

**The effectiveness of cathodic corrosion protection under shielding
conditions: Disbonded factory applied coatings**

**Die Wirksamkeit des kathodischen Korrosionsschutzes bei Abschirmung:
Enthaftete Werksumhüllungen**

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Abstract

In the context of cathodic corrosion protection (CP), the shielding effect of delaminated coatings is often discussed. Particularly in the Anglo-Saxon countries, the use of non-shielding coating systems is required for certain pipelines. This is leading more and more to the displacement of coating systems based on polyethylene (PE). In recent years, the debate on shielding has also intensified in Central Europe, which is accompanied by the increasing marketing of so called non-shielding products. Since the use of coatings with significantly poorer dielectric properties is in contradiction to European practice, a detailed discussion of the topic is necessary. The relevant aspects are discussed with taking into account the work of Prof. Schwenk, the statements of DIN 30670:2012, today's understanding of the effectiveness of CP and the latest laboratory investigations.

Zusammenfassung

Im Zusammenhang mit dem kathodischen Korrosionsschutz wird oft die abschirmende Wirkung von enthafteter Umhüllung diskutiert. Insbesondere im angelsächsischen Raum wird für bestimmte Rohrleitungen der Einsatz von nicht-abschirmenden Umhüllungssystemen vorgeschrieben. Dies führt dort zunehmend zur Verdrängung der Umhüllungssysteme basierend auf Polyethylen. In den letzten Jahren wird die Diskussion in Bezug auf Abschirmung auch vermehrt in Europa geführt, was mit der zunehmenden Vermarktung von angeblich nicht-abschirmenden Produkten einhergeht. Da die Verwendung von Umhüllungen mit deutlich schlechteren dielektrischen Eigenschaften im Widerspruch zur mitteleuropäischen Praxis steht, ist eine vertiefte Diskussion der Thematik erforderlich. Die relevanten Aspekte werden unter Berücksichtigung der Arbeiten von Prof. Schwenk, den Aussagen der DIN 30670:2012, dem heutigen Verständnis der Wirkungsweise des KKS sowie neusten Laboruntersuchungen behandelt.

1. Introduction

The corrosion protection of pipelines in Central Europe is usually achieved by a high-quality coating with three-layer polyethylene (3LPE) in combination with cathodic corrosion protection (CP). This technical principle has an excellent track record with respect to corrosion protection. Despite the positive experience with the combination of high-quality dielectric coating and CP, discussions on the shielding effect of disbonded 3LPE coatings on the entry of protective current to the steel surface outside the German-speaking countries continue to take place. Reference is usually made to the importance of the adhesion of the coating, the disbonding by the so-called overprotection (see EN ISO 15589-1:2017) and the excellent dielectric properties of 3LPE. This discussion has led to fundamental differences in the corrosion protection concepts between North America and Central Europe. In the USA, for example, the use of non-shielding coatings is prescribed for certain pipelines (see DOT CFR 192.112). This leads to the use of comparatively thin (approx. 0.5 mm) Fusion Bonded Epoxy (FBE) coatings, which are generally described as non-shielding [1]. In addition, the use of comparatively thick (2.5 mm) 3LPE coatings has proven to be very effective in Central Europe, even though these have distinct insulating and shielding properties. Both coating systems achieve demonstrably good results in practical use, although the underlying concepts are very different. In particular, in Central Europe, despite the shielding of 3LPE coatings, hardly any damage is reported due to disbonded factory applied coatings. The current DIN 30670:2012 "Polyethylen coatings of steel pipes and fittings - Requirements and testings" describes the problem of disbonding and the resulting shielding as follows:

"Extensive investigations and practical experience have demonstrated that, regardless of the manufacturing method, disbondment of damaged polyethylene coatings can occur depending on the salinity of the soil water and the extent of cathodic polarization. However this involves neither an increased risk of corrosion (underrusting) nor an increase in the protective current density requirement in cathodic protection."

