Microbiological influenced corrosion

Table 1: Coating shielding behavior according to literature²¹

Shielding	Nonshielding	Potentially nonshielding
3LPO (3-layer polyolefins)	FBE (Fusion Bonded Epoxy)	Asphalt enamel
HSS (Heat Shrink Sleeve), polyolefins based	Mesh baked tapes	Coal tar enamel
Solid film baked tapes, polyolefins		Two-part epoxies

**Fig. 1: CP current permeability paths for (1): intact coating, (2): blister, (3): disbonded coating open to soil**

and the processes underneath disbonded coating. For instance, CP current permeability can be discussed considering three commonly encountered scenarios, i.e., intact coating, blisters and open coating defect (Fig. 1).

Scenarios 1 and 2 seem to be less discussed by the coatings community compared to scenario 3 which can be questionable since scenario 2 can also lead to a corrosion situation. In the third scenario (open disbonded coating), CP current permeability has two paths, i.e., soil in contact with trapped solution, and through coating. What is well established is that CP current will progress through the least resistive path. To determine this path, we should consider soil characteristics (texture, moisture level, resistivity), coating characteristics (chemistry, thickness, porosity, ageing) and trapped solution (chemistry, volume/steel surface ratio, exchange with soil). To our knowledge, this research gap is still not fully explored in open literature. On the other hand, limitations of techniques to get reliable information on these processes from field creates an additional challenge for scientists.

In the following section, a general overview is given of the main external coatings adopted for buried pipelines, especially in terms of characteristics affecting their compatibility with CP. This includes fusion bonded epoxy (FBE), 3layer polyethylene (3LPE) and cold field applied tapes. Heat shrink sleeves are out of the scope of this review.

Buried pipelines coatings

Depending on the industrial standard, external coatings for buried pipelines are classified in generic systems that can vary according to the coating chemistry, application method (cold, hot), application purpose (new, repair), and the pipeline component (main

pipe, field joint/ girth weld). Table 2 summarizes the most adopted classification of underground pipeline external coatings.

In terms of coatings mostly adopted for buried pipelines, Buchanan¹² reported a global market distribution of the main ones including 3LPO, FBE and others as shown in Fig. 2. It appears that regional coating choice is influenced by many factors including field performance and local understanding of CP shielding among others. For instance, FBE is widely used in North America while 3LPO dominates Europe.

Fusion bonded epoxy

FBE coatings have a long track record exceeding 50 years. Argent and Norman²³ reported that FBE was subject to many developments since its introduction in the market in the late 1950 s. This includes mechanical resistance, cathodic disbonding (CD), and other properties.

FBE is a solvent free one-part thermosetting epoxy resin powder which can consist of one (single) or two (dual) layers showing different thicknesses and relatively different dielectric properties. The manufacturing of FBE is conducted according to industrial standards (ISO21809-2, AWWA C213, and CSA Z245.20) to ensure high quality and excellent field performance. The typical nominal thickness of the single layer system is about 350–450 μm while for the dual (two) layers system, the average nominal thickness is about 700 μm . It is important to mention that in the dual layer system, the FBE primer layer thickness does not exceed 280 μm .

FBE is often applied during pipe manufacture in the factory. This provides production efficiency, controlled environment for the application and easy quality control. This increases the success of this coating if both transportation and installation of the pipe are well conducted.

The main characteristics of FBE coatings related to the topic of CP shielding are its relatively lower thickness, optimal water absorption, resistance to cathodic disbonding, and electrical resistivity. Unfortunately, due to the variation of testing standards and conditions followed by FBE manufacturers, as well as the variation of FBE formulation it is difficult to quantify properly the main features of FBE coatings. For instance, FBE formulation variation showed a significant impact on CD as shown in Fig. 3. The

Table 2: Generic external coating systems for carbon steel pipe for underground and submerged pipe. Adapted from the literature^{9, 22}

Generic external coating system	
Asphalt/coal tar enamel + concrete	Polymeric tapes
Coal tar enamel	Fusion bonded epoxy
Cold-applied and hot applied tape	Sprayed applied liquid coatings
Concrete	2 or 3 layers of polyolefin (PLO) coatings
Elastomeric materials (Polychloroprene or equivalent)	
Field-applied coatings for repair and rehabilitation	
Field joint coatings	

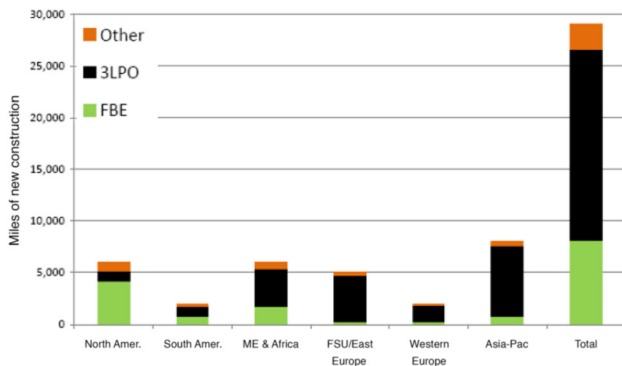


Fig. 2: Global coatings market share by region¹²

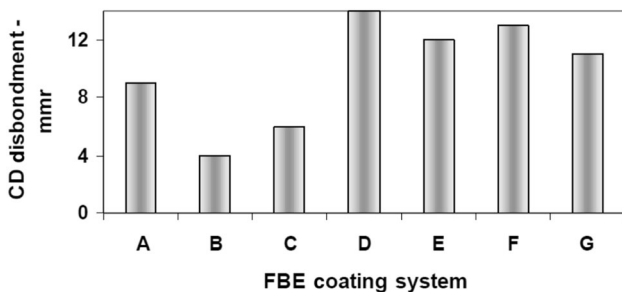


Fig. 3: Cathodic disbondment expressed as mm radius of FBE coatings from different manufacturers conducted at – 1.5 V vs Ag/AgCl in 3% NaCl at 65 °C and for 28 days²⁵

cathodic disbonding extent of FBE coating was also found to highly affect CD testing parameters such as CP potential, and temperature.²⁴ The consequence of this scattering of CD rate can be relevant when discussing disbonded region geometry where CP current progress will be affected.

In terms of electrical resistance of FBE coating, different works were performed considering variable factors and measurement methods. The effect of water or electrolyte absorption on the electrical resistance has been quantified by many authors.^{11, 12} However, electrical resistance (which is mainly the electromigration of dissolved oxygen) values can vary depending on

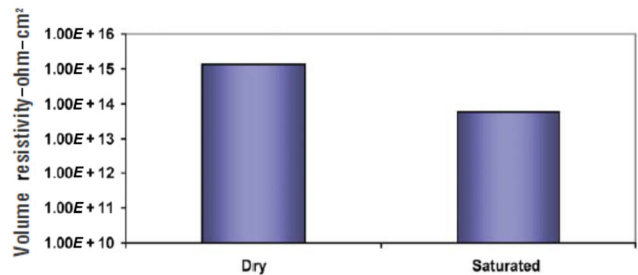


Fig. 4: FBE was saturated in a 3% NaCl solution for 40 days with and without a six-volt cathodic protection set-up¹¹

the electrolyte used, the exposure duration, the coating thickness and the FBE product. For instance, while Kehr¹¹ observed a decline of volume electrical resistance from $10^{15} \Omega \text{ cm}^2$ (dry state) to $\sim 10^{13.5} \Omega \text{ cm}^2$ after saturation in 3% NaCl for 40 days (Fig. 4), Buchanan¹² reported a more severe decline from 10^{15} to $10^9 \Omega \text{ cm}^2$ after saturation in water achieved after 500 h (20.8 days). Missing information on coating thickness and other factors makes it difficult to explain this difference between the works.

