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**The effectiveness of cathodic protection: A critical discussion of
protection criteria and threshold values**

**Die Wirksamkeit des kathodischen Schutzes: Eine kritische Diskussion
von Schutzkriterien und Grenzwerten**

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Abstract

In recent model calculations the physical-chemical significance of the IR-free potential was discussed. The relevance of the various threshold values of EN 12954 was demonstrated and the conditions for their application were explained. These considerations demonstrated clearly the importance of the mass transport processes and the increase of the pH value at the steel surface. On the one hand these results are compared to field data and on the other hand the significance of the parameters current density, pH value, and on-potential is investigated with respect to the evaluation of the effectiveness of cathodic protection. The methodology for determining these parameters and the possible corresponding threshold values are critically discussed. Based on this evaluation a new procedure for evaluating the effectiveness of cathodic protection is proposed.

Zusammenfassung

In Modellrechnungen wurde die physikalisch chemische Bedeutung des IR-freien Potentials diskutiert. Die Bedeutung der verschiedenen Grenzwerte der EN12954 wurde aufgezeigt und die Bedingungen für deren Anwendung erläutert. Diese Betrachtungen haben klar die Bedeutung der Stofftransportprozesse und der Erhöhung des pH-Werts an der Stahloberfläche gezeigt. Zum einen werden diese Resultate nun mit Daten von Felduntersuchungen verglichen und zum andern wird die Bedeutung der Parameter Stromdichte, pH-Wert und Einschaltpotential hinsichtlich der Bewertung der Wirksamkeit des kathodischen Korrosionsschutzes untersucht. Die Methodik für die Bestimmung dieser Parameter und die entsprechenden Grenzwerte werden kritisch diskutiert. Basierend auf dieser Auswertung wird eine neue Vorgehensweise für die Bewertung der Wirksamkeit des kathodischen Korrosionsschutzes vorgeschlagen.

1. Introduction

In the last years various investigations with respect to the cathodic protection (CP) have raised the understanding, that the pH is an important parameter in providing the corrosion protection [1-4]. In many cases relatively small protection current densities result in an increase of the pH-value at the steel surface of coating defects of pipelines. This increase of the pH favors the formation of a passive film, which significantly limits any further corrosion [2-4]. By means of model calculations, that are based on thermodynamic and kinetic data, all currently used protection criteria in CP can readily be explained when taking into account the relevance of the pH and the formation of a passive film [5-8]. Based on these considerations the mass transport at the steel surface is a key determining factor in the effectiveness of CP.

An increase of the pH-value at the steel surface can only occur, when the pipeline is bedded in fine sand and soil, or if the precipitation of calcareous deposits from water with increased hardness is taking place. Under these circumstances the convection of water at the coating defect will be limited and the hydroxide ions that are formed by the cathodic current entering the steel surface can only be transported by means of diffusion and migration. Hence the pH-value at the steel surface will increase. In the case of streaming and especially soft water, as it can be expected in rough bedding material, the generated hydroxide ions will rapidly be diluted. Alternatively the increase of the pH can be limited by the activity of sulfate reducing bacteria [1]. The increase of the pH-value and the formation of the passive film will not occur under these circumstances. The model calculations have resulted in the following conclusions for these two cases:

1. Limited mass transport due to bedding in soil and sand, or formation of calcareous deposits on coating defects:
 - The required current density for the increase of the pH-value and the formation of a passive film is in the range of 1 mA/m^2
 - After passivation of the steel a current density will establish that is determined by external parameters such as the on-potential, the diffusion limited oxygen reduction current and the spread resistance
 - In presence of passivity an IR-free potential more positive than any protection criterion does not have to be interpreted as corrosion
2. Fast mass transport due to contact with streaming and especially soft water or neutralization of the formed hydroxide ions due to microbial activity:
 - The corrosion protection is achieved by shifting the IR-free potential in negative direction
 - The required current densities are in the range of 1 A/m^2 or higher
 - IR-free potentials more positive than the protection criteria indicate corrosion

- Under typical operation conditions of CP it can be difficult to achieve protection of larger coating defects in higher resistive soil

These results demonstrate clearly the importance of mass transport and hence the bedding of the pipeline. An effective CP is very easy to achieve on a well bedded pipeline with limited mass transport. In contrast, in the case of bad bedding conditions and fast mass transport it can be very difficult to achieve a sufficient corrosion protection.

