



Commission 2

Menthon-Saint-Bernard DAYS – 24st –26th May, 2011

Paper 2-17

Field investigation of a.c. corrosion

M. Büchler, C.-H. Voûte and D. Joos
SGK Swiss Society for Corrosion Protection, Technoparkstr. 1, CH-8005 Zürich,
markus.buechler@sgk.ch

Abstract

Based on laboratory studies and model concepts, a profound understanding of the involved processes in a.c. corrosion and the required limits has been obtained in the last years. But there is no information whether these thresholds can be effectively applied to pipelines or whether operational constraints make their implementation impossible. Therefore, an extensive field test with seven pipeline operators in Germany was carried out. Thereby the relevance of the laboratory tests for field application was investigated.

Zusammenfassung

Aufgrund von Laboruntersuchungen und Modellvorstellungen besteht ein vertieftes Verständnis über die bei Wechselstromkorrosion ablaufenden Prozesse und die erforderlichen Grenzwerte. Es gibt aber keine Informationen ob diese effektiv auf Rohrleitungen angewendet werden können oder ob betriebliche Randbedingungen deren Umsetzung verunmöglichen. Es wurde daher ein umfangreicher Feldversuch mit sieben Rohrleitungsbetreibern in Deutschland durchgeführt. Dabei wurde die Relevanz der in den Laborversuchen gewonnenen Erkenntnisse überprüft werden.

Résumé

Ces dernières années ont permis d'acquérir une profonde compréhension des processus impliqués dans la corrosion par courant alternatif et des limites requises pour l'éviter en se basant sur des études en laboratoire et des modèles. Mais il n'y a aucune information indiquant si ces seuils peuvent effectivement être appliqués à des canalisations ou si des contraintes opérationnelles rendent impossible leur implémentation. Par conséquent, un essai *in situ* de grande envergure a été mené en Allemagne avec sept exploitants de canalisations. La pertinence des essais en laboratoire pour les applications de terrain a ainsi été investiguée.

1. Introduction

In 1988, the first damages by alternating current (a.c.) corrosion of cathodic protected pipelines have been observed [1, 2]. As a result, this type of corrosion was investigated and soon the a.c. current density was identified as the critical parameter [3-5]. Later the influence of the protection current density on the corrosion rate was reported [6-9]. A deeper understanding of the processes involved has been missing for a long time though. Only in recent studies it was possible to develop a model that was able to explain all empirical observations [10-12].

Based on this concept, the corrosion rate can be reduced to a negligible level when the protection current density is limited [7, 13]. Preferably, it should be less than 1 A/m^2 . This should be achieved if the on-potential is in the range of -1.2 V CSE and the average a.c. voltage is below 15 V [14, 15]. Additionally, the off-potential must be more negative than the required criterion of protection according to EN 12954. Under these conditions, the driving voltage for the direct current flow is minimized, which reduces the risk of a.c. corrosion to a significant extent.

Based on the model concepts and experimental data it is likely that a.c. corrosion can be prevented even at high protection current densities. Based on laboratory tests it is likely that this is possible when the protection current density is larger than one third of the a.c. current density [6, 14].

Based on laboratory studies and model concepts, there is a deep understanding of the involved processes in a.c. corrosion and the required limits [16, 17]. But there is no information whether these can be effectively applied to pipelines or whether operational constraints make their implementation impossible. It is therefore unclear whether these newly developed protection schemes can be implemented in pipelines.

Therefore, an extensive field test with seven pipeline operators in Germany was carried out [18]. Thereby the relevance of the laboratory tests for field application should be investigated.

2. Experimental Methods

2.1. Pipelines

The measurements were made at seven pipelines from the entire German supplying network. In most cases, there was a 50 Hz alternating current interference and the influence of stray current was generally negligible. In terms of the pipeline coatings, the specific soil resistance (soil resistivity), the type of rectifiers and the protection lengths various configurations were covered by the investigations. The selection of the three measuring points for each pipe was based on soil conditions, the induced a.c. voltage and the already occurred a.c. corrosion.

2.2. Setup of monitoring sites

The installation of coupons was made in accordance with the following principles: the distance between the coupons was at least 1 meter and their distance to the pipeline was at least 0.4 m. The surface was installed upwards at an angle of 45°. This should prevent a loss of contact between the soil and the coupon in the case of a settlement of the ground. Every measurement point was equipped with 2 corrosion sensors (ER Probe Flush Type from Metricorr with an initial thickness of 500 microns and an area of 1 cm²) and an ILC-02 data logger. The ER coupons are strip-shaped and have a length of 3 cm. Furthermore, a coupon with a circular defect area of 1 cm² and a reference electrode were installed. For corrosion protection of the coupons in the period between installation and the start of the experiment, a galvanic anode has been installed additionally. Since the installation of the coupons could not be realized simultaneously at all sites, the corrosion protection by means of the galvanic anode was guaranteed until the start of the experiment.

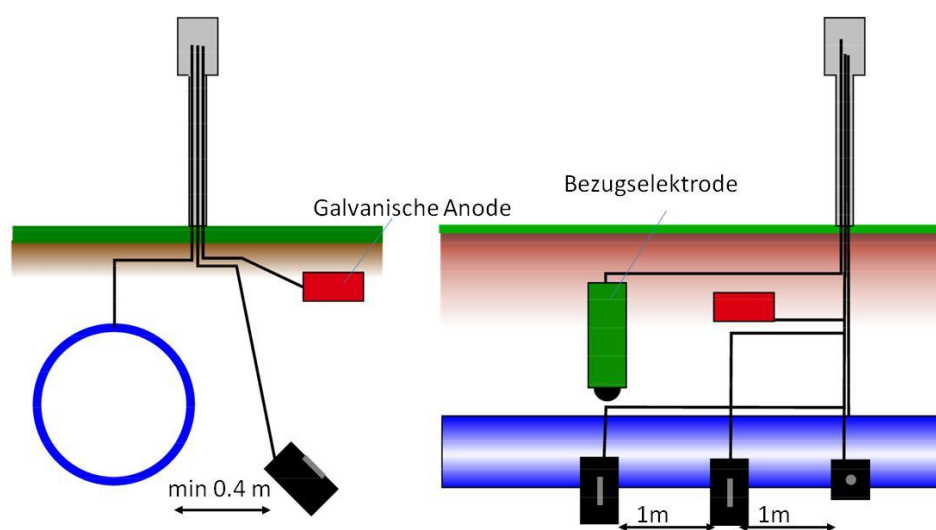


Figure 1: Schematic setup of a monitoring site

During the test, these galvanic anodes were also used for the corrosion protection of excessively corroding coupons, which had to be separated from the pipeline. The schematic design of a monitoring site is shown in Figure 1.

In addition, at least at one point of the pipeline's worst polarization a coupon with 10 cm² was installed. At this coupon the compliance with the safety conditions for the CCP has been verified.

A continuous measurement with an interval of one hour and the following parameters was made: potential and a.c. voltage, a.c. current density and d.c. current density as well as the thickness of the ER coupons.

During the field test the maintaining of different on-potentials over a period of 2 months was scheduled. At the end of the experiment for a period of 2 weeks the on-potentials was planned to be set to very negative values, as they are typically used in the intensive defect detection (IFO). Due to operational constraints, it was necessary to make various adjustments to the planned schedule.

