Determining the effectiveness of cathodic protection of buried pipelines

-A comparative study between field experience, existing standards and the application of “on-potential” criteria-

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Abstract

At Open Grid Europe (and for most gas transmission operators in Germany) the method of choice for assessing the effectiveness of cathodic protection of non-piggable pipelines is the so called Intensive measurement technique according to EN 13509 By using this technique the IR-free potentials of coating defects are determined and compared to the protection potentials as stated in the ISO 15589-1. Any coating defects which do not meet the protection criteria are excavated and thoroughly inspected. In more than 90 % of inspected excavations no corrosion was found, conclusively the effectiveness of cathodic protection in this cases was proven even without meeting the protection criteria as mentioned in the ISO 15589-1. The data was analyzes by considering aeration conditions and soil resistivity. By doing so a number of unnecessary excavations with no corrosion risk could be saved.

Re-analyzing the data by application of the on-potential criteria according to EN 14505 (cathodic corrosion protection of complex structures) without the knowledge of coating and convective conditions leads to wrong assessment of the data.

However the combination of the on-potential criterion with multi-parameter analysis according to the method proposed within the CeoCor Working Group H “Protection Criteria” leads to very similar results as obtained by assessment according to ISO 15589-1. It is suggested that a further validation and refinement of the input parameter is needed.

Furthermore it can be concluded that by using the off-potential criterion of -0.85 V the technically relevant corrosion sites could not be found.

Introduction

Open Grid Europe operates a gas transmission pipeline network of around 12,000 km. For the vast majority of these pipelines integrity can be verified by intelligent-pigging, whose results are used as an indirect proof for the effectiveness of cathodic protection. In contrary for the non-piggable pipelines with an approximate length of 3000 km the intensive measurement technique according to EN 13509 (Measurement techniques for cathodic corrosion protection) is the option of choice for determining the effectiveness of cathodic protection. Briefly, on-, and off potentials and corresponding potential gradients are measured with this technique to detect coating defects and to determine the IR-free potential within the defect.The effectiveness of cathodic protection is determined with the IR-free potentials stated in ISO 15589-1 (table 1).

Table 1: Protection potentials according to ISO 15589-1

Soil conditions	**IR-free potential / V**
Aerobic conditions	-0.85
Aerobic conditions with sol resistivity $100 < \rho < 1000\ \Omega$ m	-0.75
Aerobic conditions with sol resistivity $\rho > 1000\ \Omega$ m	-0.65
Anaerobic conditions	-0.95

Generally coating defects where the protection potential is not met are excavated, inspected for loss of wall thickness and re-coated.

Experience from excavation showed that in more than 90 % of cases no corrosion was found despite not meeting the potential criteria. This experience reflects the recent development as discussed in the CeoCor Working group H and concludes the multi-dimensionality of a corrosion process.

Within this work the data from intensive measurements and from excavations are presented. Furthermore the results are compared to the protection criteria as mentioned in EN 14505 “cathodic protection of complex structures” and as well to the protection criteria developed by SGK (Swiss Society for Corrosion Protection) within the framework of CeoCor Working Group H “Cathodic Protection Criteria”.

-0.95 V IR-free potential criterion

For assessing the effectiveness of cathodic protection according to ISO 15589-1 aeration and soil resistivity needs to be measured. If no additional information of aeration and soil resistivity is available the -0.95 V (IR-free) criterion is the only safe option of choice.