2. The mechanism of cathodic protection

2.1. Introduction

The model calculations provide a possible explanation for the relevant processes taking place at the steel surface under cathodic protection. In order to verify those concepts the key conclusions are compared to field data.

2.2. Comparison with field data

Investigations of CP and the related protection criteria were performed by Barlo in extensive field investigations. Coupons were cathodically protected under defined conditions during 5 years in Australia, Canada and the USA [9]. The corrosion rates and the IR-free potentials determined under these conditions are shown in Fig. 1. Clearly increased corrosion rates are observed on coupons with IR-free potentials more positive than $-0.95 V_{CSE}$. However, there are a large number of coupons, which do not show significant corrosion although the protection criterion was not met. This is in line with the expectations of the model calculations and the postulated significance of the mass transport conditions.

In Fig. 2 the dependence of the IR-free potential on the protection current density is shown. Clearly there is no correlation between the two parameters as expected based on the model calculations. As predicted for limited mass transport, protection can be achieved and maintained with very small current densities in the range of 1 mA/m^2 . Moreover, significant corrosion is observed in the case of current densities larger than 1 A/m^2 . This observation is in line with the model calculation for fast mass transport conditions and the experiments reported by Leeds [10] for soft water. In this case no sufficient increase of the pH at the steel surface will take place, the formation of the passive film will not be possible and no corrosion protection will be achieved. Based on the results in Fig. 2 significantly larger corrosion rates than $30 \text{ }\mu\text{m/year}$ are observed at substantial protection current densities. Nevertheless, the shifting of the IR-free potential to more negative values is expected to decrease the corrosion rate.

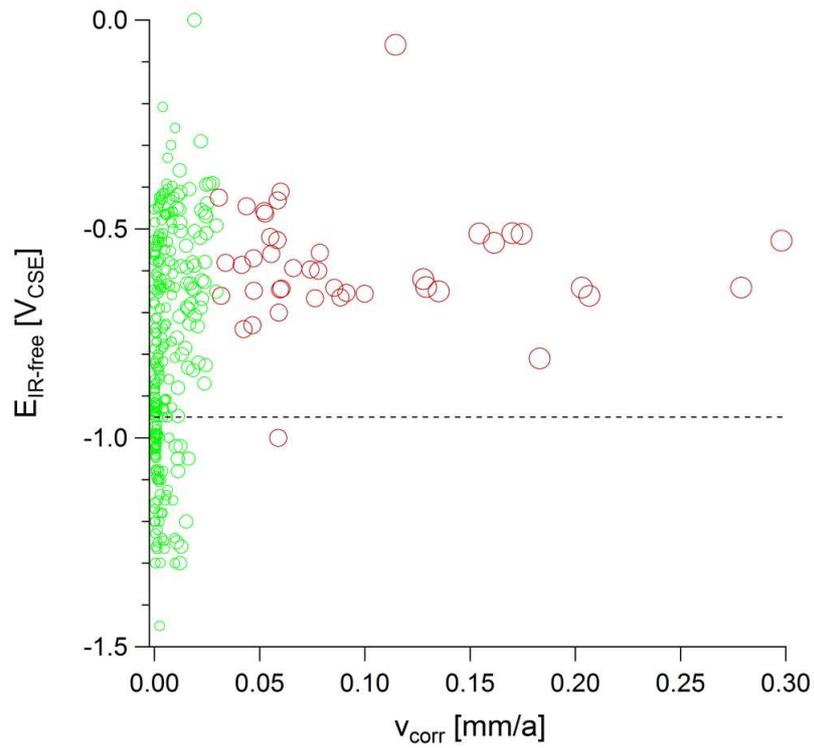


Fig. 1: Corrosion rate of the coupons plated vs. the IR-free potential [9]. Additionally, the protection criterion of $-0.95 V_{\text{CSE}}$ is shown.