3. Basics

The cathodic protection provides an entering current into the metal surface of the tube, which is in contact with the surrounding soil in the case of a damaged coating. This direct current prevents the occurrence of corrosion by removing the oxygen in the soil and by eliminating potential differences between different sections of the tube. In addition, the entering cathodic protection current leads to an increase in alkalinity at the steel surface.

When an a.c. voltage is induced in a cathodic protected tube, an alternating current flows through the steel surface in the coating defect additionally. The a.c. current density depends on the a.c. voltage and the impedance of the system. During the cathodic half cycle, the cathodic reduction reactions are amplified on the metal surface. On the other hand a current can leak from the steel surface in the anodic half cycle, when the a.c. voltage is sufficiently high enough. An anodic current causes oxidation reactions and can therefore lead to corrosion according to reaction (1).



The electrical charge resulting from the anodic current may additionally lead to charging of the capacitive double layer, to the oxidation of hydrogen, and the oxidation of corrosion products. Under cathodic protection the oxidation of iron leads to the formation of a passive film according to reaction (2), since the pH value on the metal surface of the steel is high enough (e.g. pH > 9), given that the protection criteria is reached.

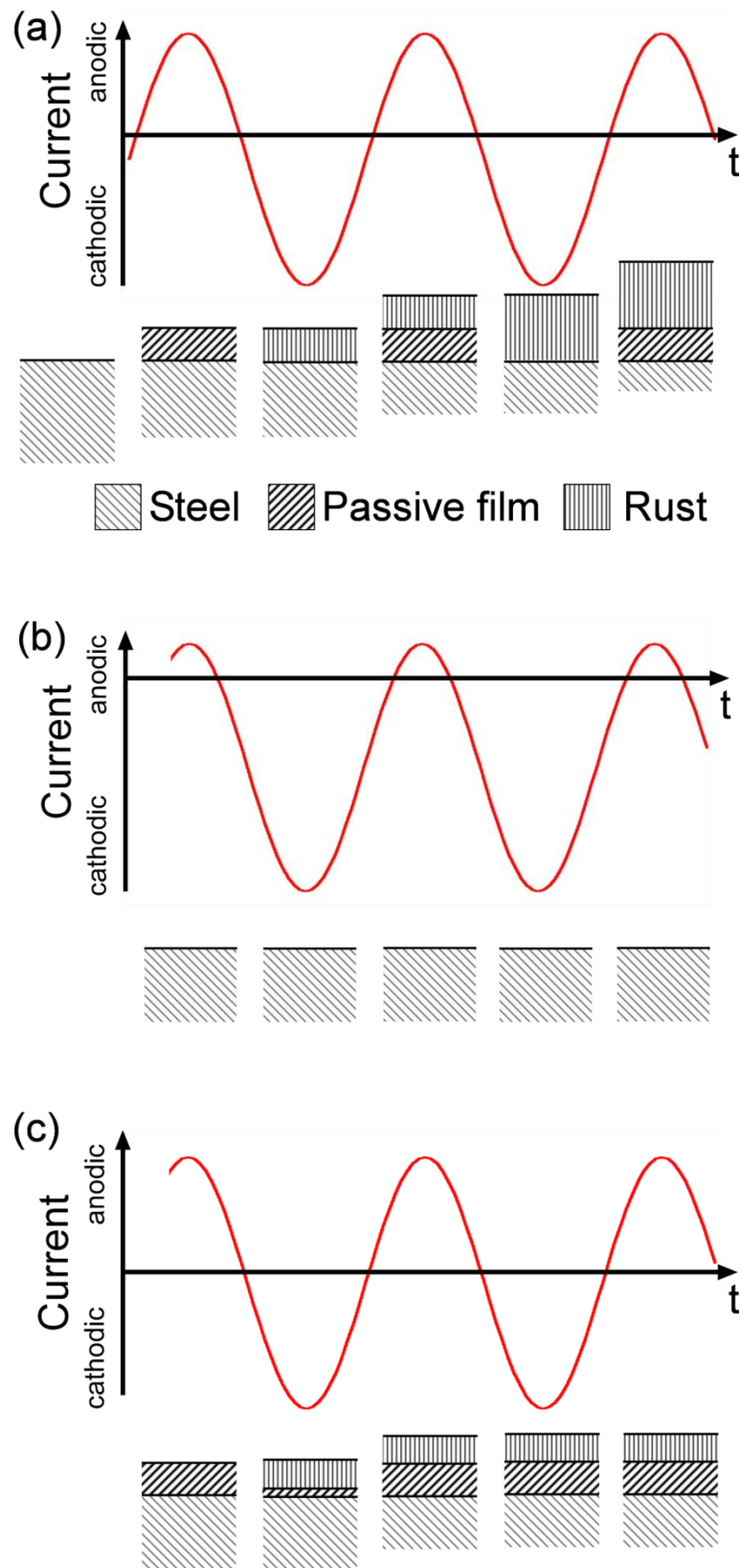


Figure 2 Schematic representation of the processes which take place on the steel surface at different protection currents: a) high cathodic protection current, b) very high cathodic protection current, c) low cathodic protection current.

On the other hand, the electrical charge generated in the cathodic half-cycle leads to a capacitive charging of the double layer, to the reduction of oxygen, the formation of hydrogen and the reduction of oxidized corrosion products. In addition, the cathodic charge can electrochemically reduce the passive film formed in the anodic half-wave. It is empirically observed that very high as well as very low protection current densities are able to reduce a.c. corrosion. The negative influence of a mid-ranged protection current can be explained with the increase in pH, the associated decrease of the spread resistance and the enhanced reductive reactions on the metal surface. These effects lead to increased protection currents and a.c. currents, changes in the solubility of the formed iron oxides and their oxidation state.

A simplified description of the involved processes in a.c. corrosion is shown in Figure 2a. During the anodic half-cycle the steel surface is oxidized by the current, leading to the formation of a passive film. During the cathodic half-wave this passive film is electrochemically reduced and thus converted into a porous layer of rust. In the subsequent anodic cycle, a new passive film is formed under the porous, non-protective rust layer. In the subsequent cathodic reduction of the passive film the amount of porous rust is increased [19, 20]. Assuming that this process is leading to a formation and dissolution of a passive film with the thickness of about one atomic layer with each half-wave, corrosion rates in the range of 70 mm/year can be expected. Since such high corrosion rates are observed only under extreme conditions, it can be concluded that in most cases the formation and / or dissolution (reduction) of the passive film according to reaction (2) does not proceed completely during a period of a.c. voltage.

Based on this approach it is possible to explain several empirical observations. The corrosion process only occurs when the passive film is at least partially formed and dissolved (reduced) by the alternating current. The formation of the passive film can be prevented with sufficiently high protection current densities (Figure 2b). The condition is that the remaining anodic charge can be absorbed by the capacitive loading of the double layer.

Likewise, a.c. corrosion can also be prevented if the reductive dissolution of the once formed passive film is prevented (Figure 2c). This is possible if the protection current density is limited. Under these conditions, it is observed that even a.c. current densities up to 1500 A/m^2 do not lead to corrosion. The anodic and cathodic charge of the alternating current is consumed for the oxidation and reduction of the rust layer corresponding to reaction (3) [10, 11]. Consequently, a.c. corrosion can be prevented at low protection current densities if the pH is sufficiently high to allow passivation and if a rust layer can be formed to absorb the anodic and cathodic charge of the alternating current.