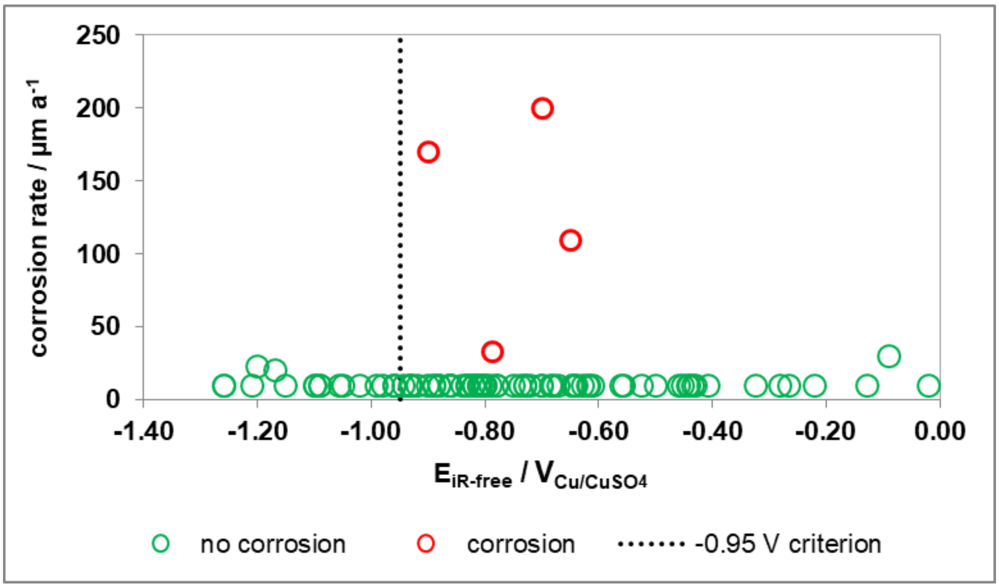

Figure 1: Calculated corrosion rate from excavation sites as a function of IR-free potential assessed with intensive measurement technique. Results for IR-free potential < -0.95 V were added from operational excavations, as no excavations will be suggested from intensive measurement data assessment for potentials IR-free potential < -0.95.

Figure 1 shows the corrosion rate as a function of IR-free potential for overall 89 excavations. From 89 excavations 71 were due to assessment of intensive measurement data within the pipeline integrity management procedure. The rest 18 excavations were added from operational excavations where beforehand an intensive measurement was performed.

The corrosion rate was calculated from extrapolating the maximum depth of corrosion pits found on the steel surface to the year of operation. At four out of 71 excavations (~5 %), where the

-0.95 V criteria was not met technically relevant corrosion was found. This shows that the criterion is conservative enough, to detect coating defects with substantial corrosion. At the same time there is a noticeable amount of excavations, where the protection criteria were not met and no corrosion was found. This is in accordance to the observations presented by Joos and Buechler (Angst, 2016) (Joos & Büchler, 2016) that there is seemingly no correlation between the IR-free potential and corrosion rate. Conclusively applying the strictest potential criteria without the knowledge of aeration condition will result in vast amount of excavations for maintaining the integrity of pipelines.

-0.95 V and -0.85 off-potential criterion

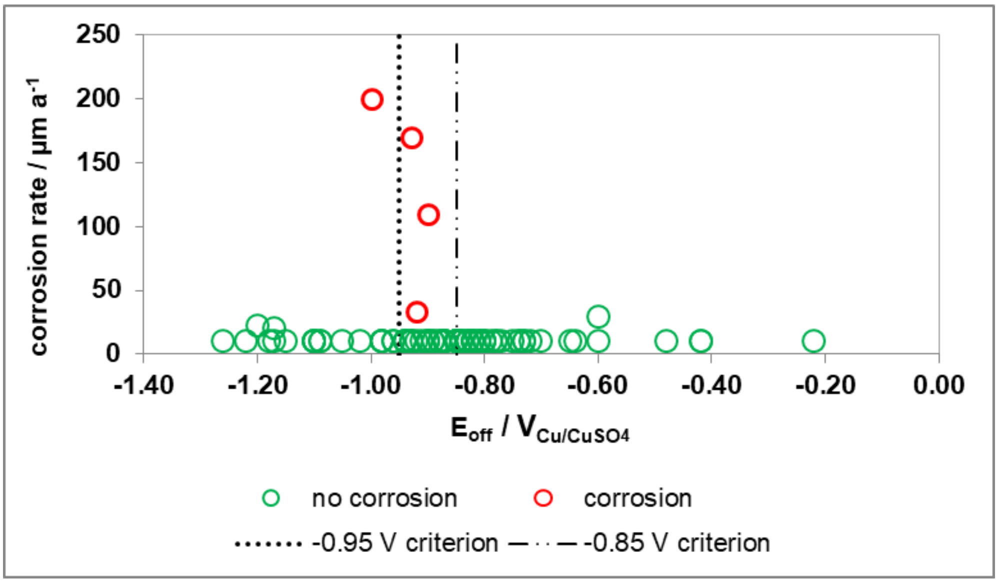

Figure 2: Calculated corrosion rate from excavation sites as a function of off-potential from intensive measurement technique.