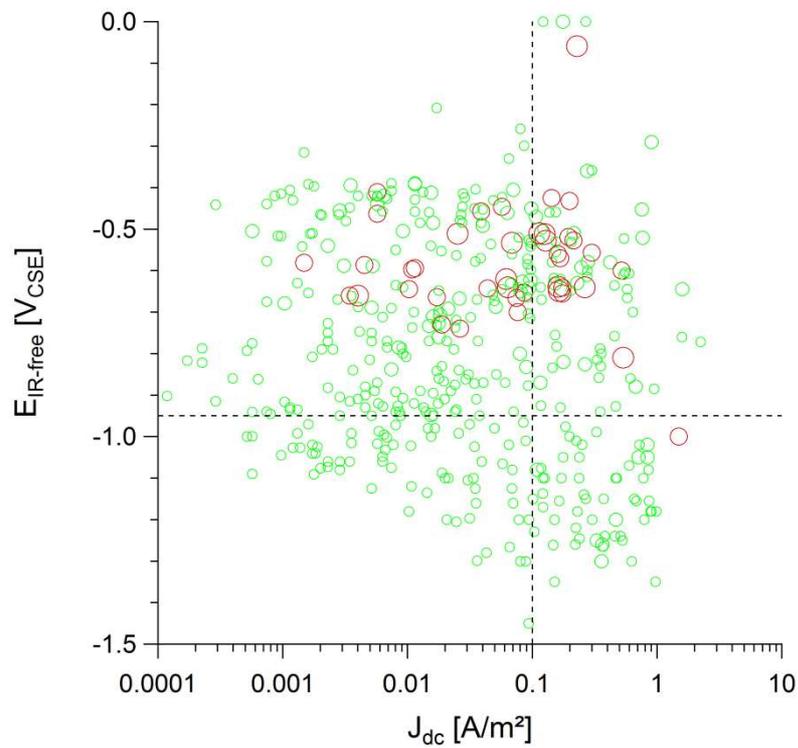


Fig. 2: IR-free potential plotted vs. the protection current density. Additionally, the protection criteria of $-0.95 V_{\text{CSE}}$ and the current density of 0.1 A/m^2 are shown. The corrosion rates are based on the size and color of the circles and can be determined from Fig. 1.

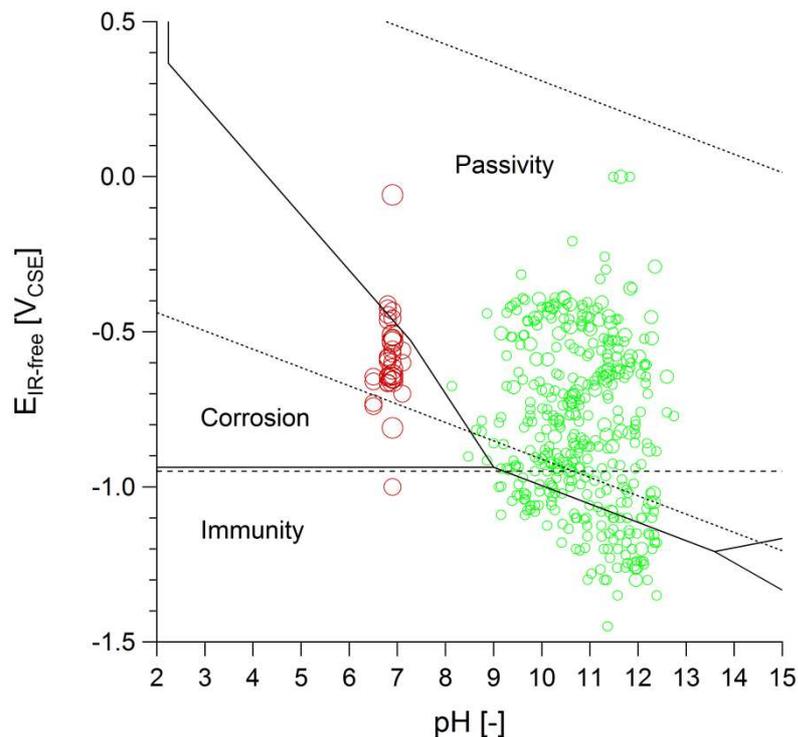


Fig. 3: Representation of the corrosion rate in the Pourbaix diagram. Additionally, the protection criterion of $-0.95 V_{CSE}$ is plotted as a dashed horizontal line. The corrosion rates are based on the size and color of the circles and can be determined from Fig. 1.