The electrolyte effects and CP potential on electrical resistance can be observed through the study conducted by Eltai et al.²⁶ Considering a commercial two parts unpigmented epoxy coating with a thickness of 50 μm , the effect of the electrolyte (0.6 M NaCl) on the coating electrical resistance was pronounced in early days of immersion but starts to become insignificant after two weeks, approaching $10^{6.5} \Omega \text{ cm}^2$ (Fig. 5). So, this highlights the effect of electrolyte saturation on the evolution of electrical resistance where a steady state can be defined depending on the coating microstructure (porosity). It is important to mention that Eltai et al.²⁶ obtained the coating electrical resistance through electrochemical impedance spectroscopy (EIS) which is based on AC small perturbation. However, most of other authors rely on the procedure based on DC current and described in EN 62631-3-1²⁷ to determine the volume electrical resistance. Therefore, it is important to check whether the measuring method influences the passing current and the obtained electrical resistance.

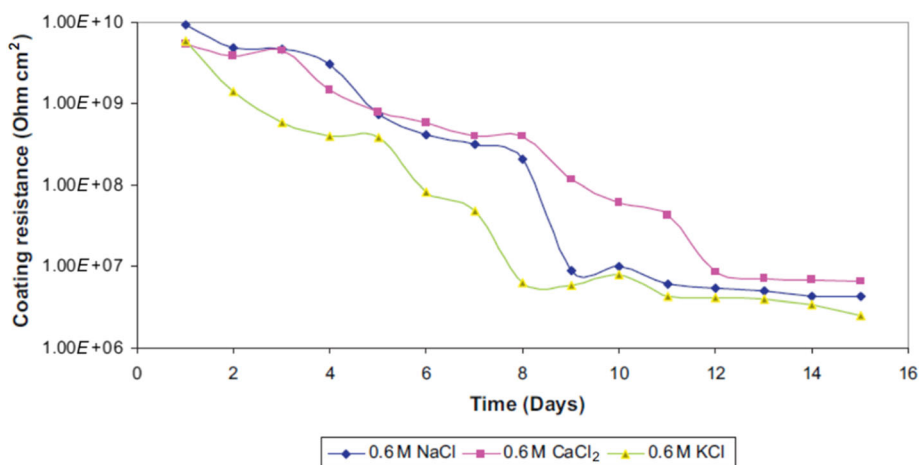


Fig. 5: Evolution of electrical resistance for a two-parts unpigmented epoxy coating in different electrolytes at ambient temperature²³

As with all coatings, FBE can be subject to blistering and loss of adhesion for typical reasons like improper surface preparation. In the context of CP, Heim et al.¹⁹ discussed electrochemical blisters which develop mainly for CP combined thin coatings with low electrical resistance and when exposed to saline medium for a long period. Usually, the pH of the electrolyte inside these electrochemical blisters is basic, offering good passivation of the steel pipe. Argent et al.²³ reported some cases of adhesion loss of FBE with different scenarios including formation of high pH carbonate-bicarbonate environment, or flash rusting. Then, in all cases corrosion did not develop, which was attributed to the nonshielding of the coating to the CP current.^{23, 24}

Wong and Lam²⁸ presented some results and reported data from FBE suppliers showing clearly that this coating does not allow enough CP current to pass through to achieve the protective level. Otherwise, it will then defeat the purpose of a barrier coating and is not needed. Such statement emphasizes the need to properly understand the CP shielding and its relationship with electrical resistance of the coating.

Three-layer polyethylene

As for the FBE, the three-layer polyethylene (3LPE) belongs to the third generation of coatings. It is a multilayer coating that has been used since the 1980s for the protection of pipelines against the external corrosion when buried in different soils. It consists of epoxy primer, polyethylene or copolymer adhesive intermediate layer and a final top-coat polyethylene layer. The epoxy primer can be either a FBE or a liquid epoxy primer and the adhesive layer must be compatible with the outer PE. The outer PE can be low-density LDPE, medium-density MDPE or high-density HDPE. This made the three (epoxies, adhesive and

polyolefins) manufacturers work closely to achieve the best performance for the whole system.

The three-layer system is intended to combine the excellent adhesion and cathodic disbonding (CD) resistance of an epoxy with the high mechanical strength and flexibility of a polyolefin (polyethylene). The epoxy thickness shifted from 75 μm in early products to 200 μm in recent applications.²⁹ In some cases, both the adhesive and the top-coat PE layer are sprayed as a powder on the epoxy primer for a total coating thickness of 1.2 mm. However, for extruded coatings, the total thickness exceeds 3.5 mm.

The electrical resistance values of the 3LPE coating system are limited in the literature. Buchanan¹² reported an electrical resistance of $10^{17} \Omega \text{ cm}^2$ for both dry and wet HDPE coating. Therefore, this value should be considered in series with FBE primer resistance without neglecting the contact resistance between the two layers. HDPE is known for its very low water absorption where the same author observed a stabilization at 0.02% after 24 h of exposure. This can be explained by the nonpolar characteristic of HDPE which limits its water absorption even for longer immersion durations as revealed in the study conducted by Kuang and Cheng.³⁰ Also, it would be interesting to get more electrical data of other PE materials (LDPE and MDPE) for long immersion duration.

The field performance of the 3LPE coating is considered as good and limited to the cracking of the topcoat and the disbondment that occurs at two locations: primer and steel pipe or primer and topcoat. Roche et al.¹⁶ reported some cases including disbonding after 10–15 years where no significant corrosion was noticed on the pipe metal (Fig. 6). It is important to specify that disbondment cases were observed for buried pipelines operating at temperature up to 60 °C and that the longitudinal crack in PE layer was attributed to thermal ageing.³¹ The good performance



Fig. 6: Common field failures of 3LPE coating systems¹⁶

of the 3LPE coating system in Europe was also reported by Büchler.¹⁵

While many authors consider 3LPE as CP shielding coating, which means that it can lead to corrosion damage under disbondment, the field performance reported by many pipeline professionals does not fully support this claim. On the other hand, a laboratory study conducted by Campaignolle et al.³² showed that 3LPE can lead to severe corrosion if the trapped solution underneath the disbonded coating is renewed. This can be explained by a concentration of salts and oxygen replenishment underneath the coating causing localized corrosion attack. The renewal of trapped solution in field can be hardly expected except in presence of fluctuating water table level.

Field applied tapes

In this section, the discussion will be focused on the field applied cold tapes that continue to stimulate the CP shielding debate between coating manufacturers. Under this category, two main product families can be considered, i.e., low crystallinity polyolefins and reinforced polymer tape. Usually, these coatings are applied for field joints or girth welds and are prescribed by international standards (ISO 21809-3 and NACE SP0109). However, there is a growing interest for these products for the rehabilitation of old main pipes. Field joints and girth welds represent the weakest locations of buried pipelines. Their damages are considered more significant compared to the factory applied coatings such as FBE or 3LPE. Indeed, adhesion of the coating is highly affected by the conditions of application that are well controlled and optimal in factory compared to the field.³³ In addition, this type of coating applied on girth welds is known for tenting issues, creating a gap with steel pipe surface which represents one of the risky zones for inefficient CP.³⁴

The low crystalline polyolefin tapes are usually called viscoelastic tapes and consist in two layers: an inner layer for the corrosion protection and an outer



Fig. 7: Field cold applied viscoelastic tape: inner layer (blue), outer layer (black) (Color figure online)

layer for the mechanical protection (Fig. 7). The inner layer is considered self-healing with a poly-isobutene-based chemistry, as described by Doddema.³⁵ This layer is claimed to provide weathering resistance through its low water absorption and bacteria resistance. The adhesion relies on the sticky nature of the inner layer combined with the application method which can be made either by hand wrapping or using a dedicated machine.