This description is fundamentally in contradiction with the non-shielding coatings required in North America. There are therefore fundamental differences in the choice of coating systems and the assessment of the risk of corrosion under delaminated coating between Europe and North America. Based on the current understanding of the effectiveness of CP, the relevant aspects are discussed and the good corrosion protection effect of CP under delaminated coating is explained.

2. Corrosion of steel under delaminated coating

The effectiveness of CP under disbonded coating was investigated in detail by Schwenk [2]. The results of laboratory tests are shown schematically in Figure 1 [2]. In the framework of the investigation, a loose PE coating with a defect was applied to a steel surface. The potential of the steel surface in the defect was potentiostatically controlled to $-1.1 V_{CSE}$. In addition, the IR-free potential was measured using a reference electrodes underneath the coating at distances of 20, 40 and 60 mm from the defect. It was shown (Figure 1) that, despite the dielectric properties of the coating, the protection criteria can also be achieved under the disbonded (shielding) PE coating. Shifting the control potential from $-1.1 V_{CSE}$ to $-0.92 V_{CSE}$ in the defect leads to a change in the potential under the coating. It is interesting to note that the abrupt change of the potential at the defect (0 mm) can still be detected at the reference electrode 20 mm below the coating. At 40 and 60 mm, however, the change in potential occurs only slowly.

The same effect can be observed with the subsequent shift of the control potential at the position of the defect back to $-1.1 V_{CSE}$. Schwenk draws the following conclusion from these observations [2]: "in the case of cathodic disbonding it was shown that cathodic protection in the crevice between disbonded coating and pipeline can be achieved". He concluded further: "However, in no circumstances is it advisable to remove non-adherent but still tightly attached coatings. Since an attached and sound coating cannot form an electrolyte filled volume even if the adhesion fails, the corrosion protection is still effective."

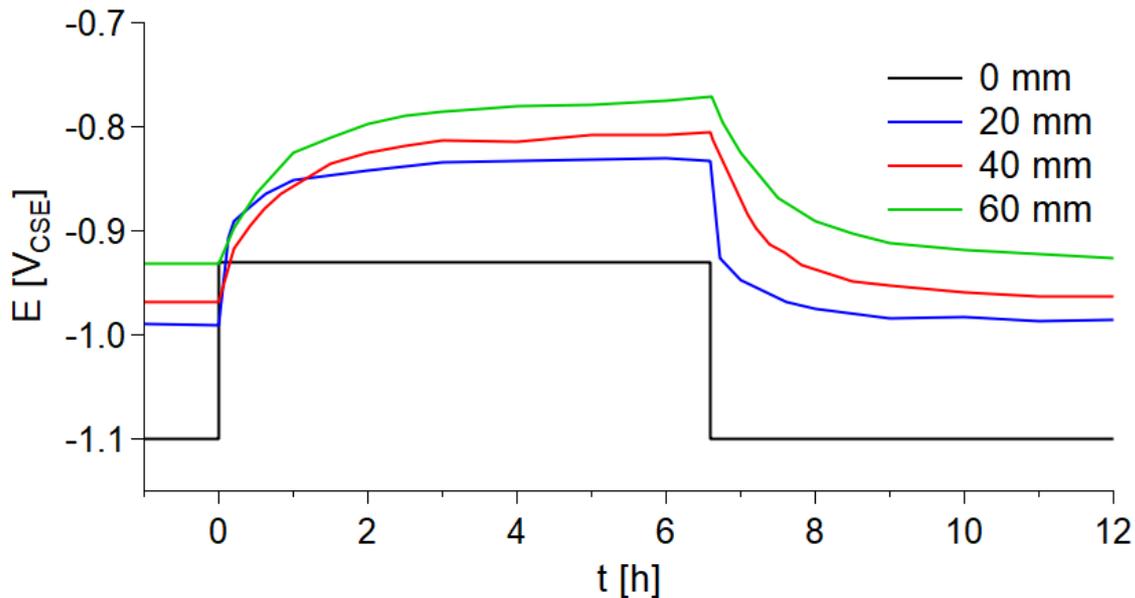


Figure 1: Influence of external polarization on potentials in the crevice between pipeline surface and disbonded PE coating according to [2]. The potential at the coating defect (0 mm) was controlled potentiostatically. The potential was measured at distances of 20, 40 and 60 mm from the coating defect underneath the coating.