Based on the current densities the pH-values at the surface of the coupons were calculated with the numerical model [5-8] and the obtained values were plotted in the Pourbaix diagram [11] in Fig. 3. In the case of coupons with corrosion rates larger than $30 \mu\text{m}/\text{year}$, it was assumed that the pH-value did not increase due to the fast mass transport of hydroxide ions or bacterial activity. Hence the pH was arbitrarily assumed to be in the range of 7. Based on this consideration the pH-value represents a better explanation for the occurrence and absence of corrosion than the IR-free potential. This analysis confirms that the IR-free potential of $-0.95 V_{CSE}$ may be used for determining the presence of corrosion protection. However, it may not be used to draw any conclusion with respect to the occurrence of corrosion when it is not met. The analysis in Fig. 3 is based on an extensive field investigation with respect to the protection criteria.

In the last years field investigations were performed with respect to a.c. corrosion [12, 13]. They again confirm the results of the model calculations when the cases with critical a.c. interference based on EN 15280 are excluded from the consideration. Corrosion protection was achieved starting at protection current densities of $1 \text{ mA}/\text{m}^2$. Corrosion only occurred in combination of significant anodic currents. Anodic currents will decrease the pH, cause the activation of corrosion and lead to galvanic corrosion. In contrast to the results of Barlo [9] no corrosion was found as long as a cathodic current flow was observed. Based on the model concepts this would require well bedded coupons and limited mass transport conditions on the steel surface. Indeed the test requirements specifically asked for

an upward orientation of the coupon to prevent the creation of water filled voids and to ensure optimal bedding conditions of the coupons in soil.

2.3. Consequences

The available field investigations [9, 12, 13] confirm the predictions of the model calculations [5-8]. Hence, the mass transport conditions at the steel surface and the corresponding bedding of the pipeline have a key influence on the corrosion behavior. Based on these results care must be taken with respect to the bedding conditions during the construction of pipelines. In this view liquid soils or cement lining of the pipelines could exhibit significant advantages. The negative effects of cavities due to insufficient filling of the trench, due to setting of the soil or washing out of the bedding material should be limited. From the corrosion protection point of view critical conditions are especially expected in streaming soft water, in peat or in confined water filled spaces.

In contrast, in the presence of an ideal bedding of the coating defects, current densities larger than 1 mA/m^2 are expected to be sufficient for an increase of the pH and the passivation of the steel surface. Under these conditions the ohmic potential drop becomes negligible even in soils with increased resistivity [6, 7]. If these considerations are correct, the effectiveness of CP could be demonstrated based on an on-potential that is sufficiently negative (i.e. $< -1.2 V_{\text{CSE}}$) and the demonstration of limited mass transport at the coating defect surface.

based on the current understanding an effective corrosion protection can be expected, if the IR-free potential is more negative than $-0.95 V_{\text{CSE}}$. However, not met this criterion does not necessarily indicate corrosion as can be concluded from the results in Fig. 1 and Fig. 3. In those cases further conclusions with respect to the corrosion protection are possible in case of demonstration of the mass transport conditions.

3. Assessing the effectiveness of cathodic protection

3.1. Introduction

Based on the model calculations an improved understanding of the relevant processes taking place during cathodic protection is obtained. The key conclusions are in good agreement with field data. The mass transport at the steel surface is identified as a key controlling parameter demonstrating the importance of the bedding of the pipeline in well compacted backfill or the relevance of the formation of calcareous deposits. Considering the relevance of the mass transport conditions, a new measurement procedure is proposed and the relevance of the currently applied protection criteria is discussed in the following.

3.2. Measurement of the mass transport

It is well known that the increase of the pH at the steel surface and the migration as well as the diffusion of the hydroxide ions generated by the protection current at the steel surface will result in a decrease of the spread resistance of the coating defect (e.g. [14]). Additionally, it was demonstrated that the pH at the steel surface is dependent on the protection current density [2]. Since a shift of the on-potential will cause a change in current density, this will result in a change of the spread resistance of the coating defect over time in the case of a well bedded coating defect. It was found that a shift of the on-potential to more negative values will decrease the spread resistance, while a shift to more positive values will result in an increase of the spread resistance. The time constants of these effects are different, since in the first case migration is contribution to the mass transport, while in the latter it is primarily based on diffusion. Model calculations and considerations based on the Kirchhoff's second law demonstrate that a shift of the on-potential to more negative values will cause an increase of the voltage gradient measured at the soil surface. The corresponding experimental set-up is shown in Fig. 4.

