An objective discussion of cathodic protection criteria based on literature data

Eine objektive Diskussion der Schutzkriterien für den kathodischen Korrosionsschutz basierend auf Literaturdaten

D. Joos and M. Büchler

SGK Swiss Society for Corrosion Protection
Technoparkstr. 1, CH-8005 Zürich,
markus.buechler@sgk.ch

Luxembourg 2017

Abstract

There is a relevant amount of literature data on corrosion rate measurements in the field under cathodic protection. They are analysed with respect to their capability in assessing the effectiveness of cathodic protection. The conclusions are discussed in the light of the most recent understanding on the involved mechanisms. Additionally the consequences on measurement techniques are presented.

Zusammenfassung

In der Literatur gibt es eine relevante Menge an Messdaten zur Korrosionsgeschwindigkeit unter kathodischem Korrosionsschutz in der Feldanwendung. Diese werden hinsichtlich ihrer Möglichkeit analysiert, die Wirksamkeit des kathodischen Schutzes zu bewerten. Die Schlussfolgerungen werden im Lichte des aktuellen Verständnisses der beteiligten Mechanismen diskutiert. Zusätzlich werden die Konsequenzen für die Messtechnik präsentiert.

1. Introduction

Since the first application of cathodic protection (CP) for mitigating corrosion on pipelines in 1928 by Robert Kuhn [1] the discussion of protection criteria has never ceased. The description of the historic evolution of the criteria has clearly shown that the relevance of concentration polarization and the associated pH increase was early recognized [2]. These aspects have received increasing importance in the context of AC and DC interference conditions, since it is not possible to agree on protection criteria unless there is a general agreement on the underlying mechanisms. In the present paper the focus is not on the mechanistic aspects associated with the corrosion and the corrosion protection process. Instead the two largest field investigations performed in North America and Australia [3] as well as Europe [4, 5] are analyzed with respect to the currently used protection criteria.

2. Protection criteria

2.1. Introduction

There is a number of protection criteria referenced in literature and standards. The available field data [3-5] is evaluated with respect to the ones further discussed in the following chapters.

2.2. IR-free potential

The IR-free potential (or polarized potential) has been widely accepted as a protection criterion and was incorporated in EN 12954 [6]. IR-free potential ($E_{IR\text{-}free}$) is the structure-to-electrolyte potential measured without the voltage error caused by the IR drop due to the protection current or any other current. Threshold values predominantly used in the practical application are -0.95 V_{CSE} and -0.85 V_{CSE}. The -0.95 V_{CSE} [7] and -0.85 V_{CSE} [8] thresholds are based on thermodynamic considerations. In contrast, the threshold values of -0.75 V_{CSE} and -0.65 V_{CSE} for conditions with increased soil resistivity were determined empirically [9]. These values are identical with those in ISO 15589-1. Also, it is important to note the fact that these values apply to the IR-free potential of the steel of individual electrodes or coating defects only. It may not be confused with the instant off-potential. The determination of the IR-free potential according to EN 13509 is only possible by means of the so called intensive measurement or with coupons.

2.3. Instant Off-potential

The instant-off potential is the structure-to-electrolyte potential measured immediately after interruption of all sources of applied cathodic protection current. It is often used as an approximation of the IR-free potential. However, it must be clearly stated that according to EN 13509 this simplification may only be made when there are no equalizing currents (such as in the case of a coupon). The source of the equalizing currents involves multiple factors. For example, different geometry and different soil conditions at various coating defects will result in different current densities and, therefore, different IR-free potentials of the individual electrodes. When interrupting all sources of cathodic protection current, equalizing currents will establish due to the different IR-free potentials at the various coating defects. These currents will cause IR-drops that are often significant.

The instant-off potential of a structure only corresponds to the IR-free potential if it can be assumed that all electrodes of that structure are identically polarized. Naturally, this assumption is generally not fulfilled. Although used in many countries, the applicability of the instant off-potential, as an approximation of the IR-free potential, is still subject to debate, because it represents a relevant deviation from the requirements of EN 12954, ISO 15589-1 and EN 13509.

All these limitations prevent the use of the instant off potential as a valid criterion. The detailed discussion of the related implications has resulted in the following possible interpretation that can be drawn from an instant off-potential [10] without further information on the bedding conditions of the pipeline: An instant off-potential of a cathodically protected pipeline more negative than –0.95 V_{CSE} allows the conclusion that many coating defects are protected.