Based on these considerations, it is clear that the occurrence of a.c. corrosion can be prevented by high as well as low protection current densities. This observation is important in the discussion of interference limits, since there are two fundamentally different approaches to the prevention of a.c. corrosion. The model discussed above is able to explain these two approaches. Furthermore, the critical ratio between a.c. and

d.c. current density as well as the occurrence of a critical protective and a.c. current density can be justified.

4. Results and discussion

4.1. Low protection current

The original aim of the study was to test the transferability of the results found in laboratory tests in a field application, concerning limits at low protection current densities, which means a relatively positive on-potential. The further discussion in this chapter will focus on the investigation of a.c. corrosion according to the model in Figure 2c under optimized cathodic protection conditions. The results of the examination with a low protection current, determined during the first 10 months of the experimental program are shown in Figure 3 for the potential values and in Figure 4 for the corresponding current values. The images show the limits, which are to be met in order to provide a negligible risk of corrosion. Based on the present results it is clear that the thresholds determined in laboratory tests can be confirmed in the field test.

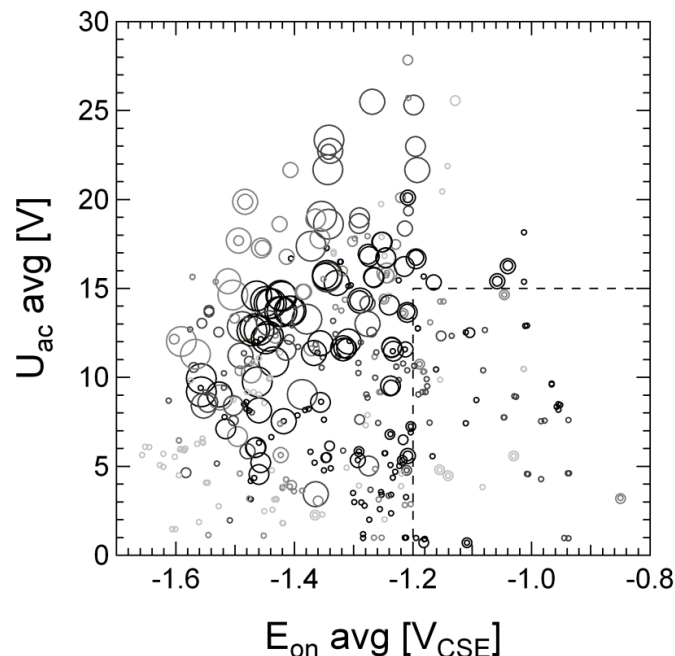
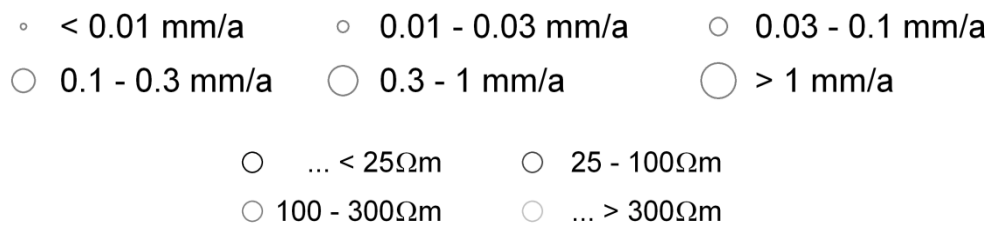


Figure 3: Corrosion rate in relation of on-potential and a.c. voltage including information about the specific soil resistance at the installation site.

The results in Figure 3 clearly show that a.c. corrosion can be largely prevented if the average on-potential over time is more positive than -1.2 V CSE and the average a.c. voltage below 15 V. Since the corrosion characteristic is mainly determined by the

effective current densities it is to be expected that in principle the potential limits should be dependent on the specific soil resistivity. In Figure 3 and Figure 4 the influence of soil resistivity is shown. It can be seen that at a soil resistivity of more than 300 Ωm no significant a.c. corrosion has occurred under the given experimental conditions. Figure 4 shows that this is due to the higher spread resistance and thus the generally lower current densities.

Therefore, the thresholds based on the current density criteria remain valid, independent from the soil resistivity. The potential values are however fundamentally dependent on the soil resistivity and thus adjustments of the threshold are possible. With the available data it is empirically found that for a soil resistivity of more than 100 Ωm even with an average on-potential higher than -1.35 V CSE no a.c. corrosion occurs. If the soil resistivity is more than 25 Ωm the empirically determined threshold is -1.25 V CSE.

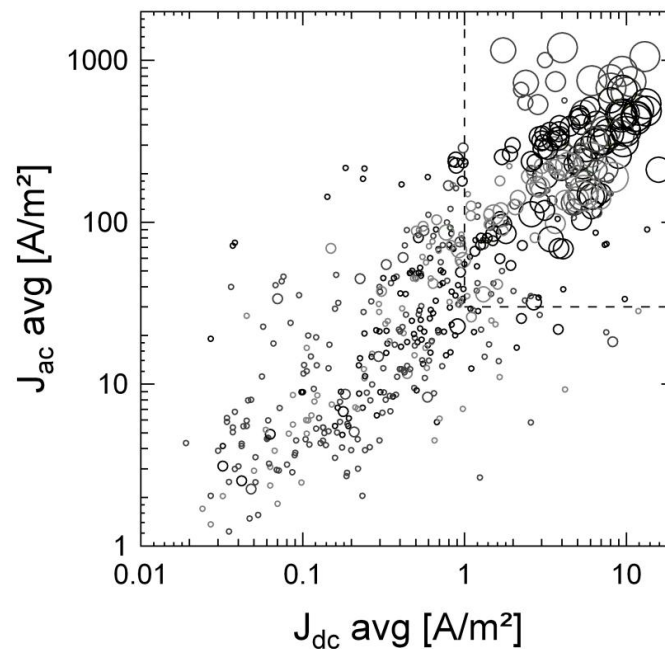


Figure 4: Corrosion rate in relation of d.c. and a.c. current density including information about the specific soil resistance at the installation site.

The influence of the protection current density and on-potentials shall be discussed based on the example in Figure 5. It clearly shows that the decrease of the on-potential from -1.1 V CSE to below -1.4 V CSE activates corrosion. Once the potential is raised again, the corrosion stops even though the a.c. current densities are well over 500 A/m^2 . The effect of the spread resistance by the increased protection current can be clearly traced too. The shift of the on-potential to more negative values results in a higher protection current, which shifts the pH at the steel surface to higher values and thus reduces the spread resistance. At a constant a.c. voltage this causes higher a.c. current densities. While an increase of the protection current is relatively quickly leading to an increase in pH and thus a drop of the spread resistance, a shift back to more positive values of the on-potential only slowly increases the spread resistance again.

The reason for this may primarily be the relatively slow diffusion of the hydroxide ions into the surrounding soil.

The influence of the a.c. current density is clearly visible in Figure 6. The on-potential is more negative than -1.2 V CSE and the protection current density is significantly higher than 1 A/m². As expected, corrosion occurs. As soon as the a.c. voltage drops from about 15 V to 2 V the corrosion process stops.