In this context, the term "form stable coating" is often used. As long as the disbonded coating is tightly attached to the steel surface, there are no corrosion problems, as the steel is still separated from the surrounding soil and polarization is also possible in the very narrow crevice between the pipe surface and the (shielding) coating. According to the tests performed by Schwenk, it must be concluded that the shielding effect of the coating is not a question of the product, its electrical resistivity or its adhesion. Rather, only the geometry of the gap, meaning the tight fitting of the coating and the absence of a relevant electrolyte volume underneath the coating, is the prerequisite for non-shielding behavior. This conclusion fundamentally puts today's international perspective and the linking of non-shielding properties with specific product classes (FBE vs. 3LPE) in question.

3. The effectiveness of CP

For a consideration of the effects under disbonded coating it is essential to discuss the current state of knowledge on the effectiveness of CP as detailed in [3-5]. It is generally accepted that the effect of cathodic corrosion protection is based on polarization of the steel surface. According to EN ISO 8044:2015, the polarization caused by the cathodic current exhibits two contributions: Activation and concentration polarization. Immediately after the cathodic current is switched on, activation polarization builds up within milliseconds by current entry into the steel

according to von Baeckmann [6]. In this short period of time, no relevant changes in concentration can occur, so that the current entering the steel primarily causes a shift of the potential in negative direction till the limit of the water's stability domain (the equilibrium line for hydrogen evolution). This effect is shown in Figure 2 (a) with the blue arrows and the blue line (representing the zone of activation polarization) and in Figure 3 with the red arrow. Both, the increased oxygen reduction and the hydrogen evolution due to activation polarization, lead to an increase of the pH value at the steel/soil interface. According to von Baeckmann [6] from about 0.1 second onward, a concentration polarization is established. This concentration polarization leads to a shift of the IR-free potential along the equilibrium line for oxygen evolution. This concentration polarization is illustrated by the green arrow in Figure 3. Figure 2 (b) schematically illustrates this change in the concentration in the soil and the resulting passivation caused by the current entering the steel surface. As the resulting hydrogen bubbles have a pressure of approx. 1 bar, standard conditions may be expected. Therefore, a good agreement with the theoretically expected values is found experimentally [7]. The measurement of the IR-free potential, therefore, corresponds to a pH value measurement as discussed in detail by Angst et al [4]. Therefore, the protection criteria according to EN ISO 15589-1:2017 can be readily explained. An IR-free potential of $-0.85 V_{CSE}$ corresponds to a pH value of 9, which according to Figure 3 (yellow circle on the left) is just sufficient for passivity. An IR-free potential of $-0.95 V_{CSE}$ corresponds to a pH value of 10.5 (yellow circle in the middle), which allows for passivation even in aggressive soils. In contrast, an IR-free potential of $-1.2 V_{CSE}$ corresponds to a pH value of more than 13 (yellow circle on the right), which (according to DIN EN ISO 15589-1:2017) can lead to problems with the adherence of coatings due to overprotection.