2.4. On-potential

The on-potential was originally introduced by Kuhn in 1928 [1] in combination with a threshold value of -0.85 V_{CSE}. He identified the galvanic corrosion among differently aerated coating defects as the reason for the high corrosion rates. Kuhn’s theoretical considerations were that the natural potential of steel electrodes in soil cannot be more negative than -0.85 V_{CSE}. Applying an on-potential more negative than -0.85 V_{CSE}, therefore, results in a current entering into all electrodes and thus ensures the compensation of these galvanic couples and a strong limitation of the corrosion process. Based on the above discussion his conclusion was technically sound and correct. The work of Schwerdtfeger and McDorman [11] has clearly shown that the IR-free potential ($E_{IR\text{-}free}$) of a steel surface corroding even under anaerobic conditions is always more positive than -0.85 V_{CSE} unless the pH is increased above 9. In most electrolytes such an increase of pH is sufficient for passivation. Based on equation (1) it must therefore be concluded that any on-potential more negative than -0.85 V_{CSE} is bound to result in a cathodic current (I) on an individual coating defect. This conclusion is independent on the spread resistance R and hence the soil resistivity.

$$I = \frac{E_{IR-free} - E_{on}}{R} \qquad (1)$$

Based on literature [12] the current density for achieving pH 9 and hence passivation is as small as 1 mA/m^2 in the case of hindered mass transport and concentration polarization. At this current density negligible ohmic drop will be obtained even with large coating defects and increased soil resistivity. This explains the good success of Kuhn's criteria based on an on-potential and underlines its technical relevance. The on-potential has been widely used for assessing the effectiveness of cathodic protection. It is still the primary protection criterion in EN 14505. According to EN 14505, a threshold value of -1.2 V_{CSE} is required for a soil resistivity less than 100 Ωm. The on-potential is also included in NACE SP0169 with respect to a threshold value of -0.85 V_{CSE}; however, with the comment that the IR drop needs to be considered. In [10] a value of -1.0 V_{CSE} for the on-potential is used to conclude that a net cathodic current is entering all coating defects.

2.5. 100 mV cathodic polarization

The shift of 100 mV cathodic polarization criterion is described in NACE SP0169 and ISO 15589-1. The criterion is based on the fact that a shift of the IR-free potential to more negative values decreases the corrosion rate. With a shift of 100 mV a decrease of the corrosion rate by a factor of 10 can be expected. This effect is empirically demonstrated by von Baeckmann [6]. This concept requires homogeneous electrodes, which is also the case for the instant off-potential criterion.

This effect is considered in ISO 15589-1 by limiting its application to homogeneously polarized cases. According to ISO 15589-1 the application of the 100 mV polarization criterion should be avoided at higher operating temperatures, in soils containing SRB, or with interference currents, equalizing currents and telluric currents. These conditions should be characterized prior to using this criterion. Furthermore, the criterion should not be used on structures connected to or consisting of mixed metal components. Many countries do not measure this criterion because the expectation and assumptions indicated above are not likely met and sometimes unfeasible. This is the reason for the absence of this criterion in the EN 12954.

3. Experimental

The evaluation of the protection criteria is based on the extensive literature data collected in field tests [3-5]. Since there are some relevant differences in the corresponding testing conditions the experiments shall be shortly described.

The field tests performed by Barlo in North America and Australia [3] are based on rod shaped coupons with a surface area of 18.2 cm^2 that were vertically installed in 14 locations and cathodically protected by individual rectifiers operating at various settings. The rectifiers were installed to just protect the experimental setup and were independent on pipelines. Five years after installation they were excavated and analyzed with respect to metal loss. The potential readings were taken manually.

In contrast the field test in Europe [4, 5] was based on equipping at least 3 locations on seven major transport pipelines with two 1 cm^2 (3x33 mm) electrical resistance (ER) probes that allowed for continuous monitoring of the corrosion rate. By changing the on-potential a number of operation conditions were tested. The IR-free potentials were determined by means of measurement of the spread resistance R on the bases of the AC voltage as well as the AC current. Then the IR-drop was calculated based on the DC current and subtracted from the on-potential. Based on the internal filtering of the instrument it can be assumed that this corresponds to an IR-free potential measurement at least as fast as 0.1 seconds after interrupting the current. The reported data are based on averaged data over a period of at least one week. The test set-up was designed in order to investigate AC corrosion. All corrosion data that showed current densities exceeding the requirements of ISO 18086 were not considered in this evaluation, since the focus was on the CP protection criteria rather than on AC corrosion. Most recent results demonstrate the relevance of the bedding conditions [10]. It is relevant to note that the coupons in the German field tests were installed oriented upward by an angle of 45 degrees assuring permanent and reliable contact to soil. This is in contrast to the field tests of Barlo, where setting soil can cause a loss of direct contact between soil and steel, causing poor bedding conditions.

4. Results

4.1. The current density

Cathodic protection is based on a current entering into the coating defect. As a consequence, the key requirement is a net cathodic current on every single coating defect. If this requirement is not fulfilled any further discussion of cathodic protection effectiveness is obsolete. In Figure 1 the dependence of the current density from the on-potential is shown. It is clear that cathodic currents are obtained over a wide range of on-potentials. A more careful analysis of the available field data, however, demonstrates that cathodic currents can only be guaranteed when the on-potential is more negative than -0.85 V_{CSE}. It is relevant to note that this is independent on the soil resistivity as expected based on equation (1). As a consequence a value of -1.0 V_{CSE} for the on-potential, that ensures a net cathodic current on all coating defects, as concluded by Angst et al. [10], is a conservative approach.