Plotting the off-potentials as a function of corrosion rate (figure 2) shows a very similar picture as the assessment with IR-free potential, namely the independency of corrosion rate from the potential. Neither high nor low potential mean any increase in corrosion risk, more the corrosion is scattered around the potential values of -1 V to -0.8 V alongside with a vast number of points with no corrosion at all.

Comparing the off-potential measurements with the assessment via IR-free potential criterion of -0.95 V it is obvious that the latter one is a more conservative approach. Based on the data presented here the use of -0.85 V off-potential criterion will lead to catastrophic misinterpretation of the data ultimately the integrity of the pipeline is not secured.

Assessment of data by considering aeration conditions

Same data as presented previously were analyzed while considering the aeration conditions at the defect site. Aeration condition at the defect side was classified according to the bedding material and ground water condition provided from geological data at pipeline depth. Coarse bedding materials (e.g. sand and gravel) might support aeration (aerobic conditions) and the presence of finer bedding materials or ground water should hinder aeration so indicating anaerobic conditions. Thus according to ISO 15589-1 the IR-free potential criteria of -0.85 V (aerobic) and -0.95 V (anaerobic) can be used to determine the effectiveness of cathodic protection of a coating defect. Figure 3 and figure 4 depict the potential/excavation data after considering the aeration condition. While the IR-free potential are scattered statistically starting from -1.2 V to almost 0 V for aerobic conditions the maximum potential resides at around -0.6 V for anaerobic conditions. This might be a first hint on successful classification of the potential data according to available geological data, as potentials higher than typically expectable potential values of iron is controlled under aerated by the thickness and oxidation levels of iron within the oxide layer (Wapner, 2006). Because of the conservative choice of the protection potential corrosion can still be detected. Nevertheless, the data indicate again an independency of IR-free potential of the corrosion rate. This applies especially to aerated conditions and is in good agreement to findings reported by Angst et al. (Angst, 2016) as on passivated iron surface under alkaline condition the potential is determined mostly by the iron oxidation state in the passive layer. Statistically seen at 98 % of the excavations not meeting the -0.85 V criterion and at 73 % of the excavations not meeting the -0.95 V criterion no corrosion was found.

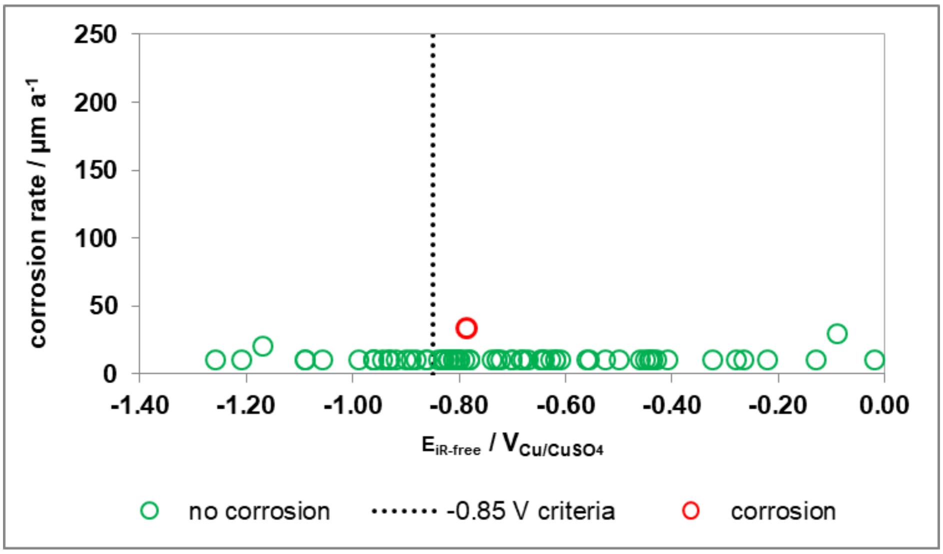

Figure 3: Calculated corrosion rate from excavation sites as a function of IR-free potential assessed with intensive measurement technique. Depiction of aerated conditions according to geological data.