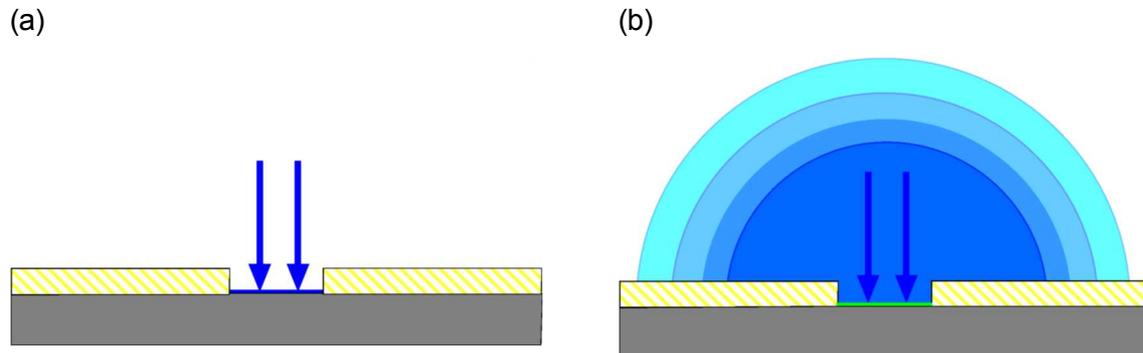


Figure 2: Schematic illustration of the effects of activation polarization (a) and concentration polarization (b). The current entry (blue arrows) causes a change in the potential of the steel surface (blue line) with pure activation polarization without a change in concentration, while with concentration polarization a depletion of oxygen and an increase of the pH value in the soil occurs. This zone with altered concentration conditions is represented by the blue-coloured semicircles, with the intensity of the blue coloring representing the relative strength of the change in concentration. Dark blue stands for high pH-value and strong oxygen depletion. The passive film that forms at an increased pH value is represented by the green line.

The importance of concentration polarization and the resulting passivation is nowadays generally accepted and also described in the relevant more recent standard text books on CP [8, 9]. The considerations with respect the depolarization after interrupting the cathodic current according to von Baeckmann make this clear [6]: The measurement of IR-free potentials between 0.1 and 1 second after the switching off the cathodic current cannot detect any

activation polarization, since depolarization is observed within one millisecond. According to von Baeckmann, if IR-free potentials or off-potentials of -0.95 , -1.0 or $-1.2 V_{CSE}$ are measured 1 second after interrupting the cathodic current in practical application, this can only be the contribution of concentration polarization. It follows from this, that the successful application of CP in the last 90 years was primarily based on concentration polarization, since only the increase in pH and the resulting passivation was measured and assessed with the usual measurement techniques.

This leads to an essential conclusion: The IR-free potential is not the primary cause for the corrosion protection, but is a consequence of the electrolytic conditions on the steel surface and is ultimately only a form of pH value measurement. This pH value measurement is influenced by oxygen. This explains the IR-free potentials of -0.75 and $-0.65 V_{CSE}$ in EN ISO 15589-1 in well aerated soils. Since these values can only be explained by the combination of an increased pH value and passivity [4], a conclusive picture of the processes under CP and the associated protection criteria is obtained. In particular, this puts into perspective the importance of the current entering the steel surface and the IR-free potential for the assessment of CP. It is essential to understand that concentration polarization of a steel surface does not require current entering the steel (at this very location). For the polarization of the steel by concentration polarization it is sufficient to change the concentration conditions in front of the steel surface. This will have important consequences for the discussion of the effectiveness of CP in the case of disbanded coating.