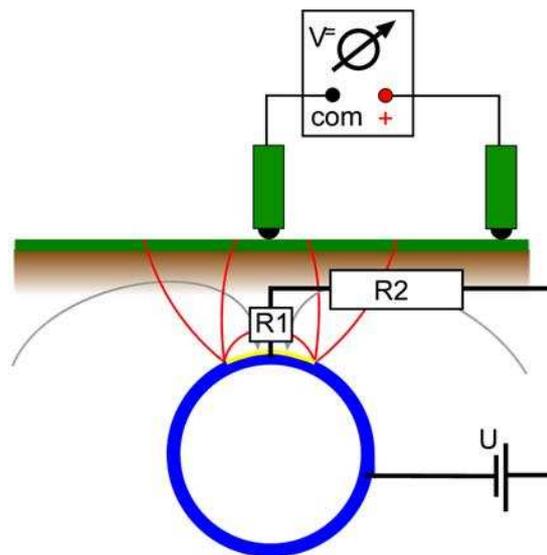


Fig. 4: Experimental set-up for the determination of the mass transport or the bedding conditions respectively at the coating defect surface.

Based on these considerations the determination of the bedding conditions is relatively simple. In the case of a well bedded coating defect a shift of the on-potential will cause a decrease of the spread resistance over time. When the on-potential is switched back to its original value a different spread resistance compared to the original one is expected, since the additionally generated hydroxide ions have decreased the spread resistance and will maintain the lowered spread resistance over a certain period of time. By means of two reference electrodes positioned on the soil surface the change of the spread resistance over time can be determined according to Fig. 4. At a given on-potential (versus remote earth) the voltage gradient measured over R2 will depend on the variation of R1 over time. The evaluation of the measurement is based on the following procedure:

- If changing the on-potential does not cause any change in the voltage gradient over time and the return to the original on-potential results in the originally measured gradient, no change in spread resistance and therefore no change in the pH distribution in the soil has occurred. This demonstrates the presence of potentially corrosive conditions. The additionally generated hydroxide ions were either neutralized or rapidly diluted in the environment.
- If, in contrast, a variation of the gradient is observed over time with changed on-potential, the hydroxide ions must have been accumulated at the steel surface and transported into the surrounding soil. This can only be explained with an increase of the pH-value at the steel surface. This is in line with favorable mass transport conditions or a well bedded coating defect.

Various measurements have so far confirmed the correctness of these considerations. Hence, the distinguishing of well bedded and poorly bedded coating defects should be readily possible. An important advantage of the proposed measurement procedure is the circumstance that the set-up in Fig. 4 is identical with the one for DCVG. Hence, after suitable optimization of the switching processes at the rectifier or their adaptation during the measurement, it should allow for both the localizing of the coating defects and the determination of their corresponding mass transport conditions. In case of stray current interference it may be useful to additionally record the a.c. voltage gradient and control the a.c. voltage on the pipeline. This may help to overcome the problems associated with variation of the on-potential over time. Based on the presented model concept it should therefore be possible to draw conclusions with respect to the effectiveness of CP based on the combination of the on-potential with a mass transport measurement.

3.3. Consequences with respect to protection criteria

The discussion with pipeline operators worldwide has shown strong variation of methodology, operation parameters, applied protection criteria and especially measurement techniques. Despite of these differences there is general agreement that CP is effective in controlling corrosion. There are still instances however, where corrosion was reported even with a CP that was considered to be effective. Usually the given explanations for these incidents are microbial influenced corrosion (MIC) and shielding. In the view of the above discussion and the practical experience it could be important to reconsider the criteria in EN 12954 or ISO 15589-1. The following aspects could be relevant in this discussion:

- Based on the field data of Barlo [9], it is not possible to systematically achieve a corrosion rate of 10 $\mu\text{m}/\text{year}$ and below. Instead a value of 30 $\mu\text{m}/\text{year}$ appears to be more realistic.
- Meeting the IR-free potential criterion of $-0.95 V_{\text{CSE}}$ demonstrates that an effective cathodic protection is achieved. However, not meeting this protection criterion does not necessarily indicate corrosion.

- The protection criteria of -0.75 and $-0.65 V_{CSE}$ were empirically determined on coupons bedded in sand and thus with limited mass transport. Hence, they may only be applied in cases with good bedding conditions of the pipeline. Using them to demonstrate the $10 \mu\text{m}/\text{year}$ in cases of unknown conditions at the coating defect surface could therefore be considered questionable.
- The use of a current density criterion could be difficult to justify unless the bedding conditions are known.