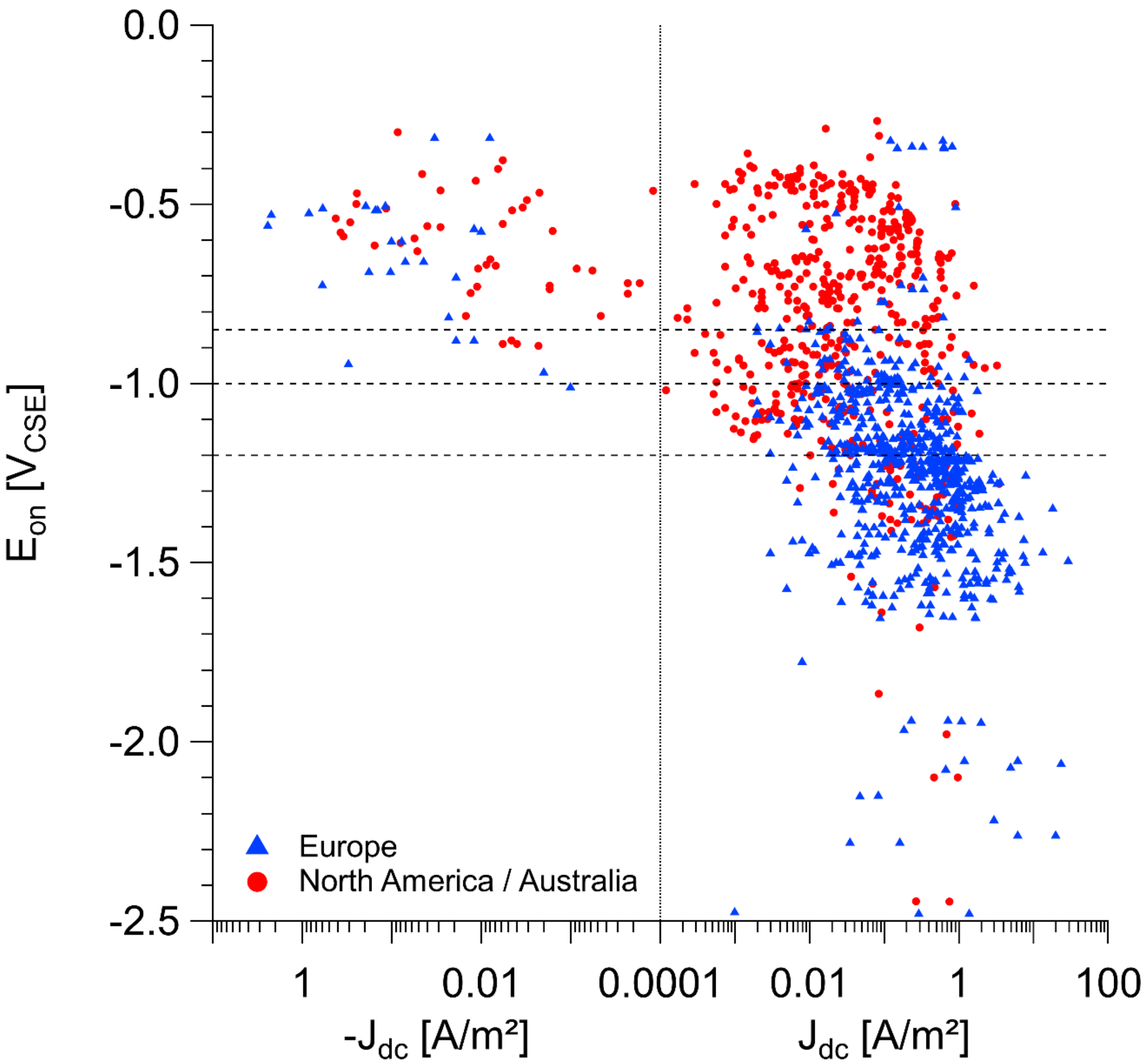

Figure 1: Relation between on-potential (E_{on}) and current density (J_{dc}). Cathodic current has a positive sign.

Based on these data operating a CP system at on-potentials more positive than -0.85 V_{CSE}, represents an important corrosion risk. In the case of time variant on-potentials, as it may be the case of DC interference, a net average cathodic current can be assured if the average on-potential is more negative than -0.85 V_{CSE} [4, 5].

4.2. The IR-free potential

In Figure 2 the dependence of the corrosion rate on the IR-free potential is shown. As discussed in [10] there is no correlation between the IR-free potential and the corrosion rate. This is due to the fact that the IR-free potential is irrelevant for assessing the corrosion situation of a passive steel surface [13]. Instead it has been demonstrated that the IR-free potential measurement corresponds to a pH-measurement that is influenced by the oxygen in the soil [10]. In all the cases where the IR-free potential is more negative than -0.95 V_{CSE} a sufficient increase of the pH beyond pH 10.5 is achieved that ensures corrosion protection even in aggressive soils. If, however, a more positive value is determined it is not possible to draw any conclusions with respect to the corrosion situation. It is possible that the steel is actively corroding at relevant rates in the presence of MIC or in poor bedding conditions, where the pH cannot increase. Alternatively the steel can be passive and the pH measurement based on the IR-free potential is compromised by the oxygen at the steel surface.