The outer layer used for mechanical protection is usually based on polyvinylchloride (PVC) or polyethylene (PE) polymers. The application of this coating is performed considering either a single or a double overlap reaching 50%. The total thickness of this kind of coatings is significantly high and ranges between 2 and 6 mm.

The specific electrical resistance of commercial viscoelastic tapes is expressed as R_{s100} measured after 100 days of immersion in 0.1 mol/L NaCl solution according to ISO 21809-3. Most viscoelastic tapes show a specific electrical resistance of $R_{s100} \geq 10^8 \Omega \text{ m}^2$ ($10^{10} \Omega \text{ cm}^2$), which is required by the same standard to consider a coating compatible with cathodic protection. Unfortunately, no rationale is given for this required value.



Fig. 8: Geotextile mesh backed tape applied on large diameter water pipeline

Limited data exist on the field performance and laboratory studies of these coatings in terms of durability and CP shielding issues. Meroufel³⁶ conducted a survey of the available technical studies on the aging of this type of coatings. Two perspectives were noticed in the literature including manufacturers and end-users.^{37, 38} From end-user perspective, Moosavi³⁸ reported the weakness of cold-applied tapes in terms of soil mechanical stress resistance. This would induce a loss of adhesion (a phenomenon called sagging) and development of crevices between the inner layer and the metal pipe steel that can be questionable in terms of CP protection.

An inspection made by Meroufel³⁹ on large water pipe coated with this type of tape, showed no disbondment, a neutral pH and absence of corrosion after 5 years of service. The pipe was buried in basic and salty sandy soil (subkhas) with significant water table presence.

In addition, thermal degradation, highly expected in case of oil pipelines, can also cause multiple failures, as reported by Neal.⁴⁰ Also, some “spiral” corrosion was reported for cold applied tapes in general, but no data are available for the viscoelastic tapes.

To overcome the soil stress resistance weakness and CP shielding concerns, reinforced polymer tapes were developed. The main example is the mesh geotextile fabric backing on the top of rubberized bitumen developed in the late 1990s.⁴¹ Figure 8 shows the mesh backed bitumen tape applied on large diameter pipeline.

The adhesion of this tape is ensured by the fast-drying adhesive primer (rubber-based material in solvent) applied prior to the wrapping of the tape. The corrosion protection is ensured by the rubberized bitumen layer and the soil stresses are controlled through the polypropylene geotextile mesh. No data are available on the electrical resistance of commercial geotextile mesh backed tape. Neither ISO 21809-3 nor NACE SP0109 provided qualification criteria in terms of electrical resistance. However, some literature data on bituminous can be mentioned where it was found

that the electrical resistivity (measured by two-probe method) of dry bitumen specimen (1 mm thickness) containing carbon black is in the order 10^5 – 10^{14} Ω m (10^7 – 10^{16} Ω cm) for a content of carbon black ranging from 2.5 to 18 wt.%.⁴² Nevertheless, the electrical properties of the geotextile mesh backed tape in dry and saturated conditions remains an aspect to be explored. The field performance of geotextile backed tape remains also unexplored which can be attributed to many aspects. This includes the coating presence in the market (about 20 years) with limited use to the girth welds, field joints and occasionally for rehabilitation purposes.

One of the drawbacks of field applied cold tapes is the creation of microtunnels in the overlapping area as illustrated in Fig. 9. The size of these microtunnels depends on inner layer type and application procedure.

To overcome this risky area where CP current may not reach and corrosion can proceed (called spiral corrosion), some coating manufacturers have developed the concept of hose-like coating. Three-ply tape technology is a typical example of this hose-like coating where microtunnels are eliminated based on adhesive tape with butyl-rubber on the outside and inside of the tape. This forms a water/oxygen proof hose, eliminating the disbonding risk and is not affected by the soil environment changes. Therefore, coating manufacturer claim that CP is nonmandatory due to the absence of disbonding risk. Unfortunately, the lack of published articles on spiral corrosion and long-term performance, or laboratory data make it difficult to conclude on the abovementioned claims.

Cathodic protection knowledge update

Cathodic protection (CP) is an electrochemical protection method with a long record and many developments. However, some of its aspects continue to be discussed like the interfacial (metal substrate/coating) pH (and its evolution) and passive layer formation as expected by the Pourbaix diagram. Some of these aspects were investigated through many studies, as reported by Büchler et al.⁴³ An important discussion found in literature is on the necessary current density to achieve basic/alkaline pH.

According to the pioneering works surveyed recently by Angst,⁴⁴ a current density of 0.1 A/m^2 was enough to passivate steel through the production of hydroxyls (OH^-). This would create a concentration gradient of OH^- which was called “concentration polarization” and is well accepted by many authors.^{43, 45} However, this concept should be discussed by considering first the soil characteristics that control oxygen transport and availability at the metal surface. A recent work conducted by Martinelli-Orlando and Angst⁴⁵ showed both oxygen and pH evolution within 24 h in the case of CP polarized carbon steel buried in quartz with different porosities and saturated at

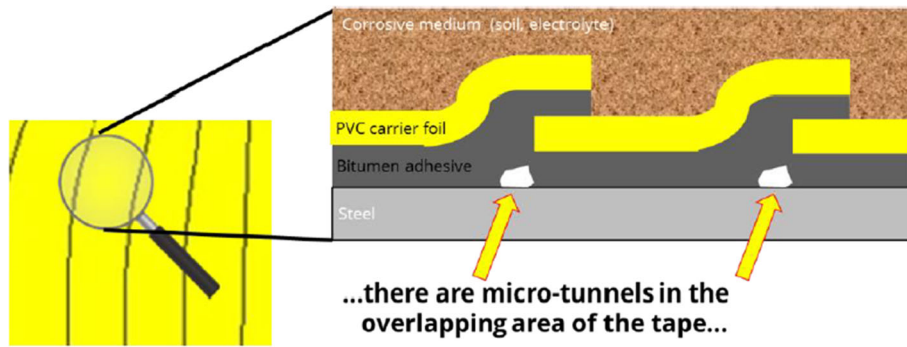


Fig. 9: Microtunnels created by field applied cold tapes

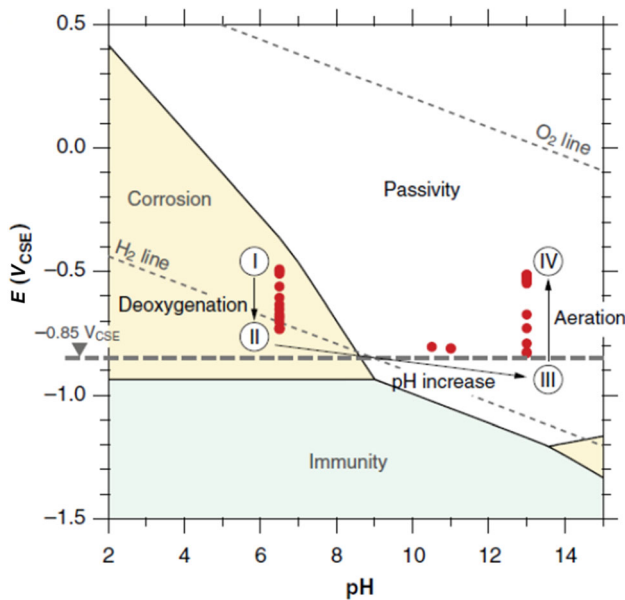


Fig. 10: The behavior of iron (red dots) on the Pourbaix diagram depending on oxygen availability⁴⁴

different levels with simulated soil solution. This can be a good starting point but needs further work since those conditions are limited in terms of chemical inert character of the quartz, solution replenishment, and contribution of microorganisms.