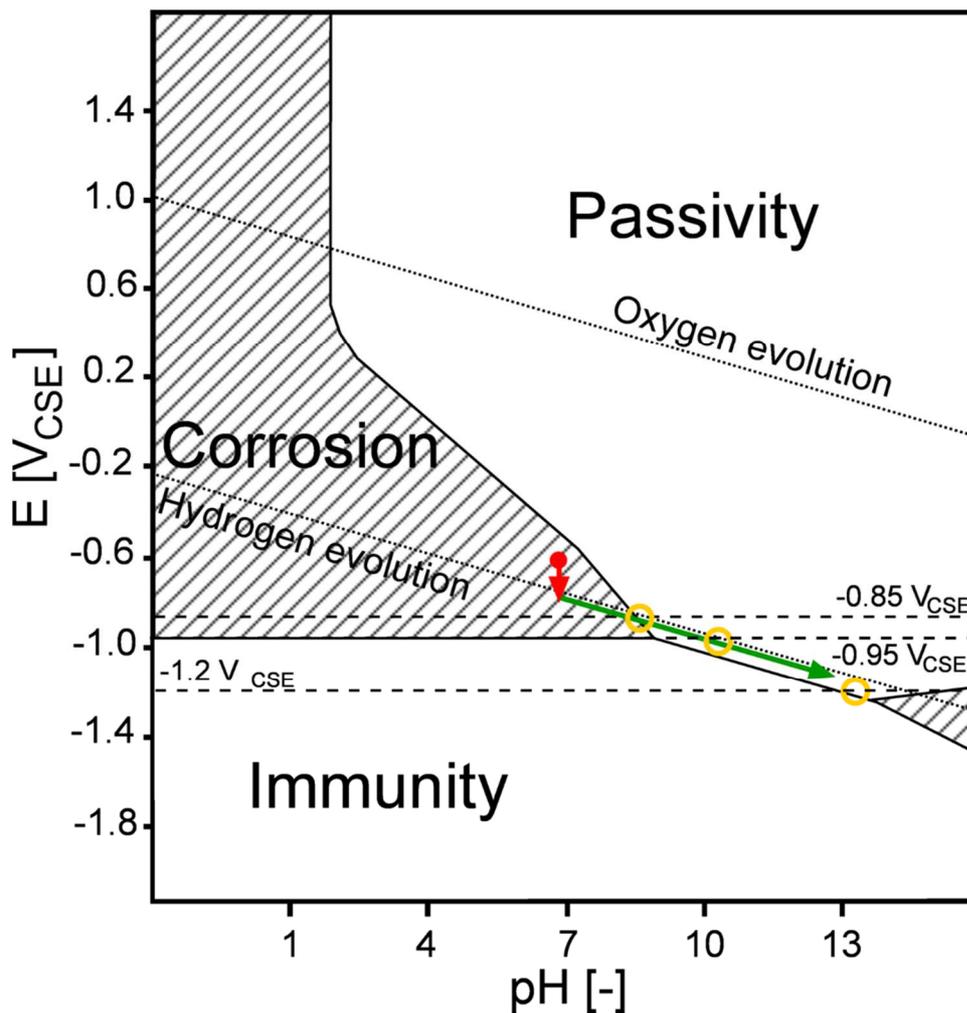


Figure 3: Polarization of steel with a cathodic current represented in the Pourbaix diagram [10]. The red arrow represents the contribution of activation polarization and the green arrow

represents the contribution of the much slower concentration polarization. The yellow circles show the location of the protection criteria according to EN ISO 15589-1.

4. Consequences for CP in the case of disbonded coating

When considering the situation in the case of an disbonded coating, it becomes clear that the current entering into the steel under the delaminated coating is severely impaired by the limited electrolyte volume and the resulting high ohmic voltage drop. This situation is shown in Figure 4 (a). This reduces the current flowing into the steel to the area of the defect as well as the immediate adjacent areas underneath the disbonded coating. This makes it clear that a polarization of the steel under disbonded coating based on activation polarization must be technically excluded. The current entry into the steel surface required for activation polarization is not possible. As already discussed at the beginning of this article, however, the entering current at the coating defect will lead to a depletion of oxygen and an increase of the pH value on the steel surface and in the adjacent soil. Due to diffusion, the concentration of oxygen and hydroxide ions will change over time, even under the disbonded coating. The depletion of oxygen and the increase of the pH-value can thus lead to concentration polarization of steel surfaces without a current entering at the polarized areas. This effect can be called "tele-polarization", because the current entry required for polarization occurs spatially separate from the location of polarization. Provided the exposure time is sufficiently long, the concentration polarization is expected to reach the same values for pH and oxygen concentration under the entire area with disbonded coating. This effect is illustrated by means of homogeneous blue coloration under the disbonded coating in Figure 4 (b).