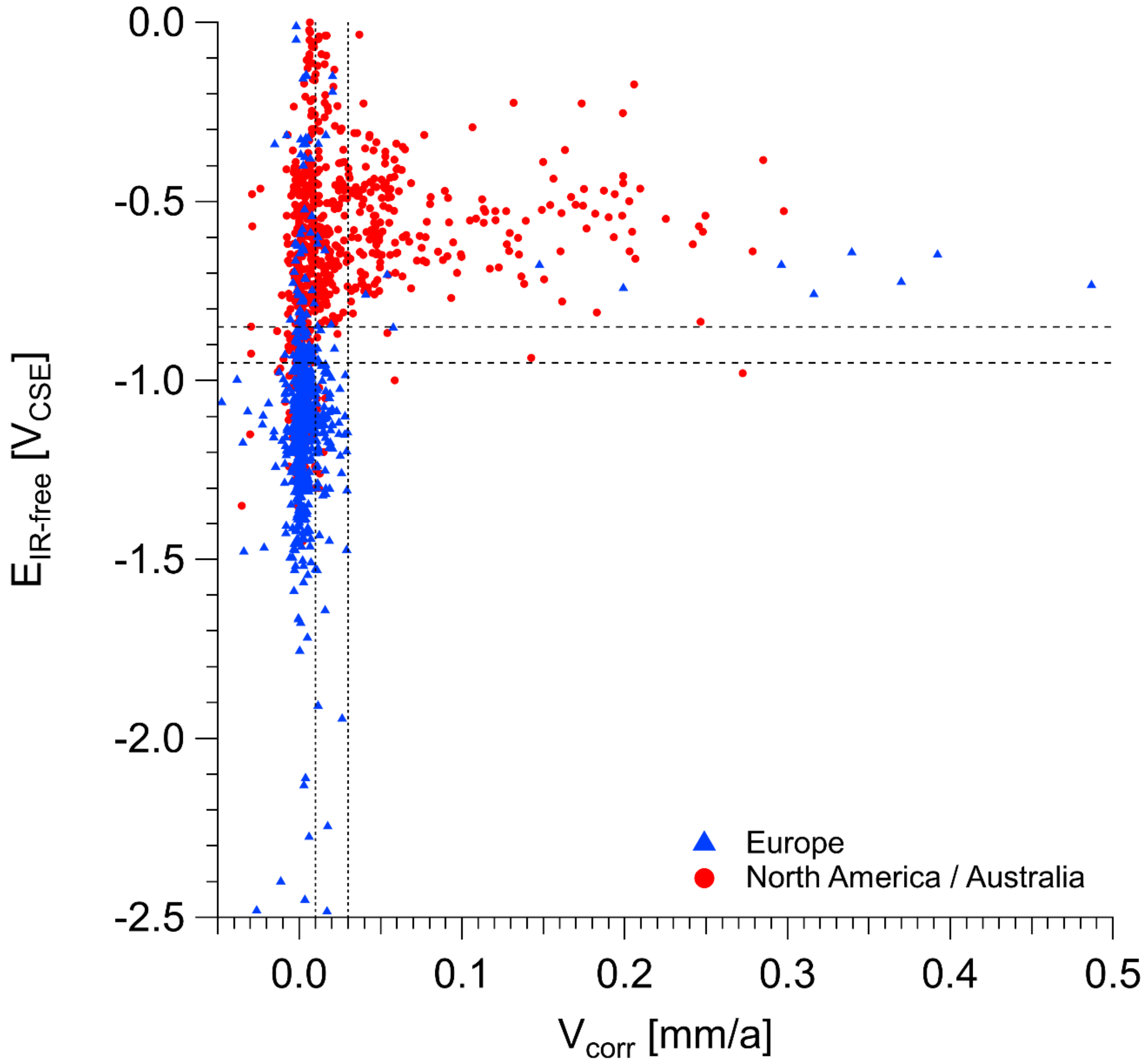

Figure 2: Relation between IR-free-potential ($E_{IR-free}$) and corrosion rate (v_{corr}).

It is relevant to note that there was one case where the IR-free potential value was met, but the corrosion rate is relevant. Interestingly, the current density in this case was 1.5 A/m², which normally is assumed to be sufficient to provide protection. Based on the discussion in [10] this behavior is expected for conditions that do not allow an increase of the pH at the steel surface. Indeed Leeds [14] reported the need of IR-free potentials more negative than -1.0 V_{CSE} in poor bedding conditions. A different case, where relevant corrosion rate occurred although the IR-free potential value was met, was one, where the on-potential was more positive than the IR-free potential, which was -0.98V_{CSE}. There is field and laboratory data that shows relevant corrosion at IR-free potentials more negative than -0.95 V_{CSE}. This puts the plausibility of ISO 15589-1 in question.