The impact of oxygen availability on interfacial pH was studied by Angst⁴⁴ to define the passivation level (Fig. 10). However, these experiments were done following a pure chemical experimental approach (no CP polarization) which can be different in terms of kinetics and equilibrium when compared to electrochemical-based phenomena.

Moreover, the interaction between interfacial pH increase and surrounding soil characteristics remains a pending research question. Soil characteristics that may affect interfacial pH increase include pH buffering capacity, chloride concentration, possible contribution of the dissolved CO₂ and microbial activity. In the context of CP, pH buffering capacity corresponds to the soil resistance to the pH increase. This can be

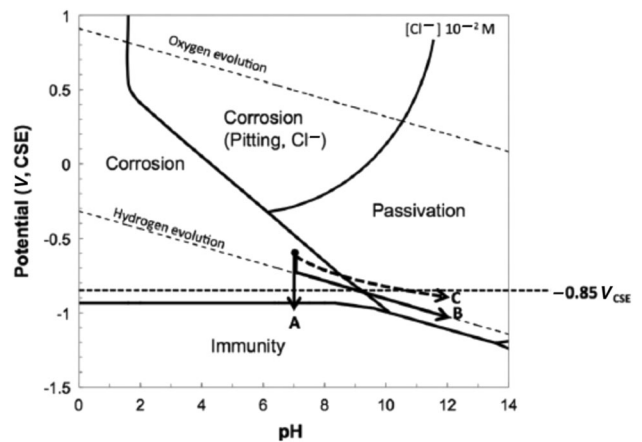


Fig. 11: Modified Pourbaix diagram considering chlorides and CO₂ roles proposed by Ackland and Dylejko⁴⁹

expected for soil containing carbonates/bicarbonate system and subject mass transport which is affected by the soil texture. However, literature works on this topic showed that usually kinetics of CP producing OH⁻ overcome the buffering capacity of soil system.⁴⁶ This later may only postpone pH elevation induced by CP but does not stop it. Then, any factor that decreases the kinetics of CP reaction will be favorable to the soil buffering capacity.

For instance, the performance of CP for different chloride concentrations was not fully studied in the context of soil corrosion. Most of the studies dealing with the interaction between CP and chlorides have been conducted for steel reinforcement in concrete. A typical example being a recent study where it was necessary to adjust the right impressed current.⁴⁷ Unfortunately, the initial passivation of the steel was not considered, and the chlorides were added to the mixing water from the beginning.

A long time ago, Pourbaix reported a critical chlorides concentration of 355 ppm (10⁻² M) as a boundary limit between passivation and pitting initiation of steel.⁴⁸ This aspect together with 0.01 M of CO₂ were considered in the Pourbaix diagram presented by Ackland and Dylejko⁴⁹ when they revisited the use-

fulness of the CP potential criteria of -0.85 V vs Cu/CuSO₄ (Fig. 11).

The effect of 5% CO₂/N₂ gas mixture on the under disbonded coating local environment was studied by Eslami et al.⁵⁰ in the context of near neutral SCC corrosion of X65 steel for 90 days. The authors studied this factor for a fixed crevice geometry using soil simulated solution. As expected, a limited supply of CO₂ would support the development of high pH favorable to passivation conditions under CP polarization. The limitation of CO₂ supply is mainly affected by the soil chemistry/texture and microorganism activity. Then, the synergy between the different factors highlight again the need for a holistic approach to study the phenomena.

For microorganism activity, some authors claim that CP is effective against microbiologically influenced corrosion (MIC).⁵¹ However, this remains disputed due to the aspect of possible participation of microorganisms in the different chemical, physical and electrochemical phenomena. A recent study conducted by Jansen et al.,⁵² showed that pH increase at the CP protected steel surface was less in the presence of specific bacteria type biofilm and the CP current demand was higher. It is important to know that biofilm may contain bacteria with electroactive behavior (such as several SRB bacteria) offering cathodic sites and participating in the cathodic current. At the same time, bacteria also consume oxygen for their respiration without generating OH⁻. These phenomena together with the patchy aspect of biofilm (not covering the whole surface) would explain the lesser pH increase in presence of CP polarization. Also, these results exclude the speculation made in the past on the biofilm elimination through the high pH induced by CP at the metal surface. For the CP shielded zone, microbial activity would stimulate the corrosion process either by secreting acids (acid producing bacteria, APB), or oxidizing Fe⁺² to Fe⁺³ (iron oxidizing bacteria, IOB).

Thus, further understanding of this aspect should bring a more complete figure of what is happening at the interface in the presence of biofilm depending on its composition and maturity level.

That is why the conditions that favor concentration polarization are the subject of many studies. According to Büchler et al.,⁴³ this would happen only if the pipe were bedded in fine sand and soil or in contact with calcareous precipitate which comes from hard water. The same opinion is shared with Ackland and Dylejko.⁴⁹ Then, the extent of the concentration polarization area was found to depend not only on the ionic strength or the pH buffer capacity of the electrolyte, advection, and soil microstructure but also on the experimental time of the different studies.⁴⁴ The variation of these factors induced the difference observed in the relationship between the pH increase and the CP protection degree (current density) as shown in Fig. 12.

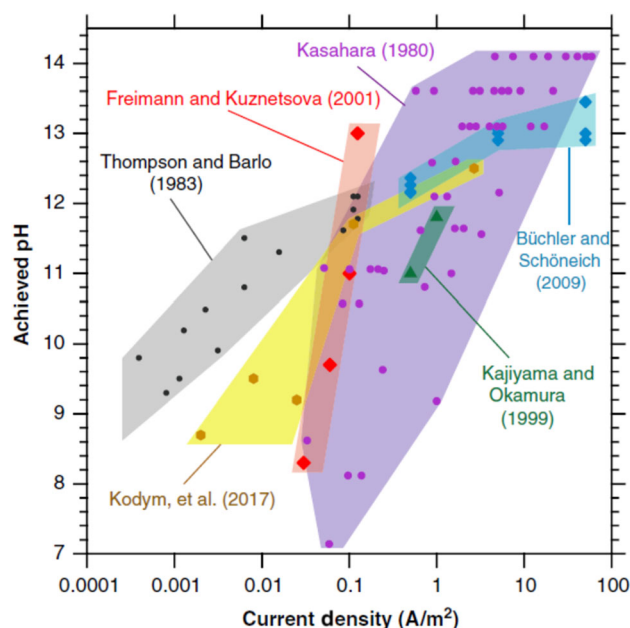


Fig. 12: Literature compilation for the relation between pH achieved at steel surface embedded in soil and the applied protection current density⁴⁴

All the above discussion on the passivation induced by CP is for a potential of -0.85 V vs Cu/CuSO₄ where the pH would be at least equal to 9 or 10.

Alternatively, if the passivation (via pH increase) cannot be achieved in field through CP, the second mechanism is considered, i.e., activation polarization by CP. Activation will shift the potential toward the steel immunity domain which requires high current density demands that can reach 1 A/m².⁴³ This relies on the fact that immunity domain is out of the water stability domain.

Until now, the above discussion was made without integrating the presence of a disbonded coating with a hole where transport phenomena and chemical/electrochemical processes will affect the interface steel/trapped electrolyte (discussed in the following).