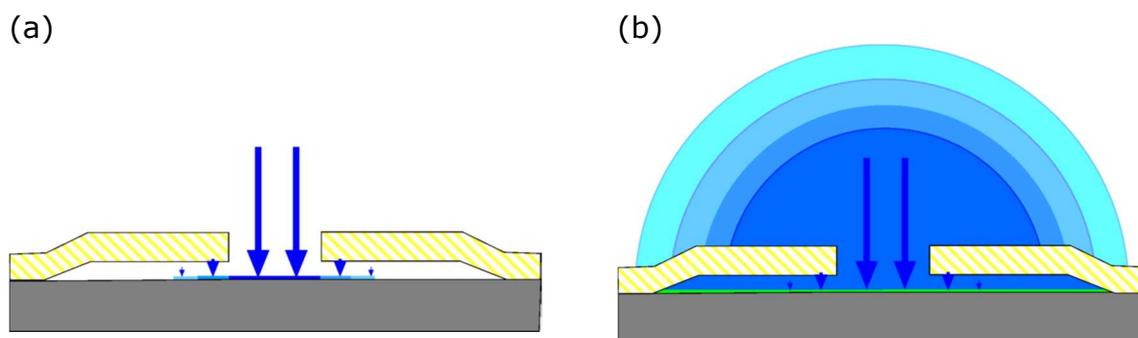


Figure 4 Schematic illustration of the effects of activation polarization (a) and concentration polarization (b) in the case of a delaminated coating. The current entry (blue arrows) does not cause any relevant polarization under the coating (blue line) in case of pure activation polarization. In contrast, the depletion of oxygen and the increase of the pH value in the area of the coating defect leads to a relevant change in the concentration conditions and passivation (green line) under the delaminated coating.

This consideration is in good agreement with the description of Schwenk of the polarization and protective effects of CP under disbonded coating [2] according to Figure 1. The change in the control potential (0 mm) did not cause an immediate change in the potential at a distance of 60 mm, as would be expected in the case of an activation polarization. Rather, a slow change of the potential is observed, which is to be expected in the case of a concentration polarization. This potential and pH-value change is faster in the vicinity of the defect due to the smaller diffusion distance. The experimental findings of Schwenk are, therefore, in good agreement with

the concentration polarization shown in Figure 3 and Figure 4 (b). This confirms the statements of DIN 30670:2012 with respect to the effectiveness of CP under disbonded coatings.

These results of Schwenk in Figure 1 and the interpretation based on concentration polarization are fully confirmed by recent studies of Yan et al. [11]. In a comparable test setup, the pH value under the coating was measured in addition to the potential. The control potential was reduced from $-0.85 V_{CSE}$ (during 10 days) to $-0.90 V_{CSE}$ (during 17 days) to $-1.0 V_{CSE}$ (during 31 days) and finally to $-1.2 V_{CSE}$ (during 54 days). Figure 5 shows the results for a coating of 3LPE (thickness 1.5 mm) and FBE (thickness 0.75 mm) for the sensors underneath the disbonded coating with a distance of 50 mm to the defect. The determined potential and pH-values were transferred directly into a Pourbaix diagram (analogue to Figure 2). It is shown that the polarization underneath the disbonded coating is proportional to the increase of the pH value, as it is expected for concentration polarization. This confirms that the measurement of the IR-free potential is equivalent to a pH measurement based on the hydrogen electrode [4]. In fact, a good correlation is found between the equilibrium line for hydrogen evolution and the measured values. In addition, the green arrow from Figure 3 is shown in Figure 5, which indicates the theoretically expected behavior in case of concentration polarization. The red circle marks the theoretically maximum possible concentration polarization, which was calculated by means of the of the numerical model validated in the context of the DVGW research project [7]. By entering the following experimental boundary conditions: on-potential ($-1.2 V_{CSE}$), AC voltage (0 V), electrolyte resistivity (approx. $6 \Omega m$), defect diameter (3 mm) and coating thickness (1.5 mm) in the numerical model (CP expert.exe) the following parameters were determined: IR-free potential of $-1.184 V_{CSE}$, pH value of 12.5 and current density of $1.8 A/m^2$. Additionally, the concentration polarization of $-1.057 V_{CSE}$ and an activation polarization of 127 mV as well as an ohmic voltage drop of 16 mV can be calculated. These values are in very good agreement with the experimentally determined data of Yan et al. [11]. The slight deviation is likely to be a result of the neglect of the current entry under the disbonded coating in the model calculation, which leads to slightly higher pH values. The case is calculated for the configuration in Figure 2 (b), whereas a slightly lower current density in the defect would actually be expected in accordance with Figure 4 (b).