A more careful analysis of the available field data shows clearly that it is not possible to justify the maximum corrosion rate of 0.01 mm/year in case of effective cathodic protection as stated in ISO 15589-1. Instead, corrosion rates of up to 0.02 mm/year are observed in the case of the data reported by Barlo. In the case of the European field tests the corrosion rates range up to 0.03 mm/year, which is probably a result of the increased levels of AC interference. These data show that ISO 15589-1 should be reconsidered.

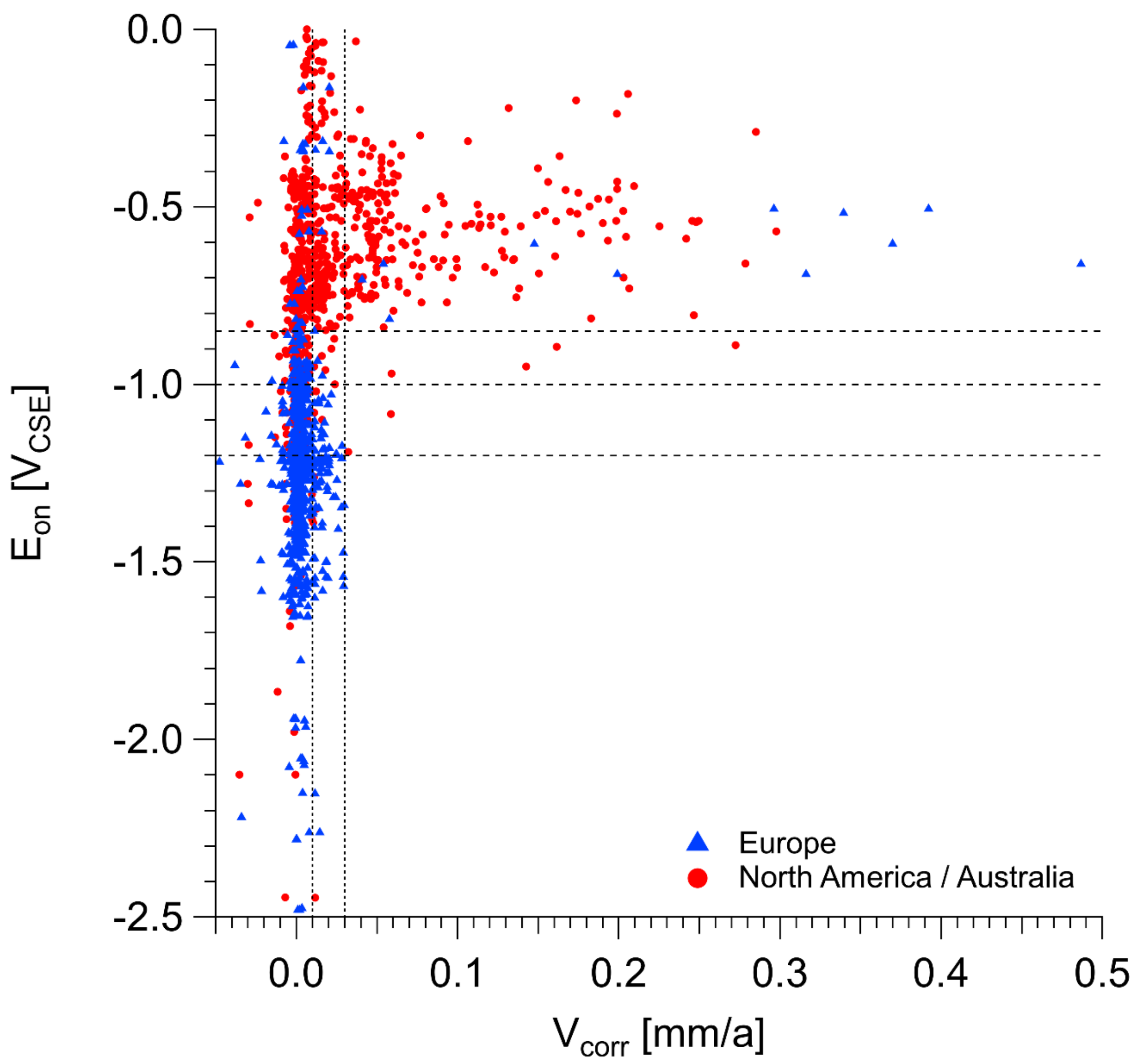

Figure 3: **Relation between on-potential (E_{on}) and corrosion rate (v_{corr}).**

4.3. On-potential

In Figure 3 the dependence of the corrosion rate on the on-potential is shown. It is evident that sufficiently negative on-potentials ensure corrosion protection. Applying the threshold of EN 14505 of -1.2 V_{CSE}, is sufficient to ensure corrosion rates as small as 0.03 mm/year in both field tests. Applying the value of -1.0 V_{CSE} proposed in [10] to ensure current entering all coating defects there is decrease of the corrosion rate below 0.03 mm/year in most cases. Only the coupon relevantly corroding at 1.5 A/m^2 at an IR-free potential as negative as -1.05 V_{CSE} cannot be excluded with an on-potential of -1.0 V_{CSE}. In contrast, all the well bedded 1 cm^2 ER-probes in the European field test show corrosion rates smaller than 0.03 mm/year even if the on-potential averaged over 24 hours is just more negative than -0.85 V_{CSE}. These data are nicely in line with the discussion in [10]: If the bedding conditions allow for an increase of the pH at the steel surface an on-potential more negative than -1.0 V_{CSE} ensures protection.