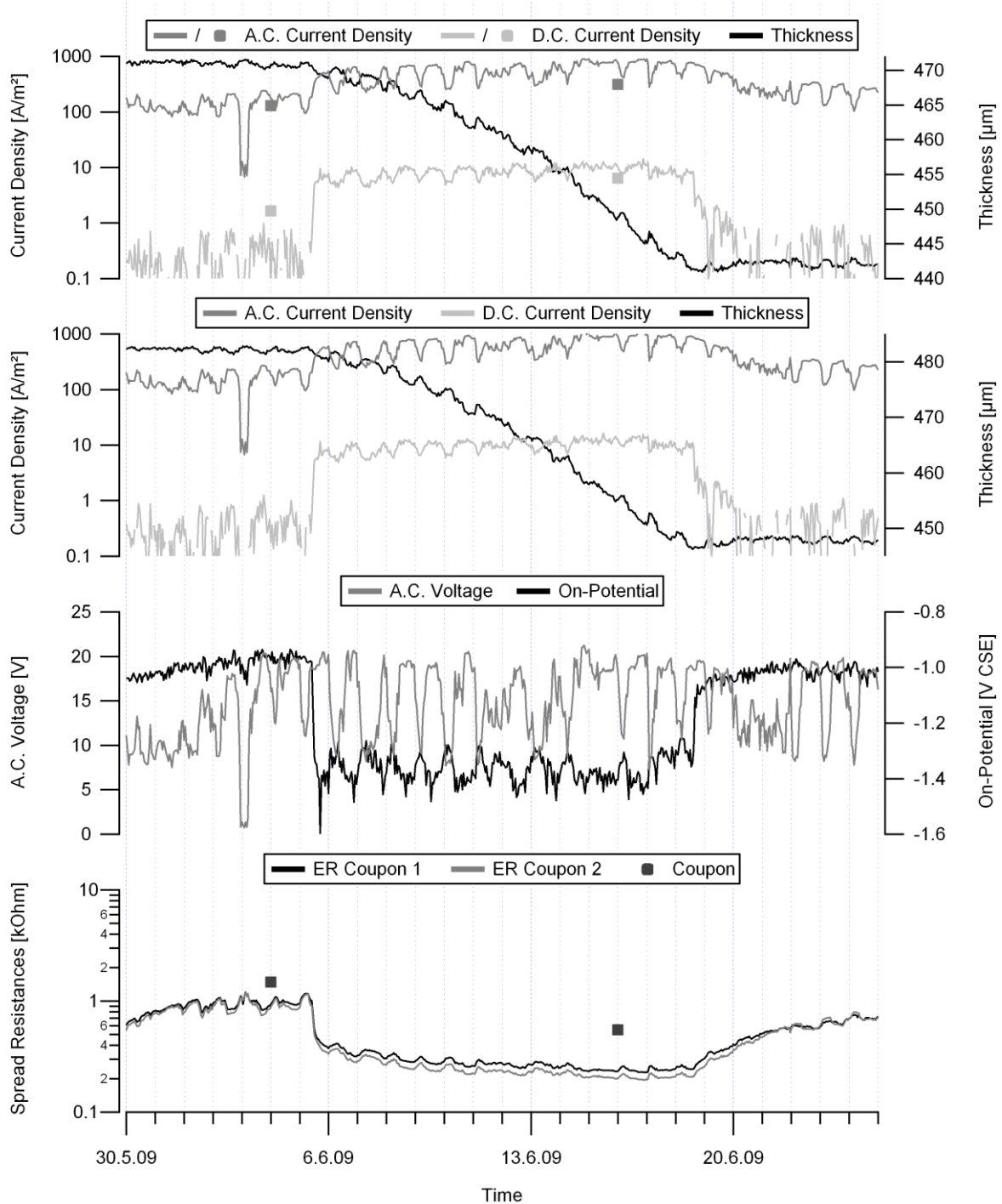


Figure 5: Influence of the on-potential on the corrosion behavior. In the two graphs at the top, the current densities and the values of the ER coupons of sample 1 and sample 2 are shown. Additionally, the values of the manual measurement of the round 1 cm² coupon are shown.

The third graph shows the potential values and the fourth graph shows the spread resistances of the coupons.

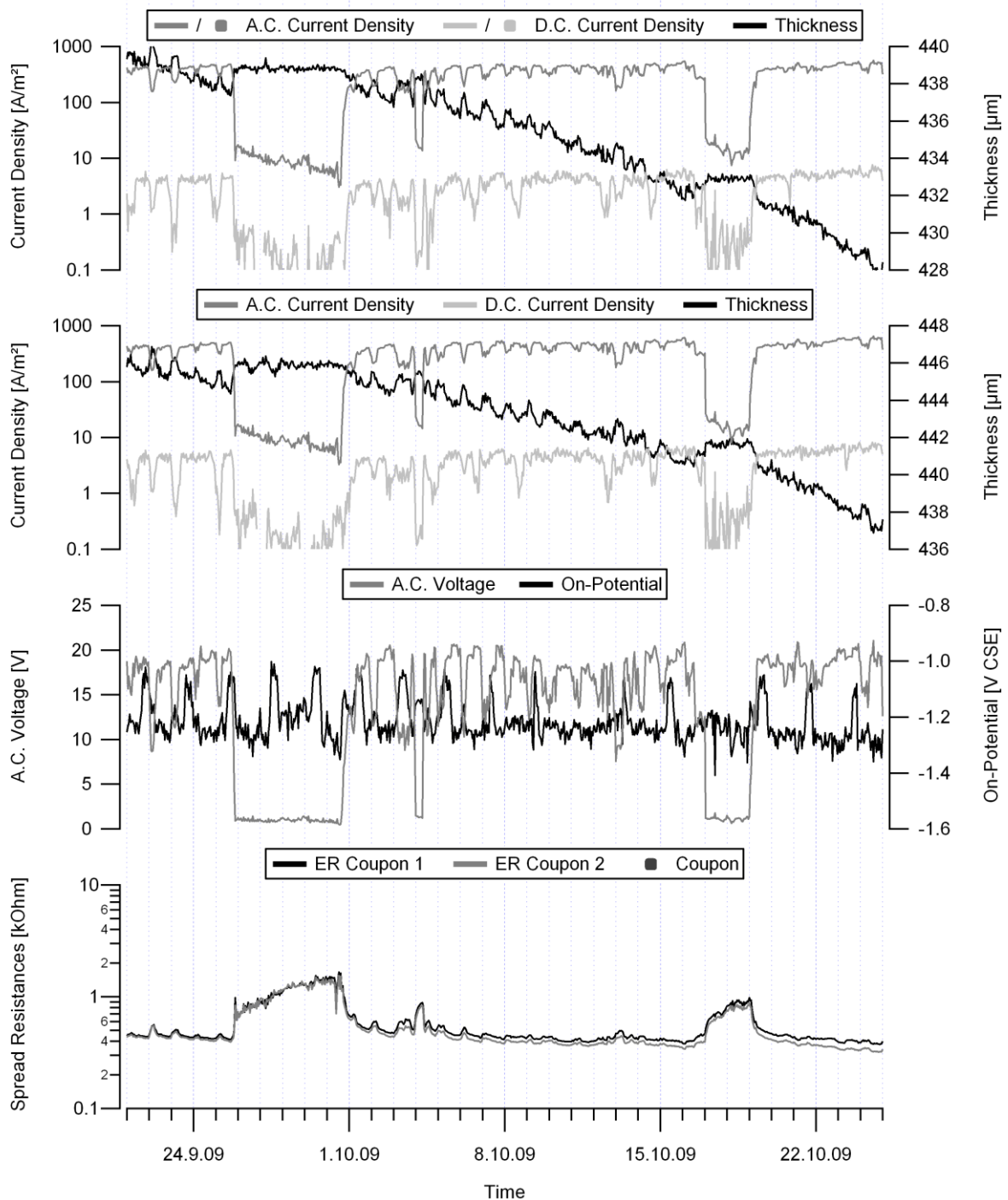


Figure 6: Influence of the a.c. current density on the corrosion process. In the two graphs at the top, the current densities and the values of the ER coupons of sample 1 and sample 2 are shown. The third graph shows the potential values and the fourth graph shows the spread resistances of the coupons.