The good correlation between the validated numerical model and the experimental data confirms once again its correctness and applicability for the evaluation of CP. However, it also clearly shows the importance of concentration polarization, pH value and passivation for the effectiveness of CP under disbonded coating. The present numerical model can be obtained as freeware [12].

In the discussion of the various influencing variables on the effectiveness of CP under disbonded coating, the electrical resistivity of the coating was not taken into account. In fact, the studies performed by Yan et al. [11] confirm that very similar behavior was observed for both FBE and 3LPE. This is in good agreement with the theoretical expectations. The findings, however, contradict the assessment of these coatings in the Anglo-Saxon countries, where the FBE is classified as non-shielding and the 3LPE as shielding. This illustrates the necessity of a detailed discussion of these terms and the associated protection mechanisms.

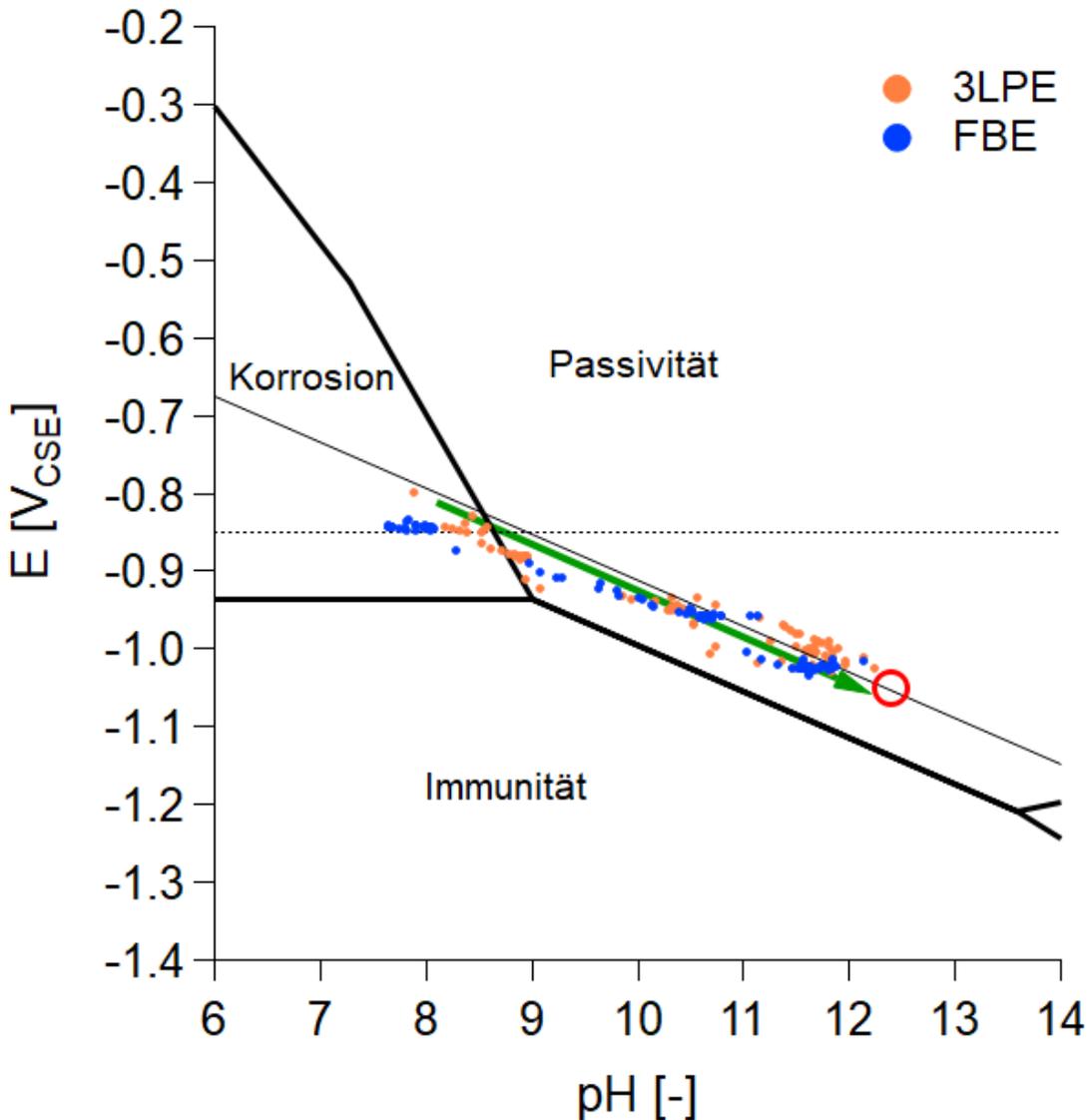


Figure 5: Polarization under a disbonded coating at a distance of 50 mm from the coating defect according to Yan et al. [11] for 3LPE and FBE. The control potential was -0.85, -0.90, -1.0 and finally -1.2 V_{CSE} . In addition, the theoretically possible concentration polarization under the coating at a control potential of -1.2 V_{CSE} is marked with a red circle.

5. Conclusion

The discussion of the relevant mechanisms based on the present understanding of the effectiveness of CP confirms the observation of Schwenk. The effectiveness of CP is achieved under a disbonded but tightly attached coating by means of concentration polarization. The steel is polarized without direct current entry by a change in concentration of oxygen and hydroxides. The protection criteria according to EN ISO 15589-1 can therefore be achieved even with a completely shielding coating. Due to the key relevance of concentration polarization, the statements of DIN 30670:2012 can be confirmed:

- The disbonding of the coating does not lead to corrosion under the disbonded coating, since the concentration polarization causes a depletion of oxygen, an increase of the pH-value and subsequent passivation.

- The disbonding of the coating does not lead to an increase in the protection current requirement, since due to the ohmic drop in the small electrolyte volume between the coating and the steel, no relevant current can be enter the steel surface under the disbonded coating. The coating acts as a shield for activation polarization. As a result, the protective current requirement is still dominated by the original defect size, even in the case of extensive disbonding. This typically comparatively small protective current is able to protect the often very large steel surface under the disbonding from corrosion by means of concentration polarization.
- The discussion of "shielding" properties of coatings is based on a fundamental misunderstanding of the relevant mechanism involved in cathodic protection. The shielding properties only apply to activation polarization, but CP works based on concentration polarization.

This discussion addresses the important aspects of the shielding effect of factory applied coatings based on 3LPE or FBE. The disbonded but still tightly attached coating based on 3LPE does not show any disadvantages due to the central importance of concentration polarization in relation to the effectiveness of CP, despite its significantly higher electrical resistivity. On the contrary, recent studies [3], have found that the better mechanical properties are an important advantage of 3LPE in the case of AC corrosion. In the case of AC voltage interference, the better shielding effect for activation polarization leads to higher allowable AC voltages.

6. Literature

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