4.4. 100 mV cathodic polarization

In Figure 4 the dependence of the corrosion rate on the 100 mV depolarization criterion is shown.

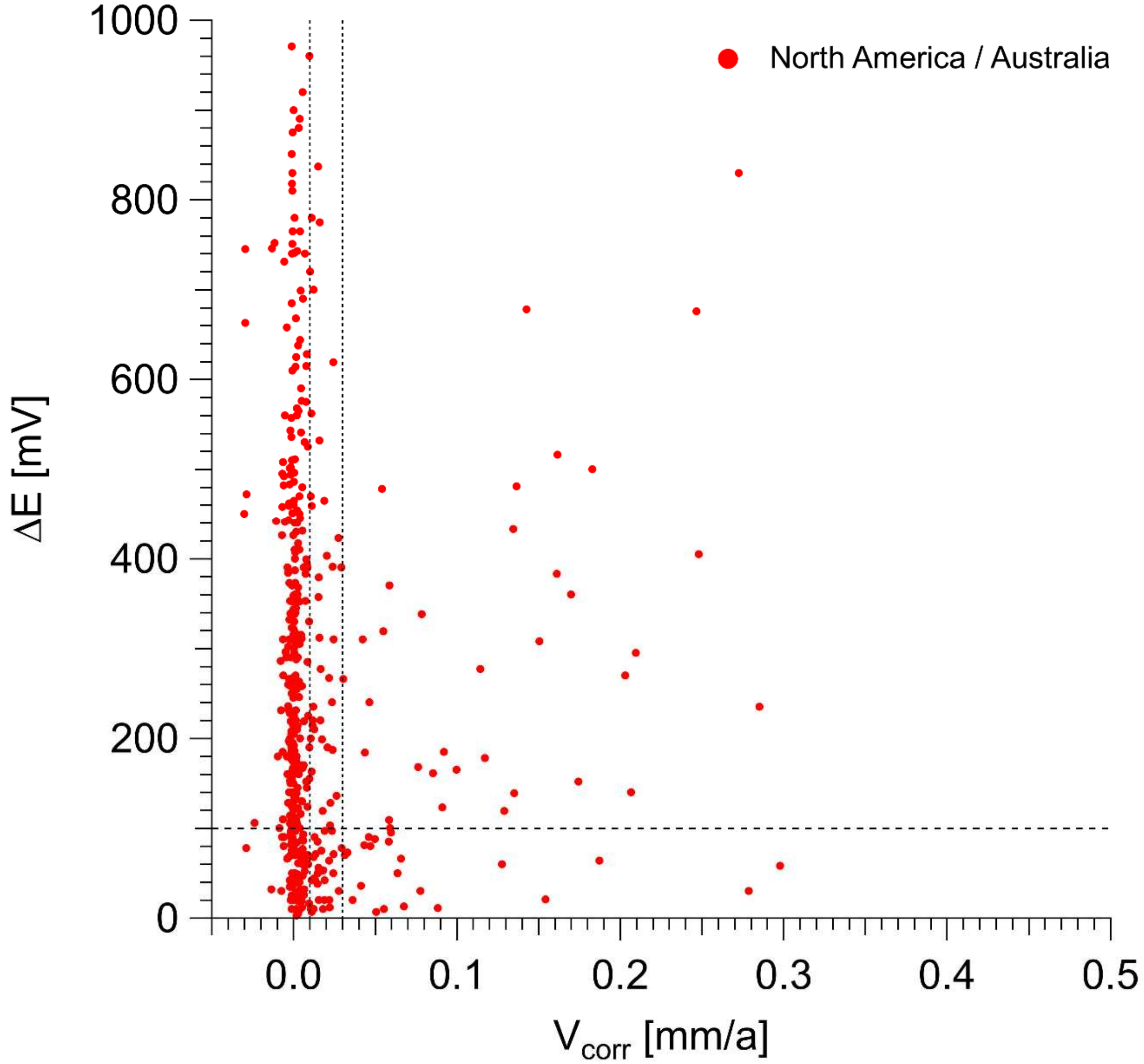

Figure 4: Relation between depolarisation (ΔE) and corrosion rate (v_{corr}).

It is evident that this criterion is not able to provide any reliable information with respect to the corrosion protection. Depolarization values as high as 400 mV and more can be associated with important corrosion rates. It is relevant to note, that in all these cases all the requirements of ISO 15589-1 with respect to the use of the 100 mV criterion were met: Neither stray current, nor compensation current influenced the measurement. Based on these data it becomes evident that this criterion is lacking any justification and needs to be removed from ISO 15589-1.