Mechanisms beneath disbonded coatings

Pipeline coatings may suffer from different types of degradation that can be due to improper application, damage during transportation and installation, or unexpected service conditions. Consequently, a coating disbondment (delamination, adhesion loss) occurs and can be further enhanced in the presence of cathodic protection (cathodic disbonding). While cathodic disbonding affects disbonded region geometry of all CP shielding topics, its mechanism is out of the scope of the present review and can be found elsewhere.^{53–55} Then, despite a coating disbondment, can we continue to have efficient CP in the crevice area?

According to Carpentiers et al.,⁵⁶ corrosion under disbonded coating started to receive attention in 1965. Most authors have tried to propose different chemical and electrochemical processes to explain stress corrosion cracking (SCC) and pitting failure cases.

Insufficient CP of the crevice area underneath the disbonded coating was pointed out as the main cause of failures. However, the absence of significant data from the field on the conditions at the crevice led to the development of two streams: laboratory tests simulating conditions and modelling studies. The mathematical models developed will be discussed in the next section.

Different laboratory set-ups were developed to study CP performance under simulated coating disbondment environments. The influencing factors were controlled such as coating defect size, crevice geometry, solution chemistry, CP parameters (current, potential), and water circulation rate. The characterization of local environmental parameters was possible for many authors including pH, oxygen, chlorides, potential/current (distribution).

Perdomo and Song⁵⁷ observed a corrosion protection in the crevice area despite the small flowing current. The extent of current flow was dependent on the solution resistivity and holiday/crevice size. Small crevices were affected faster by environmental change compared to the larger ones.

Li et al.⁵⁸ observed three facts with time: more uniform potential and current distributions, increase of crevice solution conductivity and depletion of oxygen. The experiments were conducted on steel polarized cathodically between -0.95 and -1.25 V vs SCE (located at the center of coating holiday) for 25 h in neutral diluted and ambient NaCl solution. The authors proposed a mechanism of CP protection against crevice corrosion in high resistivity solution including three steps: finite electrochemical protection stage, oxygen depletion stage and complete electrochemical protection stage. The three stages are affected by oxygen presence and chemical modification of the environment in the crevice.

Campaignolle et al.³² found that for a large (disbonding) crevice area, the corrosion risk was high especially when considering a circulation of the trapped solution contrary to its stagnancy. However, in the context of buried pipelines, circulation of the trapped solution is less expected unless the pipe is subject to a fluctuating water table situation and the disbonded coating gap geometry is significant. In this case, a cycling process develops a severe corrosive condition as demonstrated by Tan et al.²⁰ using interesting probes measuring corrosion under disbonded coating in field conditions.

Later Yan et al.⁵⁹ used a similar experimental set-up and included an additional microelectrode to monitor the pH, chlorides, and potential gradient. In addition to the chlorides exclusion from the crevice area, the obtained results confirmed the development of local protective chemical environment in the crevice area

which can be sustained for a certain period even after CP interruption. However, this work was conducted for a fixed crevice geometry.

Yan et al.⁶⁰ studied the deaeration effect through the bubbling of CO_2/N_2 in the crevice area and could establish the E-pH diagram to explore the potential risk of SCC on X70 steel. The local steel potential in the deep crevice location was independent of the applied CP potential measured at the crevice opening. According to the authors, the near neutral pH SCC risk must be considered, especially when with potential decay and when CO_2 is absorbed following the CP interruption. This study may be relevant for relatively acidic soils.

More recently, Wang et al.⁶¹ studied the effect of different crevice geometries on the potential gradient between the crevice mouth and further into the crevice. It was concluded that the potential drop is due to the crevice solution resistance and current dissipation. The effectiveness of CP to reach deep into the crevice was found to increase when the crevice increases in length and decreases in width. This is an indirect way to consider the volume of crevice solution and its effect on CP protection efficiency as expressed by Büchler.¹⁵

With simpler set-up associated with a pH microelectrode, Kuang and Cheng³⁰ assessed the CP permeability through two known coatings: FBE and HDPE. The methodology is like membrane studies where the counter electrode is placed on the top chamber and the working electrode (steel) is in the bottom chamber. The gap between the coating (membrane) and the steel represents the crevice area (Fig. 13).

The main finding of this study is the time dependence characteristic of CP permeability through FBE. This behavior was attributed to the molecular structure evolution assessed by FTIR spectroscopy. Further, more negative CP potentials seem to enhance the CP permeation only for FBE. HDPE was confirmed to shield CP current due to its very low water absorption even for an exposure duration of 30 days.

In more realistic conditions, some authors have investigated the effect of alternating current (AC) interference on CP shielding of disbonded coating. Kuang and Cheng⁶² performed a series of measurements in the laboratory to study this. At small (100 A/m^2) AC current densities, an enhancement of CP current permeation (steel potential shifting toward a more negative region) to the crevice was observed. However, an increase in AC current density favored corrosion product development, blocking the ionic diffusion and CP permeation.

In terms of localized corrosion in the case of CP and disbonded coating, Varela et al.⁶³ presented a differential aeration sensor (DAS) which allows for very useful electrochemical measurements (Fig. 14). For the first time, both anodic and cathodic currents were determined in the crevice area. Two different analysis methods (Faraday law and corrected currents) were used to estimate corrosion and its distribution. An improved corrosion estimation was observed in diffu-

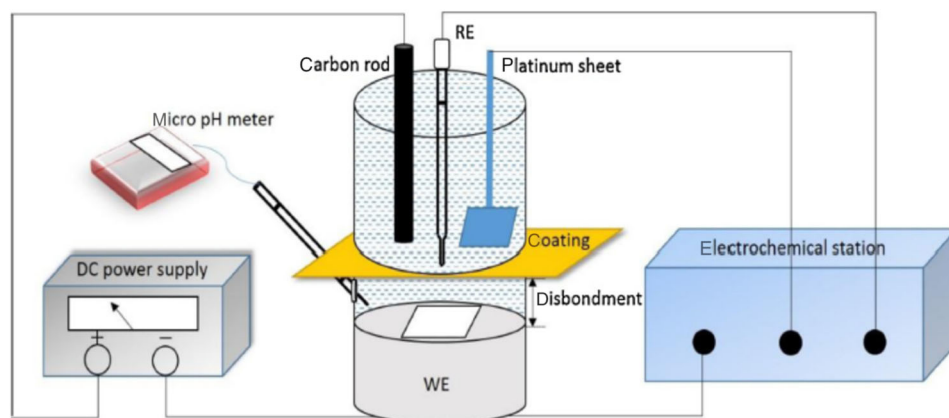


Fig. 13: Schematic diagram of the experimental setup to measure the permeability of coatings to CP³⁰

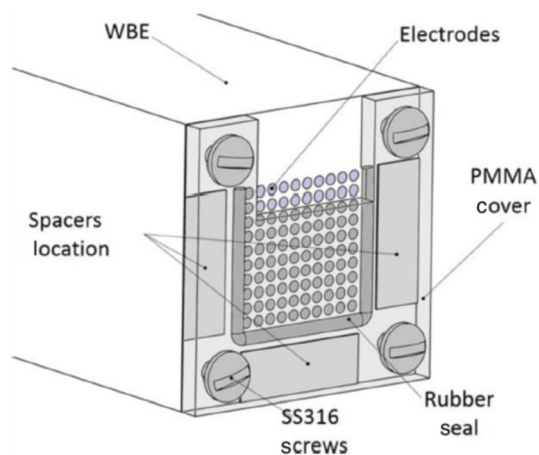


Fig. 14: Schematic illustration of differential aeration sensor (DAS)⁶²

sion control using the corrected currents method. In addition, this method allowed the estimation of corrosion patterns outside the crevice under CP. A good correlation between electrochemical calculations and surface profilometry results has been obtained.