The EN 12954 or ISO 15589-1 can be read in a way that they promise a maximum corrosion rate ($10 \mu\text{m}/\text{year}$) in case of an effective CP. This could be understood as a guarantee that a pipeline protected by an effective CP system will not exhibit corrosion rates larger than this given value. However, if the implications of the bedding, mass transport, microbial activity and shielding are actually as discussed above, offering, installing and signing-off a CP system according to EN 12954 or ISO 15589-1 could be considered as a risk. This is due to the fact that these possibly crucial parameters are typically not known when the CP system is offered and can only be influenced when calcareous deposits can form after the commissioning of the CP system. Hence, making the promise of a maximum corrosion rate should be reconsidered if the influencing factors are as assumed. This problem is even more pronounced by the fact that these standards require the demonstration of the effectiveness of CP based on the measurement of the IR-free potential. While the measurement of the IR-free potential is possible based on an intensive measurement according to EN 13509, the application of this technique becomes more difficult with increasing levels of interference and increasing coating quality. As a consequence, it is very difficult to actually demonstrate that the requirements of EN 12954 or ISO 15589-1 are met on every coating defect.

Often the use of coupons or the measurement of the off-potential is proposed instead of the IR-free potential measurement on every coating defect. These methods inherently assume the presence of homogeneous conditions on all the coating defects. If corrosion is indeed only expected in the case of poor bedding conditions, its occurrence is also linked to heterogeneous conditions at the steel surface. So the key assumption for their application is homogeneity of the conditions and based on the above discussion corrosion is only occurring when heterogeneity is present.

3.4. What would a more adequate criteria look like?

It is out of question that CP is a technology that can be applied in order to improve the corrosion situation. Decades of successful application demonstrate this undoubtedly. There is worldwide agreement on this observation despite of significant variation in methodology, measurement techniques and criteria applied. A new set of criteria should reflect this variety and leave room for these different approaches. For this discussion it is therefore important to understand that cathodic protection can either be achieved by immunity or passivity. For achieving passivity it is crucial to have a well compacted backfill or calcareous deposits

forming on the coating defects allowing for an increase of pH directly at the steel surface. With this in mind the following proposals are made with respect to a possible next standard.

For coating defects with unknown mass transport conditions the following criteria should be applied allowing for the corresponding conclusion:

- $E_{on} < -1.0 V_{CSE}$: a cathodic current will be entering all coating defects on the pipeline
- $E_{off} < -0.95 V_{CSE}$: many coating defects are protected
- $E_{IR-free}$ on coupon $< -0.95 V_{CSE}$: The coupon and all coating defects identical to the coupon are protected
- $E_{IR-free}$ on coating defects $< -0.95 V_{CSE}$: all measured coating defects are protected
- Determining the mass transport conditions at the coating defect surface: This can justify to use the less restrictive criteria stated in the following

For coating defects with limited mass transport due to well compacted backfill or calcareous deposits, the following criteria could be used allowing for the corresponding possible conclusions:

- $E_{on} < -1.0 V_{CSE}$: all coating defects are protected
- $E_{off} < -0.85 V_{CSE}$: all coating defects are protected

While most of the above criteria are currently applied with generally good success, the identification of the possible conclusions that can be drawn from the measurement is considered relevant. This will help improving the conditions necessary for cathodic protection already in the construction phase of the pipeline. While these concepts appear to be in good agreement with theoretical considerations they will have to be critically tested in the field application.

4. Conclusions

The discussion of the mechanism of cathodic protection based on model calculations and the comparison of the obtained results with field data indicate that the mass transport is a key parameter. Since cathodic protection can only partially influence the mass transport in the case of the precipitation of calcareous deposits, care is required in the laying of the pipelines in order to provide the conditions required for corrosion protection. In order to improve the assessment of the effectiveness of cathodic protection, a new method for determining the mass transport conditions at the surface of coating defects is proposed. Based on laboratory investigation as well as field trials, the technique is capable of identifying the bedding conditions of given coating defect from the soil surface.

Based on these considerations a critical discussion of the currently used criteria is performed. This analysis confirms the significance of the IR-free potential of $< -0.95 V_{CSE}$ and leads to the suggestions of additional possible alternative protection

criteria. Before they may be applied, their critical discussion in combination with actual field testing and a general discussion on these aspects will be required.

5. Literature

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