4.5. Evaluation

The different criteria were evaluated based on the following concept:

- Correct: The conditions are critical (corrosion rate > 0.03 mm/year) or not critical (corrosion rate < 0.03 mm/year) and the criterion with the associated threshold indicated the correct status.
- Wrong negative: The conditions are not critical (corrosion rate < 0.03 mm/year) and the criterion with the associated threshold has erroneously indicated critical conditions.
- Wrong positive: The conditions are critical (corrosion rate > 0.03 mm/year) and the criterion with the associated threshold has erroneously indicated non critical conditions (corrosion rate < 0.03 mm/year).

The presented criteria are summarized in Table 1. It becomes clear that the highest reliability, meaning the least amount of wrong positive results, is obtained based with the on-potential criterion in combination with a threshold of -1.2 V_{CSE}.

Table 1: Different criteria with respect to a corrosion rate of less than 30 µm/a

Criterion	Threshold	Correct [‰]	Wrong negative [‰]	**Wrong positive [‰]**
IR-free potential	-0.85 V_{CSE}	704	293	**3**
	-0.95 V_{CSE}	622	377	**1**
On-potential	-0.85 V_{CSE}	737	259	**4**
	-1.0 V_{CSE}	653	346	**1**
	-1.2 V_{CSE}	459	541	**0**
Polarization	100 mV	210	683	**107**

5. Discussion

Cathodic protection is based on applying a cathodic current to a steel surface. For individual and homogeneous coating defects a cathodic current flow into the steel surface is most effectively controlled by an on-potential more negative than the most negative possible corrosion potential. This is a direct consequence of Ohms law in equation (1) and the very basis of the protection criterion proposed by Kuhn [1]. The results of the largest field investigations ever performed confirm Kuhn's concept. This approach only provides information with respect to the polarity of the current but not on its absolute value. It turns out that this is sufficient in the case of good bedding condition. Under these conditions a current density of 1 mA/m^2 provides an increase of the pH at the steel surface above 9 leading to its passivation. In contrast, in case of poor bedding conditions [10] or in the case of heterogeneous coating defects [15] such small current densities are not sufficient to provide corrosion protection.

The presented data must be considered in the light of the specific experimental conditions such as bedding condition and coupon size. Generalizing the conclusion may be dangerous. Nevertheless the quantity of data and the importance of the protection criteria for the durability of pipelines require a careful evaluation of these data. While it is not possible to justify the application of a specific set of criteria and thresholds, it is possible to draw some conclusions with respect to their applicability:

100 mV polarization

This criterion has is not providing any reliable information with respect to corrosion protection. This may appear irritating since the criterion is based on a kinetic consideration with a Tafel slope in the range of 100 mV/decade. As a consequence a shift of the IR-free potential by 100 mV should result in a decrease of the corrosion rate by a factor of 10. This argument is indisputable and must be correct based on the well accepted electrochemical concepts used in corrosion protection. It assumes that the metal is corroding in the active state and that the corrosion process is occurring on a homogeneous electrode and that the mixed potential theory of Wagner and Traud [16] is applicable. The poor correlation between 100 mV polarization criterion and corrosion behavior shows that these conditions cannot be fulfilled. Indeed Freiman [17] has demonstrated that the metal is normally not corroding in the active state, but is protected from corrosion by passivity that is initiated by cathodic protection. In the case of partial passivation of the steel surface galvanic corrosion can occur as demonstrated in [18]. This can lead to localized galvanic cells within individual coating defects as discussed in [15]. It is important to note that the 100 mV polarization criterion, developed for a homogeneous mixed electrode cannot be transferred to a galvanic corrosion situation as discussed in detail in [19]. As a consequence the potential dependence of the corrosion rate is not under activation, but rather an ohmic control. Therefore, the 100 mV criterion is expected to show a poor performance even under the very conditions stated in ISO 15589-1, which is indeed empirically confirmed.

The IR-free potential

According to ISO 15589-1 an effective cathodic protection is defined by the corrosion rate, which is smaller than 0.01 mm/year. Effectiveness can be demonstrated based on an IR-free potential measurement. The data show clearly, that the 0.01 mm/year cannot be justified based on the empirical data. Instead the corrosion rate at these IR-free potentials is rather 0.02 or even 0.03 mm/year in the case of an interference situation. The data clearly show that there is no correlation between the IR-free potential and the corrosion rate. This is in line with the concepts presented in [10], since the IR-free potential of a passive surface is irrelevant for judging its corrosion behavior. It is, however, irritating that even at IR-free potentials more negative than -1.0 V_{CSE} significantly increased corrosion rates are reported, which is though in line with literature data. In this context, the question raises whether the currently stated threshold values in ISO 15589-1 in combination with the corrosion rate of 0.01 mm/year can still be justified.