Wang et al.⁶⁴ adopted the same sensor shown in Fig. 14 to study and visualize the effect of crevice gap geometry and water saturation level of the soil under disbonded coatings. In saturated soil, the behavior was like the one in electrolyte solutions, where crevice corrosion is mitigated by a CP-induced high pH environment and a concentration polarization mechanism. In nonsaturated soil, the crevice corrosion behavior changed significantly with coating disbondment gap size inducing a shielding condition to the CP current leading to a severe localized attack for a gap size of 1 mm. The CP current shielding condition was explained and demonstrated by the high resistivity of the nonsaturated soil.

Most of the cited studies offer some understanding of CP permeability for specific coatings but focused mostly on the crevice geometry. The role of coating thickness and its ageing, and exchange between crevice

solution with the surrounding environment have not been studied.

Modeling studies

Mathematical models to describe and predict the steel behavior underneath a disbonded coating in the presence of CP protection remain an old approach. Fessler et al.⁶⁵ proposed mathematical calculated current distributions in a simulated disbonded test cell filled with a bicarbonate solution. The results showed that the values of current going into the crevice were considerably smaller than the total cell current.

Fink et al.⁶⁶ tried to solve the equation of current distribution in a simulated disbonded test cell using Laplace's equation. For relatively high resistivity solutions, a sharp decrease in the current was observed and polarization was predicted due to low oxygen levels and high pH in the crevice area.

Song et al.⁶⁷ simplified their complex (2D) model to predict pipeline steel corrosion rate under a disbonded coating with or without CP. They could suggest expressions of the steel potential in the crevice area and the extent of CP current inside the crevice. The absence of oxygen data could be overcome by the consideration of the potential of the steel at the holiday, open circuit potential and the linear polarization resistance.

Allahar et al.⁶⁸ developed a model which predicts the potential drop within the delaminated region surrounding a coating holiday. The crevice area was assumed cylindrical and symmetrical. The potential drop was obtained through a mathematical model which consists of coupled, nonlinear, partial differential governing equations that describe transport (diffusion and migration) and electrochemical reactions (anodic and cathodic) within the delaminated region. The model demonstrated that the commonly used assumption that concentration gradients can be neglected in the delaminated region was not valid. However, the potential drop expression assumes a

fixed delamination gap thickness, holiday size, and applied potential. The authors recommended further development of their model including the consideration of pH-dependent hydrogen evolution reaction, water dissociation, and coating permeability to oxygen and ionic species.

One of the interesting recent models was developed by Song⁶⁹ where the chemistry, the steel potential and corrosion rate were predicted for a variable geometry crevice area. Indeed, previous modeling works were for a uniform crevice gap for simplicity which does not match well to the reality for underground coated pipelines. The corrosion within the crevice was treated in one dimension while the oxygen diffusion was considered in two dimensions. This was justified by the slowness of the oxygen diffusion compared to its reduction. The results show that a permeable coating behaves like a membrane. In fact, under a cathodic polarization at the crevice mouth the coating tends to raise the in-crevice sodium ion concentration and pH more rapidly compared to an impermeable coating. With time and as the sodium ion concentration and pH in the crevice become greater than at the mouth, the permeable coating tends to reverse the transport direction for ions. Such behavior was not mentioned in previous works and merits further investigation.

Wang et al.⁷⁰ developed a mathematical model to determine the evolution of chemical and electrochemical transient processes in the crevice under a disbonded coating from steel and in contact with a dilute NaCl solution. The obtained results showed a dependence between the extent of crevice corrosion and the crevice geometry. The corrosion was found to be influenced by the increase of crevice depth and decrease of its width. Oxygen depletion was observed in both CP presence and absence. However, pH values and conductivity of crevice solution increase with time. The potential gradient stabilizes with time and chlorides were found to show an initial decrease followed by an increase with crevice depth increase. Again, this type of model does not account for the transport phenomenon across the disbonded coating.

The same approach was adopted by Chen et al.⁷¹ with a (1D) transient numerical model assuming stagnant diluted NaCl solution. The oxygen depleted in one hour and a very high pH (11–12) was reached depending on the applied CP potential. Both the created electric field and electroneutrality induced the exclusion of anions out of the crevice and the migration of cations toward the crevice. This was found to increase the conductivity of the trapped solution with time and crevice distance.

All the above-mentioned models were developed to ascertain the risk of crevice corrosion under a disbonded coating and especially the localized corrosion risk. It must be mentioned that not all practical conditions were satisfied with these models. This is important due to the variation of crevice geometry, transport phenomena across/through the different

coatings, the effect of chloride and sulfate concentrations versus applied CP current, etc.

Discussion

As can be noticed from previous sections, the CP shielding remains a debatable issue until its mechanism is understood. While it is accepted as CP current limitation to reach some substrate areas undercoating, its development conditions and evolution in time are missing. Despite great efforts from scientists, CP shielding complex affecting factors have been studied in separate, short and incomplete way. However, the first aspect that should be highlighted from field experience is that coating disbondment does not always mean a CP shielding associated with corrosion scenario. While the field performance of FBE and 3LPE is quite clear, the one of field cold applied tapes remains incomplete to draw conclusions.

To determine whether corrosion will develop or not, spatiotemporal field data on the local environment under the different coating types, gap geometry (size) and facing different soil characteristics represent key information that will significantly help pipeline professionals.

Factors affecting this local environment include the disbonded region size, typical buried coatings (electrical and transport) data, and the extent of interfacial (chemical and biochemical) processes and their interaction with CP. All these processes need complete assessment with reliable noninvasive methods. Failure cases should be studied considering these factors for proper understanding which requires strong collaboration among specialists with different backgrounds.

Then, due to its multidimensional aspect, a holistic approach can be beneficial considering a Multiphysics modeling phase supported with input data that can be obtained experimentally. The Multiphysics modeling should include physical-chemical processes in soil, transport phenomena through coating, chemical/biochemical processes within the trapped microenvironment and interfacial electrochemical processes. Studying these phenomena with and without CP polarizations should bring several answers related to the CP shielding mechanisms. Also, it can either support the claim that CP shielding is responsible for buried pipeline failures or highlight some additional contributing processes. To achieve this, the use of noninvasive and reliable experimental methods that can be suitable for the various coatings discussed in this review remains a core research direction.

Conclusions

The aim of this review was to summarize previous research works and capture established field experience on the cathodic protection (CP) shielding by disbonded coatings on buried pipelines. The state of

the art combines all topic aspects including pipeline coatings, cathodic protection, coating disbonding and related modeling research efforts.

Buried pipeline coatings associated with CP are selected in different ways across the globe depending among others on the understanding of CP shielding. This was related to the CP performance in the case of disbonded coating. It has been observed that there seems to be a lack of complete study on the transport properties of the different coatings. This includes all mass transport parts such as diffusion, water uptake, and their impact on electrical conductivity. While it has been applied for a century, CP for buried coated pipes with defects was subject to recent revision to provide interpretation of some field and laboratory observations based on the famous Pourbaix diagram.

Under disbonded coating, the effectiveness of CP current and by which mechanism it can protect the steel pipe were explored in different conditions. However, the results are difficult to compare due to the variation in the experimental set-up which influences the findings.

Modeling efforts continue to provide predictions of the corrosion scenario under disbonded coatings at various cathodic protection conditions. However, the variation of the crevice solution and its interaction with mass transport across the coating are not considered.