The protection current density drops below 1 A/m^2 after the reduction of the a.c. voltage at a constant on-potential. Consequently, the rectification of the alternating current by the so-called faraday rectification, is leading to an increase of the protection current. At

least some part of the negative effect of the alternating current on the a.c. corrosion behavior is thus due to the rectification.

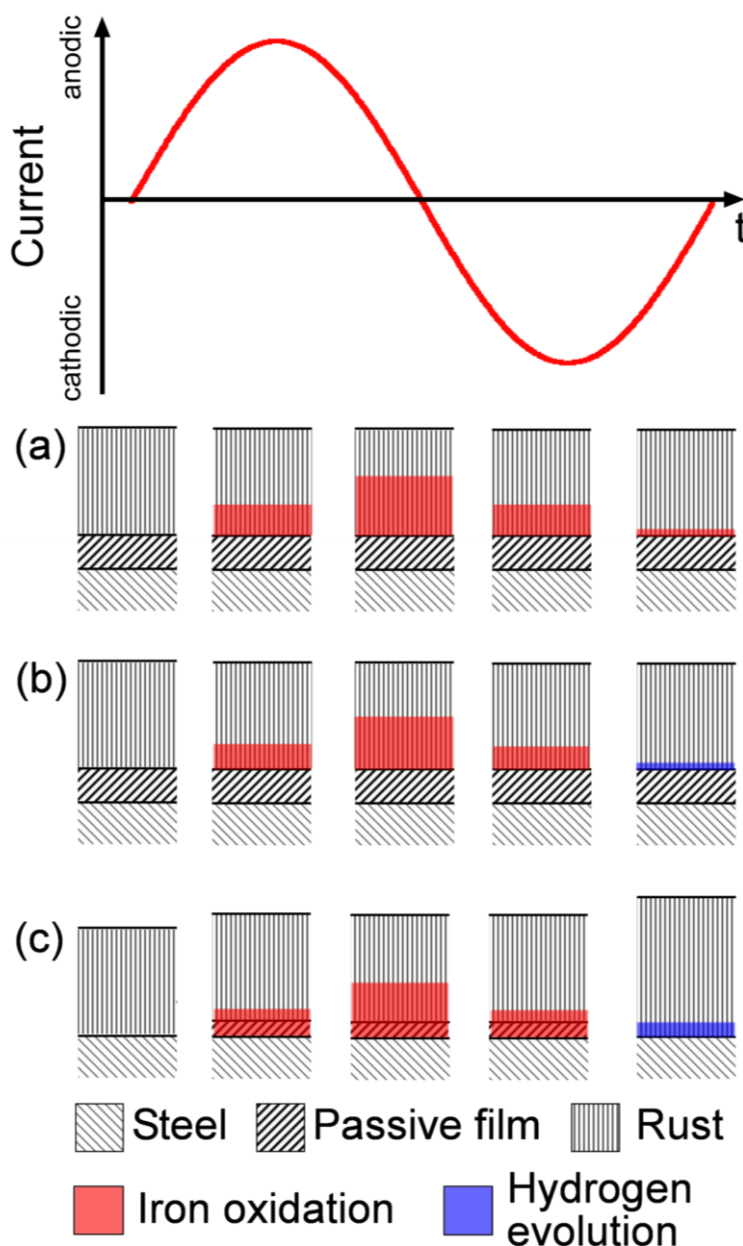


Figure 7: Schematic representation of the running processes during the anodic and cathodic half-cycle. a) No protection current for steel in alkaline medium; b) 0.5 A/m^2 protection current, c) 5 A/m^2 protection current

Based on available data it can be concluded that high protection current density as well as high a.c. current density leads to a.c. corrosion. Accordingly, also negative on-potentials and high a.c. voltages lead to the a.c. corrosion. The analysis of the data shows clearly that at a constant alternating current a high protection current density results in most cases in an increase of the a.c. current density, because the spread resistance decreases at the defect due to the increased pH. So the electrical resistance of the soil is changed by the protection current density. Concurrently, increasing the a.c. current density leads by the faraday rectification to an increase in the protection current density as well. This mutual influence between the parameters soil resistivity, a.c.

current density and protection current density is clearly shown in Figure 4. In general, high alternating currents are associated with high protection currents and therefore even with increased specific soil resistance significant current densities can result.

Based on the discussed results, it is possible to interpret the relevance of the observed limits and explain their physical and electrochemical significance [21]. Intuitively, it is surprising that an a.c. current density of 1000 A/m² and higher is not critical but in combination with a protection current density over 1 A/m² leading to corrosion. At low protection current densities, the anodic and cathodic charges of the alternating current are used for the oxidation and the reduction of the rust layer. Given the importance of the rust layer to protect against a.c. corrosion the relevant processes are briefly discussed with reference to Figure 7. In the context of a.c. corrosion, it is always essential that a minimal rust layer is formed on the steel surface according to the process in Figure 2c. It was shown that the thickness of this layer correlates with the occurring a.c. current density [22]. If the thickness is not sufficient enough- and therefore not sufficient trivalent iron ions are available for the reduction - it will lead to the dissolution of the protective passive film and thus to the formation of rust in the cathodic half-wave. The rust layer will adjust to the required thickness according to the electrochemical processes at the steel surface. For the discussion in Figure 7, it is assumed that a sufficiently thick layer of rust has already formed. Furthermore, it is assumed that the oxygen content in soil and the capacitive effects are negligible.

In Figure 7a the case is shown for steel in an alkaline medium, subjected to an alternating current. This applies for example to a reinforced concrete structure which is connected to a train earthing system. With the beginning of the anodic charge transfer the oxidation of divalent iron ions occurs in the rust layer according to reaction (3). As the rust layer is sufficiently thick, the total charge of the anodic half-cycle is consumed by this reaction. In the cathodic half cycle, the reaction (3) runs in the opposite direction. Since the anodic and cathodic half-cycles have the same amount of charge, this reversible reaction can occur arbitrarily often and does, even at high a.c. current densities not lead to corrosion.



In Figure 7b the corresponding process is shown for an alkaline medium, formed by a cathodic corrosion protection system at a protection current density of 0.5 A/m². The processes are similar as in the case without protection current. The main difference is that the amount of anodic and cathodic charge is not equal. Consequently, all reducible trivalent iron in the rust layer will already be converted according to reaction (3) before the end of the cathodic half cycle. The remaining cathodic charge is consumed for the generation of hydrogen according to reaction (4). Since in this case remaining current density is insufficient to polarize the steel surface cathodically by 85 mV [16, 17] and thus move it from the passive to the immunity region, the protective passive film is not electrochemically dissolved.

In Figure 7c the corresponding process is shown in a system with a protection current density of 5 A/m^2 . Since at the end of the cathodic half cycle, the current density is sufficiently high for the hydrogen reaction to polarize the steel surface into the immunity region, the passive film will be dissolved according to reaction (2). Thus a new passive film will form in the subsequent anodic half-cycle. The remaining anodic charge is then consumed in the oxidation of rust according to reaction (3).