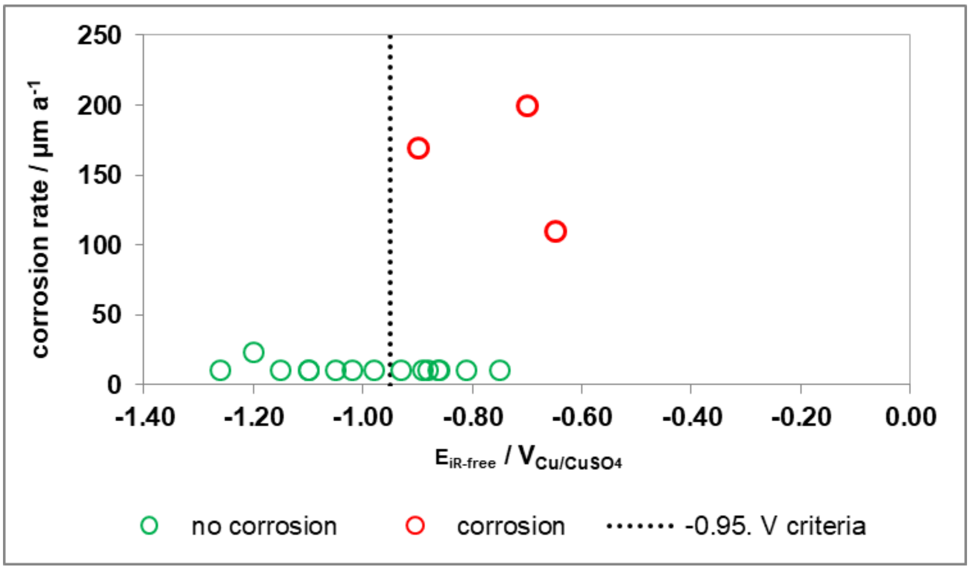

Figure 4: Calculated corrosion rate from excavation sites as a function of IR-free potential assessed with intensive measurement technique. Depiction of anaerobic conditions according to geological data.

Assessment of data by considering IR-free potential, aeration and soil resistivity

In the ISO 15589-1 the potential criteria of -0.75 V for soil resistivity between 100 and 1000 Ω m and -0.65 V for soil resistivity above 1000 Ω m can be applied. This means that soil resistivity needs to be monitored or measured at places were the potential criteria of -0.85 V is not met under aerobic conditions. Applying the soil resistivity and determining the aeration condition is in full agreement with ISO 15589-1 and is from a practical importance as unnecessary excavations with no corrosion risk can be readily reduced. In figure 5 and figure 6 data under aerobic conditions are shown.