The following are some important pending research questions that merit further investigation:

- Transport properties of the most common coatings for buried pipes need to be characterized for the long term in different disbonding and CP conditions. Coating structure evolution can also be tracked by spectroscopy.
- Steel depassivation conditions (oxygen, pH, chlorides, MIC) under disbonded coating remains not fully explored. Especially when this is related to the ionic species transport and interaction from the soil environment toward the crevice solution.
- Steel potential depending on the CP and chemical modification of the environment inside a variable crevice geometry can be further characterized using localized electrochemical techniques.
- The long-term evolution of the environment inside the crevice under disbonded coatings has not been investigated fully by some authors.
- Multiphysics dynamic models remain necessary to predict the CP performance or long-term corrosion scenario under disbonded coatings.

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References

1. Margarit, ICP, Mattos, OR, Ferreira, JRM, Quintela, JP, "About Coatings and Cathodic Protection Electrochemical Features of Coatings Used on Pipelines." *J. Coat. Technol.*, **73** 61–65 (2001)
2. "Standard Test Method for Cathodic Disbondment Test of Pipeline Coatings (Attached Cell Method)." ASTM G-95. ASTM, West Conshohocken, PA, USA (2021)
3. "Determination of Resistance to Cathodic Disbonding of Coatings Exposed to Seawater." ISO 15711 (2003)
4. "Cathodic Disbondment for Coated Steel Structures Under Cathodic Protection." NACE TM 0115. NACE International (2015)
5. Knudsen, O, Skar, J, "Cathodic Disbonding of Epoxy Coatings - Effect of Test Parameters." NACE paper N°08005 (2008)
6. Yang, Z, Allerton, D, "The Effects of Coating and Testing Variables on the Cathodic Disbondment of Protective Coatings." NACE Paper N°2609, (2013)
7. Werner, DP, Barlo, TJ, Coulson, K, "Shielding Effects of Concrete and Urethane Foam External Pipeline Coatings." PRCI Report PR-208-631 (1992)
8. Brossia, CS, Song, F, Sridhar, N, "Gap Analysis of Location Techniques for CP Shielding." PRCI Report, PR-015-03125 (2004)
9. NACE SP0169, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems." (2013)
10. Norsworthy, R, "Fusion Bonded Epoxy - A Field Proven Fail-Safe Coating System." Corrosion NACE, Paper N°06044 (2006)
11. Kehr, A, *How Fusion Bonded Epoxies Protect Pipeline: Single- and Double-Layer Systems*. Technology Publishing Company, Pittsburgh, pp. 13–22 (2012)
12. Buchanan, R, "A Critical Review of Industry Codes and Standards as they Relate to Electrically Resistive Coatings and What that Means to Shielding." Corrosion NACE, Paper N°2080 (2013)
13. Kuang, D, Cheng, YF, "Probing Potential and Solution pH Under Disbonded Coating on Pipelines." *Mater. Perform.*, **54** 40–45 (2015)
14. Norsworthy, R, Grillenberger, J, Jurgk, M, Heinks, C, "Locating Disbonded Coatings with EMAT Technology: Part-1." *Mater. Perform.*, **51** 40–44 (2012)

15. Büchler, M, “Effectiveness of Cathodic Protection Under Disbonded Coatings: on the Implications of Shielding Conditions on the Integrity of Pipelines.” *Pipeline Technology Conference* (2019)
16. Roche, M, Melot, D, Paugam, G, “Recent Experience with Pipeline Coating Failures.” *JPCL*, **23** 18 (2006)
17. “Polyethylene Coatings on Steel Pipes and Fittings - Requirements and Testing.” English Translation of DIN 30670-04 (2012)
18. Fernandez-Lagos, F, Maso-Mortera, J, Magana, CS, Lopez, MA, Padilla, J, Canto, J, Villamizar, W, Martinez-de Laescalera, LM, Ascencio, JA, Martinez, L, “Delamination Failure in a Three-layer Coating on a 24-in Gas Pipeline.” *Mater. Perform.*, **49** 38–43 (2010)
19. Heim, G, Schwenk, W, “Coatings for Corrosion Protection.” In: Baeckmann, WV, Schwenk, W, Prinz, W (eds.) *Handbook of Cathodic Corrosion Protection*, 3rd ed., p. 167, Elsevier Science (1997)
20. Tan, MYJ, Varela, FB, Huo, Y, “An Overview of Recent Progress in Probing and Understanding Corrosion Under Disbonded Coatings.” *Corros. Eng. Sci. Technol.*, **58** 323–332 (2023)
21. Latino, M, Varela, F, Tan, MYJ, Forsyth, M, “An Overview on Cathodic Shielding Produced by Disbonded Coatings.” *Corros. Prev.*, Paper N° 60 (2016)
22. Romano, M, Dabiri, M, Kehr, A, “The Ins and Outs of Pipeline Coatings: Coatings Used to Protect Oil and Gas Pipelines.” *A JPCL eBook*, Technology Publishing Company, p. 1, Pittsburgh, PA (2005)
23. Argent, C, Norman, D, “Fitness for Purpose Issues Relating to FBE and Three-Layer PE Coatings.” Corrosion NACE Paper N°05034 (2005)
24. Been, J, Given, R, Ikeda-Cameron, K, Worthingham, RG, “Factors Affecting the Rate and the Extent of Disbondment of FBE Coatings.” Corrosion NACE, Paper N°05138 (2005)
25. “Laboratory Evaluation of Seven Fusion Bonded Epoxy Pipeline Coatings.” Edmonton, Alberta, Canada: Alberta Research Council, December 23 (1998)
26. Eltai, EO, Scantlebury, JD, Koroleva, EV, “The Effect of Different Ionic Migration on the Performance of Intact Unpigmented Epoxy Coated Mild Steel Under Cathodic Protection.” *Prog. Org. Coat.*, **75** 79–85 (2012)
27. EN 62631-3-1, Dielectric and Resistive Properties of Solid Insulating Materials- Part 3-1-: Determination of Resistive Properties (DC Methods): Volume Resistance and Volume Resistivity- General Method (2016)
28. Larsson, KR, “Using Pipeline Coatings with Cathodic Protection.” *Mater. Perform.* **55** (1), 32–35 (2016)
29. Thompson, I, Saithala, JR, “Review of Pipeline Coating Systems from an Operator’s Perspective.” *Corros. Eng. Sci. Technol.*, **51** 118–135 (2016)
30. Kuang, D, Cheng, YF, “Study of Cathodic Protection Shielding Under Coating Disbondment on Pipelines.” *Corr. Sci.*, **99** 249–257 (2015)
31. Melot, D, Paugam, G, Roche, M, “Disbondment of Pipeline Coatings and Their Effects on Corrosion Risks.” *JPCL*, **1** 18–31 (2009)
32. Campaignolle, X, Meyer, M, Bernard, F, Karcher, S, Gastaud, S, “Organic Coatings Aging Consequences on Under CP Buried Pipelines Corrosion Protection—Simulated Defects.” Corrosion NACE, Paper N°04036 (2004)
33. Singh, R, *Pipeline Integrity Handbook: Risk Management and Evaluation*. Gulf Professional Publishing, Oxford, UK, p. 51 (2014)
34. Transportation Safety Board of Canada, Crude Oil Pipeline Rupture, Pipeline Investigation Report N P07 H0014 (2007)
35. Doddema, JF, “The Use of Visco-Elastic Self-healing Pipeline Coating.” Corrosion NACE, Paper N° 10042 (2010)
36. Meroufel, A, “Qualification of Cold Applied Tapes: Part 1.” *Mater. Perform.*, **59** 30–34 (2020)
37. Reeves, CR, “Pipelines Rehabilitation: Using Field Applied Tape Systems.” Corrosion NACE, Paper N° 615 (1998)
38. Moosavi, AN, “Advances in Field Joint Coating for Underground Pipelines.” Corrosion NACE paper N° 754 (2000)
39. Meroufel, A, “Water Transmission Pipeline Inspection Report.” SWCC (2016)
40. Neal, D, “Comparison of Performance of Field Applied Girth Weld Coatings.” *Mater. Perform.*, **36** (1) 20–24 (1997)
41. Norsworthy, R, “Addressing Soil Stress and CP Shielding by Using a Woven Geotextile Fabric Backed Tape System with a Rubber Modified Bituminous Compound.” Corrosion NACE Paper N° 769 (2000)
42. Wang, H, Lu, G, Feng, S, Wen, X, Yang, J, “Characterization of Bitumen Modified with Pyrolytic Carbon Black from Scrap Tires.” *Sustainability*, **11** 1–13 (2019)
43. Büchler, M, Ackland, B, Angst, U, *The Historic Evolution of Cathodic Protection Criteria*. CEOCOR, Slovenia (2016)
44. Angst, UM, “A Critical Review of the Science and Engineering of Cathodic Protection of Steel in Soil and Concrete.” *Corrosion*, **75** 1420–1433 (2019)
45. Martinelli-Orlando, F, Angst, U, “CP of Steel in Soil: Temporospatial pH and Oxygen Variation as a Function of Soil Porosity.” AMPP Paper N°16313 (2021)
46. Olesen, AJ, “AC Corrosion of Cathodically Protected Pipelines.” PhD Thesis, Technical University of Denmark (2018)
47. Calero, JC, Llorca, MAC, Terradillos, PG, “Influence of Different Ways of Chloride Contamination on the Efficiency of Cathodic Protection Applied on Structural Reinforced Concrete Elements.” *J. Electroanal. Chem.*, **793** 8–17 (2017)
48. Pourbaix, M, “Significance of Protection Potential in Pitting and Intergranular Corrosion.” *Corrosion*, **26** 431–438 (1970)
49. Ackland, BG, Dylejko, KP, “Critical Questions and Answers About Cathodic Protection.” *Corr. Eng. Sci. Technol.*, **54** 688–697 (2019)
50. Eslami, A, Kania, R, Worthingham, B, Boven, GV, Eadie, R, Chen, W, “Effect of CO₂ and R-ratio on Near-Neutral pH Stress Corrosion Cracking Initiation Under a Disbonded Coating of Pipeline Steel.” *Corr. Sci.*, **53** 2318–2327 (2011)
51. Javaherdashti, R, *Microbiologically Influenced Corrosion: An Engineering Insight*. Springer, Berlin (2008)
52. Jansen, S, Gerritse, J, Burgel, MV, Büchler, M, “Cathodic Protection and MIC-Effect of Local Electrochemistry.” Corrosion NACE Paper N° 9452 (2017)
53. Watts, JF, “Mechanistic Aspects of the Cathodic Delamination of Organic Coatings.” *J. Adhes.*, **31** 73–85 (1989)
54. Mahdavi, F, Forsyth, M, Tan, MYJ, “Understanding the Effects of Applied Cathodic Protection Potential and Environmental Conditions on the Rate of Cathodic Disbondment of Coatings by Means of Local Electrochemical Measurements on a Multi-electrode Array.” *Prog. Org. Coat.*, **103** (83–92) 55 (2017)
55. Bi, H, Sykes, J, “Cathodic Disbonding of an Unpigmented Epoxy Coating on Mild Steel Under Semi- and Full-Immersion Conditions.” *Corros. Sci.*, **53** 3416–3425 (2011)
56. Carpentiers, P, Gregoor, R, Pourbaix, A, “Corrosion Under Disbonded Coatings of Cathodically Protected Pipelines.” Eurocorr Paper N° 543 (2004)
57. Perdomo, JJ, Song, I, “Chemical and Electrochemical Conditions on Steel Under Disbonded Coatings: the Effect of Applied Potential, Solution Resistivity, Crevice Thickness and Holiday Size.” *Corr. Sci.*, **42** 1389–1415 (2000)