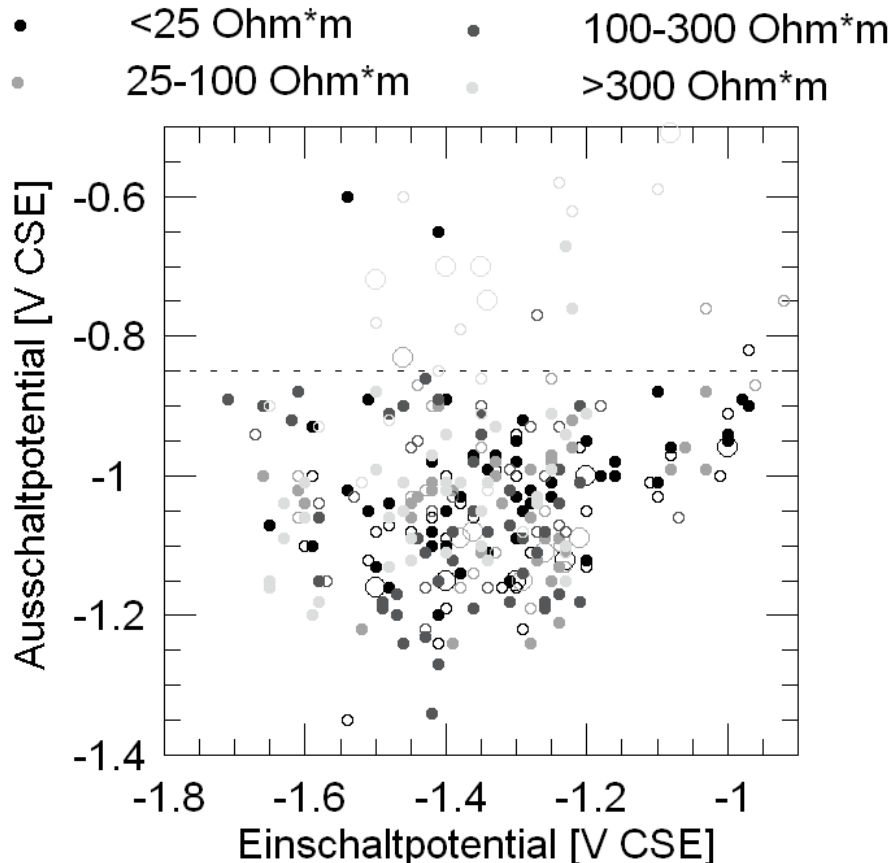


Figure 8: Off-potentials of all coupons as a function of the on-potentials depending on the soil resistivity. The filled dots represent the ER coupons, the small circles stand for the circular defects with 1 cm^2 and the big circles represent the circular defects with 10 cm^2 .

The discussion so far has only focused on the risk of a.c. corrosion risk of the pipeline. In principle however, a shift of the on-potential in a positive direction leads to an increased risk of corrosion due to insufficient cathodic protection. This protection was controlled by the measurement of the off-potential. The results for different sample geometries and different soil resistivity are given in Figure 8. It turns out that the protection criterion of -0.85 V CSE , was met in most cases for coupons with soil resistivity of less than $100 \text{ Ohm}\cdot\text{m}$. In general, however, it was found that the ER coupons were better polarized because of their strip-shaped geometry. This is also reflected in the values of the spread resistance, which was always lower compared to the ones with circular plates of the same sample surface. The coupons with a surface defect of 10 cm^2 showed expectedly the most positive off potentials. Based on available data it can

be concluded that in principle the protection criterion can be achieved also with on-potentials, which are more positive than -1.2 V CSE, as long as the soil resistivity is less than 300 Ωm , and the maximum defect size is smaller than 10 cm^2 . Further it must be concluded that the ER coupons are indeed suitable to determine the risk of a.c. corrosion as they tend to polarize stronger because of the geometry of their defects. But they are less suitable to verify the sufficient polarization of the pipeline. Accordingly, no corrosion was found on any ER coupon, even if the coupons with round geometry had insufficient off-potentials.

Two off-potential values at negative on-potentials and low specific soil resistivity do not meet the criterion for protection. It turns out that it is the same coupon plate in both cases. Since the protection current densities were in the range of 1 A/m^2 it is likely to be a measurement error.

4.2. Negative on-potential

Because of the fundamental considerations in Figure 2b it is clear that a.c. corrosion can also be prevented at high protection currents. Based on empirical data [6] it can be concluded that the ratio between a.c. and protection current density may be 3 at its maximum.

Assuming that the spread resistance of defects is the same for d.c. and a.c. current, it follows from this condition that the on-potential at a given a.c. voltage U_{ac} can be calculated according to equation (1).

$$\frac{U_{ac}}{|E_{on}| - 1.2} < 3 \quad (1)$$

This means that at an a.c. voltage of 4 V, there has to be an on-potential, which is more negative than -2.5 V CSE. Originally the case of high protection currents was not intended to be examined as a part of the project. As part of the ongoing standardization and especially in relation with the intensive defect detection (IFO), the corrosion behavior at negative on-potential is of great importance. Therefore, before the termination of the experiments, at several pipelines, the on-potential values were adjusted to negative values like they are typically set in IFO measurements. A typical result is shown in Figure 9.

The occurring effects can be clearly illustrated by the example of Figure 9. Originally, the cathodic protection of the pipeline was set to an on-potential of -1.6 V CSE. The protection current density in sample 2 was higher than 1 A/m^2 and thus leading to corrosion. Due to the higher spread resistance there is no corrosion on sample 1, since both the a.c. and the d.c. current density are not critical. Once the on-potential is lowered to -9 V CSE, the corrosion at sample 2 stops, as the ratio of the current densities is in the range of 1. Interestingly, the soil resistivity of sample 2 does not change any more, while a significant decrease in sample 1 can be noticed due to the increase in pH. Even though the protection current density is higher than 1 A/m^2 and the a.c. current density is well above 30 A/m^2 , no corrosion occurs. This corresponds to a corrosion protection in accordance with the process in Figure 2b.