On-potential

Based on the presented literature data an on-potential of -0.85 V_{CSE} provides a net cathodic current to almost all coupons of the given geometry confirming the conclusion of Robert Kuhn and justifying his original protection criteria. In the case of well bedded and small coupons corrosion protection was achieved in all cases. In the case of larger coating defects with possibly poor bedding conditions an on-potential of -1.2 V_{CSE} was sufficient to provide corrosion protection. Based on these data the threshold of EN 14505 does not have to be reconsidered. In case of well bedded coating defects that allow for an increase of the pH based on protection current densities as low as 1 mA/m^2 the assumption of full protection at an on-potential more negative than -1.0 V_{CSE} can also be confirmed since current densities in these magnitude were present in all cases. However, poor bedding conditions and circumstances that prevent an increase of the pH will require substantially higher protection current densities as well as correspondingly more negative on potentials well beyond -1.2 V_{CSE}.

Considering also the problems with the measurement of an IR-free potential on the pipeline and the uncertainties in combination with the associated threshold value the on-potential receives increased attention as a possible protection criterion. This justified based on the good success of this parameter in the performed field tests. The key question remains how the "substantially" more negative value can be determined in the case of unknown poor bedding conditions.

6. Literature

1. R. J. Kuhn, "Galvanic current on cast iron pipes", *Bureau of Standards, Washington, Soil Corrosion Conference*, 73 (1928).
2. M. Büchler, B. Ackland, U. Angst, "The historic evolution of cathodic protection criteria", in CEOCOR international Congress 2016 Ljubljana, CEOCOR, c/o SYNERGRID, Brussels, Belgium, (2016).
3. T. J. Barlo, "Field Testing the Criteria for Cathodic Protection of buried Pipelines". PRCI, Ed., PRCI (Technical Toolboxes, Inc. Housten Texas, Houston, 1994).
4. M. Büchler, D. Joos, "Minimierung der Wechselstromkorrosionsgefährdung mit aktivem kathodischen Korrosionsschutz", *DVGW - energie/wasser-praxis* **November 2013**, 13 (2013).
5. M. Büchler, D. Joos, C.-H. Voûte, "Feldversuche zur Wechselstromkorrosion", *DVGW - energie/wasser-praxis* **Juli/August 2010**, 8 (2010).
6. W. v. Baeckmann, W. Schwenk, W. Prinz, "Handbook of Cathodic Corrosion Protection". (Verlag Chemie, Weinheim, 1988), vol. Third Edition.
7. M. Pourbaix, "Atlas of electrochemical equilibria in aqueous solutions". (NACE, Houston, TX, 1974).
8. M. Büchler, H.-G. Schöneich, "Investigation of Alternating Current Corrosion of Cathodically Protected Pipelines: Development of a Detection Method, Mitigation Measures, and a Model for the Mechanism", *Corrosion* **65**, 578 (2009).
9. D. Funk, H. Hildebrand, W. Prinz, W. Schwenk, "Korrosion und kathodischer Korrosionsschutz von unlegiertem Stahl in Sandböden", *Werkstoffe und Korrosion* **38**, 719 (1987).
10. U. Angst *et al.*, "Cathodic protection of soil buried steel pipelines – a critical discussion of protection criteria and threshold values", *Materials and Corrosion* **11**, 9 (2016).
11. W. J. Schwerdtfeger, O. N. McDorman, "Potential and Current Requirements for the Cathodic Protection of Steel in Soils", *Journal of Research of the Nationa l Bureau of Standards* **47**, 104 (1951).
12. N. G. Thompson, T. J. Barlo, "Fundamental process of cathodically protecting steel pipelines", in Gas Research Conference, Government Institute, Rockville, MD, USA, (1983).
13. M. Büchler, "A New Perspective on Cathodic Protection Criteria Promotes Discussion", *Materials Performance* **54, No 1**, 44 (2015).
14. S. S. Leeds, R. A. Cottis, "Paper Nr. 09548: The influence of cathodically generated surface films on corrosion and the currently accepted criteria for cathodic protection", in Conference & Exposition, Corrosion Nacexpo 2009,
15. M. Büchler, S. Collet, U. Angst, "The effect of coating defect distribution on buried steel pipelines on the effectiveness of cathodic protection", in CEOCOR international Congress 2017 Luxembourg, CEOCOR, c/o SYNERGRID, Brussels, Belgium, (2017).
16. C. Wagner, W. Traud, "Über die Deutung von Korrosionsvorgängen durch die Überlagerung von elektrochemischen Teilvorgängen und über die

Potentialbildung an Mischelektroden", *Zeitschrift für Elektrochemie und angewandte physikalische Chemie* **44**, 391 (1938).

17. L. I. Freiman, I. V. Strizhevskii, M. Y. Yunovich, "Passivation of iron in soil with cathodic protection", *Protection of Metals* **24**, 104 (1988).

18. E. G. Kuznetsova, L. V. Remezkova, "About Corrosion Macrocells Formed on Underground Pipelines at the Switched off Cathodic Protection", *Protection of Metals* **37**, 262 (2001).

19. U. Angst, M. Büchler, "On the applicability of the Stern–Geary relationship to determine instantaneous corrosion rates in macro-cell corrosion", *Materials and Corrosion / Werkstoffe und Korrosion* **65**, 1017 (2015).