58. Li, Z, Gan, F, Mao, X, “A Study on Cathodic Protection Against Crevice Corrosion in Dilute NaCl Solutions.” *Corr. Sci.*, **44** 689–701 (2002)
59. Yan, MC, Wang, JQ, Han, EH, Ke, W, “Electrochemical Measurements Using Combination Microelectrode in Crevice Simulating Disbonded of Pipeline Coatings Under Cathodic Protection.” *Corr. Eng. Sci. Technol.*, **42** 42–49 (2007)
60. Yan, M, Wang, J, Han, E, Ke, W, “Local Environment Under Simulated Disbonded Coating on Steel Pipelines in Soil Solution.” *Corr. Sci.*, **50** 1331–1339 (2008)
61. Wang, W, Wang, Q, Wang, C, Yi, J, “Experimental Studies of Crevice Corrosion for Buried Pipeline with Disbonded Coatings Under Cathodic Protection.” *J. Loss Prev. Process Ind.*, **29** 163–169 (2014)
62. Kuang, D, Cheng, YF, “Effect of Alternating Current Interference on Coating Disbondment and Cathodic Protection Shielding on Pipelines.” *Corr. Eng. Sci. Technol.*, **50** 211–217 (2015)
63. Varela, F, Tan, MYJ, Forsyth, M, “Electrochemical Method for Studying Localized Corrosion Beneath Disbonded Coatings Under Cathodic Protection.” *J. Electrochem. Soc.*, **162** C515–C527 (2015)
64. Wang, K, Varela, FB, Tan, MY, “Probing Dynamic and Localized Corrosion Processes on Buried Steel Under Coating Disbondments of Various Geometries.” *Corr. Sci.*, **150** 151–160 (2019)
65. Fessler, RR, Markworthy, AJ, Parkins, RN, “Cathodic Protection Levels Under Disbonded Coatings.” *Corrosion*, **39** 20–25 (1983)
66. Fink, KM, Payer, JH, Savinell, RF, “Mitigation of Corrosion by Modification of the Environment Beneath Disbonded Coatings on Pipelines.” In: *Corrosion 93*, paper No. 578, NACE, Houston, TX (1993)
67. Song, FM, Sridhar, N, “A Two-Dimensional Model for Steel Corrosion Under a Disbonded Coating Due to Oxygen With or Without Cathodic Protection—Part 2: Model Simplification for Practical Application.” *Corrosion*, **62** 873–882 (2006)
68. Allahar, KN, Orazem, ME, “On the Extension of CP Models to Address Cathodic Protection Under Delaminated Coating.” *Corr. Sci.*, **51** 962–970 (2009)
69. Song, FM, “Predicting the Chemistry, Corrosion Potential and Corrosion Rate in a Crevice Formed Between Substrate Steel and Disbonded Permeable Coating with a Mouth.” *Corr. Sci.*, **55** 107–115 (2012)
70. Wang, W, Shen, K, Yi, J, Wang, Q, “A Mathematical Model of Crevice Corrosion for Buried Pipeline with Disbonded Coatings Under Cathodic Protection.” *J. Loss Prev. Process Ind.*, **41** 270–281 (2016)
71. Chen, X, Gao, F, Wang, Y, He, C, “Transient Numerical Model for Crevice Corrosion of Pipelines Under Disbonded Coating with Cathodic Protection.” *Mater. Des.*, **89** 196–204 (2016)

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