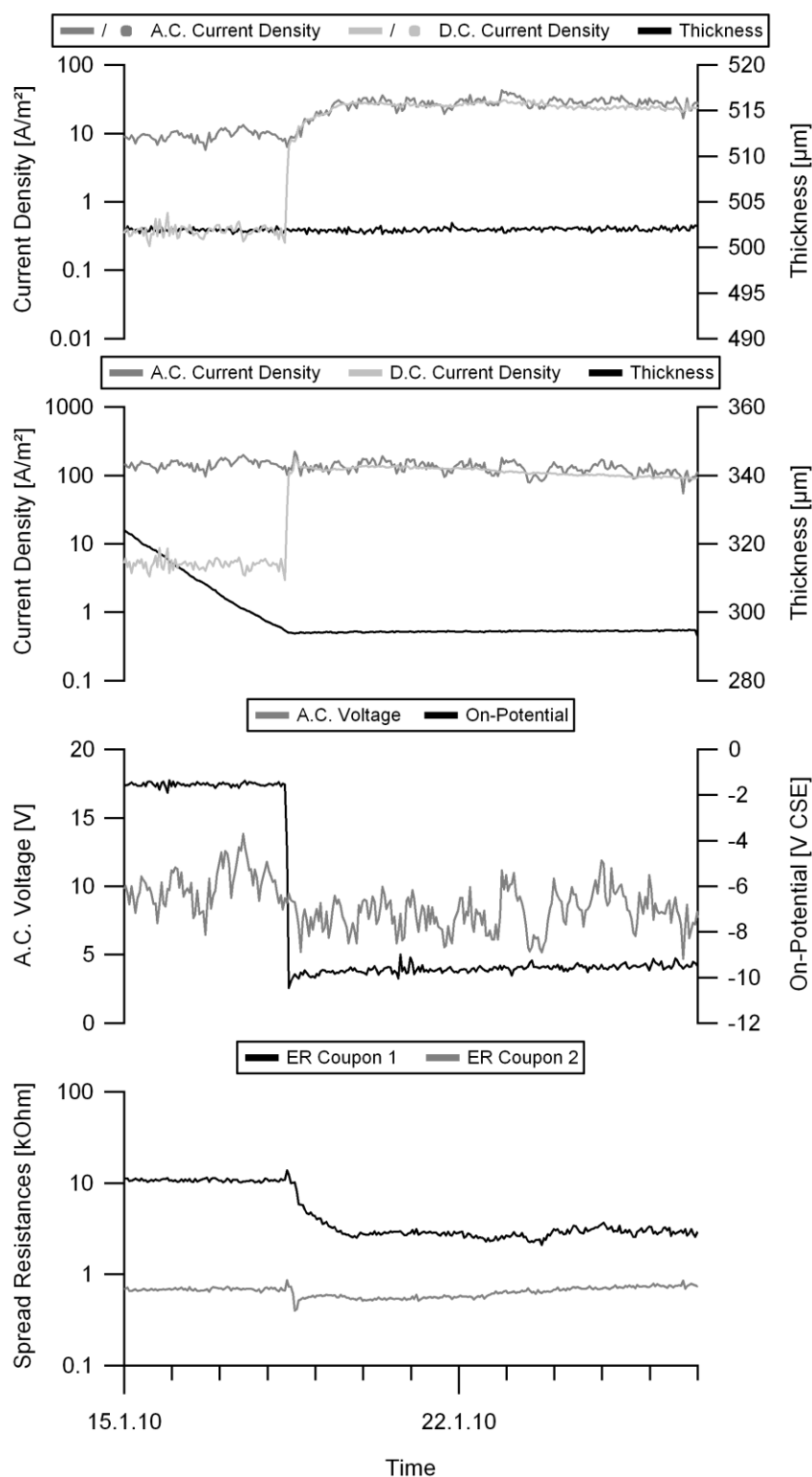


Figure 9: Corrosion behavior during the switch to a negative on-potential of -9 V CSE. In the two graphs at the top, the current densities and the values of the ER coupons of sample 1 and sample 2 are shown. The third graph shows the potential values and the fourth graph shows the spread resistances of the coupons.

The situation with insufficient decrease of the on-potential is fundamentally different. In this case, it was possible to activate corrosion on a coupon that originally showed no

corrosion a positive on-potential with protection current density below 1 A/m^2 and increased a.c. current densities. The effect corresponds to that in Figure 5. The high protection current densities led in some cases to corrosion rates of 100 mm/year . It was observed that lowering the spread resistance generally leads to higher current densities. Therefore, there is a risk of corrosion by raising the on-potential back to originally non-critical values as the protection current density may possibly be greater than 1 A/m^2 now because of the produced alkali ions during the temporary lowering and the thus resulting lower spread resistance.

The results of the measurements under IFO conditions are shown together with the other data in Figure 10. In addition, the boundary line according to equation (1) is drawn. In Figure 11 all measurement results are shown with respect to their associated current values. Further, the boundary line representing the ratio of the current densities with the value of 3 is shown.

The measurements show clearly that the processes run effectively as shown in Figure 2. By adapting the on-potential it is principally possible to obtain each of the three states. a.c. corrosion can be stopped permanently by a sufficiently low on-potential. The problem is the increase in pH at the steel surface. On the other hand, the reduction of the spread resistance may lead to an increased corrosion risk during a later shift of the on-potential in the positive direction. For minimizing this risk, the on-potential has to be more positive than -1.2 V CSE .

The results clearly show that short-term shifts of the on-potential to more negative values are only acceptable if the value is adjusted to the current a.c. voltage on the pipeline.

5. Conclusion

Based on the performed investigation it can be concluded that the threshold determined in laboratory tests are transferrable to field applications. For current density values determined on coupons one of the criteria below must be met:

- Average a.c. current density $< 30 \text{ A/m}^2$
- Average protection current density $< 1/\text{m}^2$
- Ratio of a.c. current density to protection current density < 3

These limits are shown in Figure 11. The limits allow an assessment of the corrosion risk. The discussion of the mechanism [16, 17, 21] of a.c. corrosion clearly shows that the current densities are responsible for the corrosion process. Therefore, the determination of the current density values for assessing the corrosion risk is justified. However, the use of coupons is fraught with certain problems, since the obtained results are determined to a large extent by the local soil conditions. The use of potential and a.c. voltage values for the evaluation of the corrosion risk offers significant benefits, because the statement can be applied to the entire pipeline.

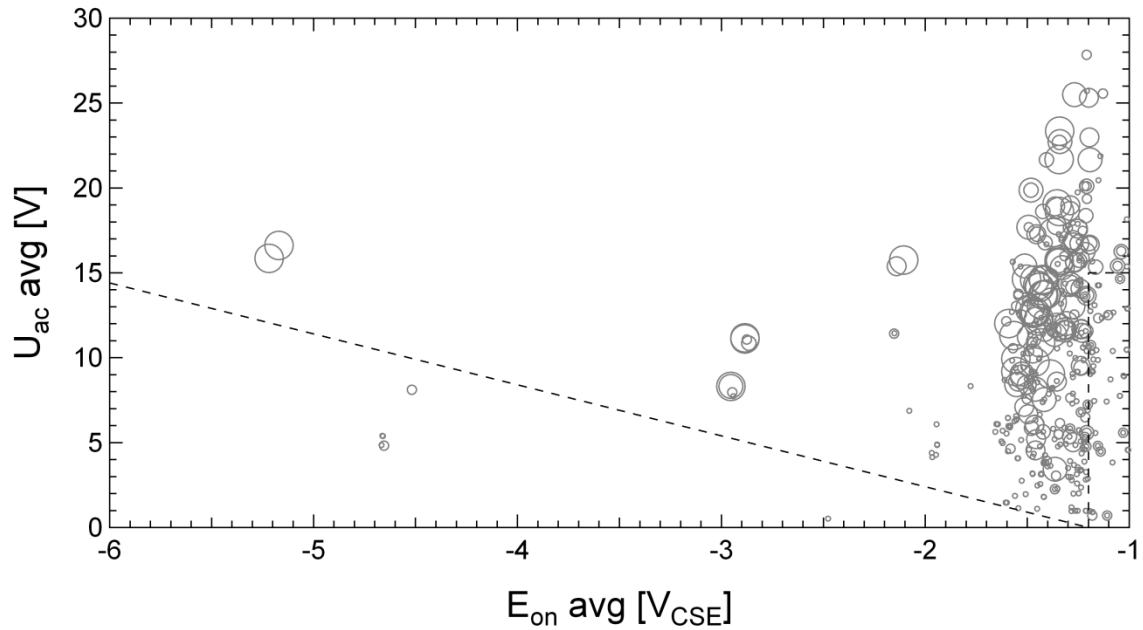


Figure 10: Potential value data of all measurements. Based on the proposed limits, there is a risk of corrosion above the drawn borderline.

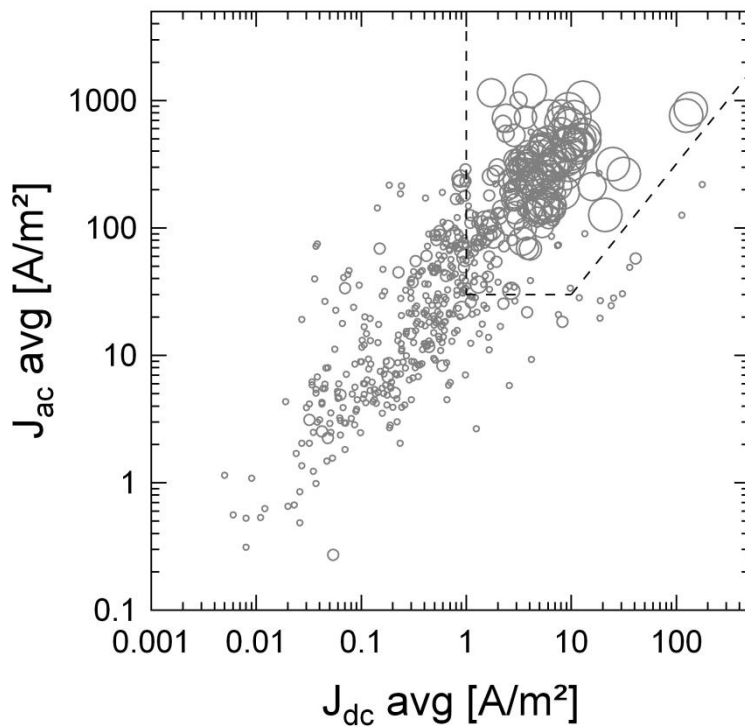


Figure 11: Current density value data of all measurements. Based on the proposed limits, there is a risk of corrosion above the drawn borderline.

The evaluation of the field data in terms of potential values is shown in Figure 10. In addition, the limits determined in laboratory tests are shown. It shows generally a good correlation of the results with respect to the thresholds. For potential values one of the criteria below must be met:

- Average a.c. voltage < 15 V and average on-potential more positive than -1.2 V CSE
- $$\frac{U_{ac}}{|E_{on}| - 1.2} < 3$$

Concerning the limit for negative on-potentials it is important to realize that there is no theoretical justification for the ratio of 3. In principle it is possible that the value could be even lower. Further it has to be taken into consideration that theoretically lower on-potential values should be used, since the spread resistance for alternating current is often lower than that for direct current.

6. Thanks

This work was only possible because of the generous support of the DVGW, ENBW Regional AG, Stuttgart, E.ON-Ruhrgas AG, MERO Germany GmbH, MVV Energie AG, RWE Westfalen-Weser-Ems Netzservice GmbH, Verbundnetz Gas AG and WINGAS GmbH & Co. KG.

7. Literature

1. G. Heim, G. Peez, "Wechselstrombeeinflussung einer kathodisch geschützten Erdgashochdruckleitung", *3R International* **27**, 345 (1988).
2. B. Meier, "Kontrollarbeiten an der Erdgasleitung Rhonetal", *GWA* **69**, 193 (1988).
3. D. Bindschedler, F. Stalder, "Wechselstrominduzierte Korrosionsangriffe auf eine Erdgasleitung", *GWA* **71**, 307 (1991).
4. G. Heim, G. Peez, "Wechselstrombeeinflussung von erdverlegten kathodisch geschützten Erdgas-Hochdruckleitungen", *gwf*, 133 (1992).
5. D. Funk, W. Prinz, H. G. Schöneich, "Untersuchungen zur Wechselstromkorrosion an kathodisch geschützten Leitungen", *3R International*, 31 (1992).
6. M. Büchler, H.-G. Schöneich, F. Stalder, "Discussion of Criteria to Assess the Alternating Current Corrosion Risk of Cathodically Protected Pipelines", in Joint technical meeting on pipeline research, p. Proceedings Volume Paper 26, PRCI, (2005).
7. L. V. Nielsen, B. Baumgarten, P. Cohn, "On-site measurements of AC induced corrosion: Effect of AC and DC parameters", in CEOCOR international Congress, CEOCOR, c/o C.I.B.E., Brussels, Belgium, (2004).
8. L. V. Nielsen, B. Baumgarten, P. Cohn, "Investigating AC and DC stray current corrosion", in CEOCOR international Congress, . Editor. CEOCOR, c/o C.I.B.E., Brussels, Belgium, (2005).
9. M. Büchler, F. Stalder, H.-G. Schöneich, "Eine neue elektrochemische Methode für die Ermittlung von Wechselstromkorrosion", *3R International* **44**, 396 (2005).
10. M. Büchler, C.-H. Voûte, H.-G. Schöneich, "Diskussion des Wechselstromkorrosionsmechanismus auf kathodisch geschützten Leitungen:

- Die Auswirkung des kathodischen Schutzniveaus", *3R International* **47**, 304 (2008).
11. M. Büchler, C.-H. Voûte, H.-G. Schöneich, "Discussion of the mechanism of a.c.-corrosion of cathodically protected pipelines: The effect of the cathodic protection level", in CEOCOR international Congress, . Editor. CEOCOR, c/o C.I.B.E., Brussels, Belgium, (2008).
 12. M. Büchler, C.-H.Voûte, "Wechselstromkorrosion an kathodisch geschützten Rohrleitungen: neue Erkenntnisse zum Mechanismus", *DVGW - energie/wasser-praxis* **6**, 18 (2009).
 13. B. Leutner, S. Losacker, G. Siegmund, "Neue Erkenntnisse zum Mechanismus der Wechselstromkorrosion", *3R International* **37**, 135 (1998).
 14. 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).
 15. M. Büchler, C.-V.Voûte, H.-G. Schöneich, "Evaluation of the effect of cathodic protection levels on the a.c. corrosion on pipelines", Eurocorr Conference Proceedings, (2007).
 16. M. Büchler, "Kathodischer Korrosionsschutz: Diskussion der grundsätzlichen Mechanismen und deren Auswirkung auf Grenzwerte", *3R International* **49**, 342 (2010).
 17. M. Büchler, "Cathodic protection: A general discussion of the involved processes and their consequences for threshold values", in CEOCOR international Congress 2010 Bruges, CEOCOR, c/o VIVAQUA., Brussels, Belgium, (2010).
 18. M. Büchler, D. Joos, C.-H.Voûte, "Feldversuche zur Wechselstromkorrosion", *DVGW - energie/wasser-praxis* **Juli/August 2010**, 30 (2010).
 19. M. Büchler, P.Schmuki, H. Böhni, "Formation and Dissolution of the Passive Film on Iron studied by a Light Reflectance Technique", *J. Electrochem. Soc.* **144**, 2307 (1997).
 20. P. Schmucki *et al.*, "Passivity of Iron in Alkaline Solutions Studied by in Situ XANES and a Laser Reflection Technique", *J. Electrochem. Soc.* **146**, 2097 (1999).
 21. M. Büchler, "Kathodischer Korrosionsschutz: Diskussion der grundsätzlichen Mechanismen und deren Auswirkung auf Grenzwerte", *3R International* **49**, 342 (2010).
 22. M. Büchler, C.-H. Voûte, H.-G. Schöneich, "Kritische Einflussgrößen auf die Wechselstromkorrosion: Die Bedeutung der Fehlstellengeometrie", *3R International* **8**, 324 (2009).