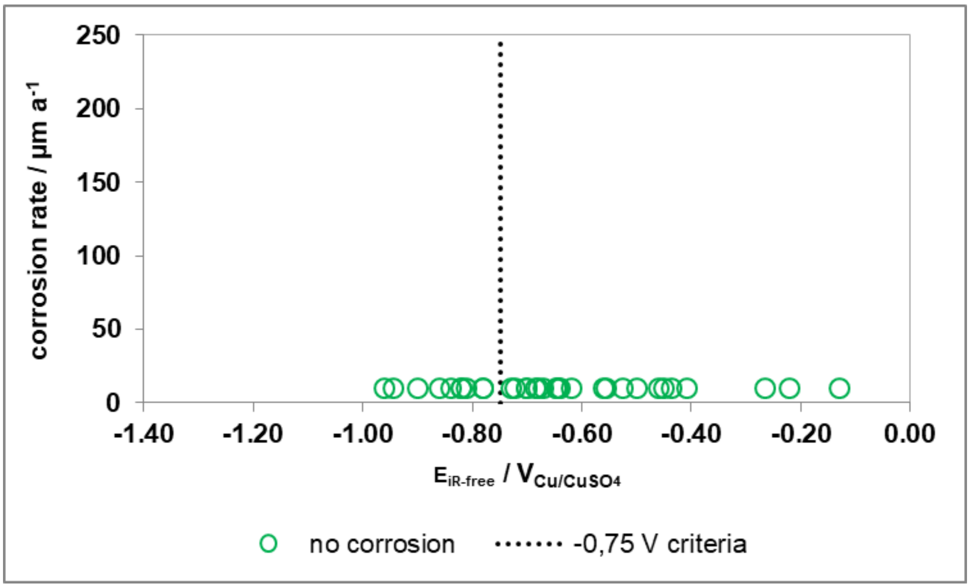

Figure 5: Calculated corrosion rate from excavation sites as a function of IR-free potential assessed with intensive measurement technique for soil resistivity between 100 and 1000 Ω m under aerated conditions.

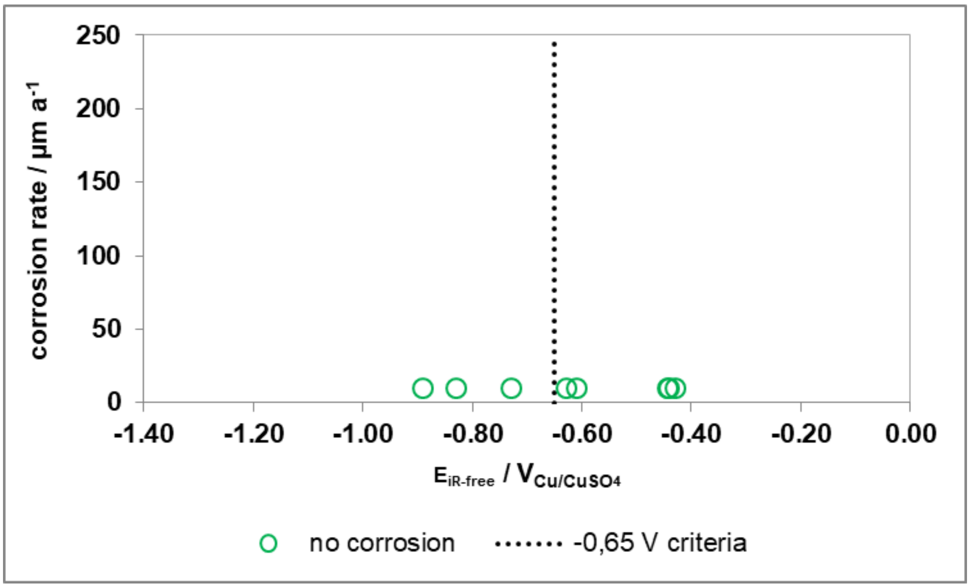

Figure 6: Calculated corrosion rate from excavation sites as a function of IR-free potential assessed with intensive measurement technique for soil resistivity above 1000 Ω m under aerated conditions.

Conclusively a combined consideration of aeration and soil resistivity will reduce the number of excavations to almost 60 % while the safety is still maintained, due to the conservative choice of the protection criteria. However the fact that the corrosion rate is independent of IR-free potential is undisputed.

Application of the on-potential criterion for complex structures

Apart from determining the effectiveness of cathodic corrosion protection of pipelines according to ISO 15589-1 for complex structures the criteria mentioned in EN 14505 “cathodic corrosion protection of complex structures” was applied to this existing data. One of the criteria mentioned in the latter is the use of the on-potential of -1.2 V for soils below 100 Ω m irrespective of aeration conditions. That means on-potentials below -1.2 V indicate an effective cathodic protection. However applying this criterion to the previously shown data for soils with a resistivity below 100 Ω m results into a situation where sites with relevant corrosion will be indicated wrongly as no-corrosion (figure 7).

As stated in the introductory part of this paper, corrosion is a multi-dimensional problem. While according to ISO 15589-1 at least two-dimensions (aeration and soil resistivity) are needed to determine the effectiveness of cathodic protection, according to EN 14505 it is only one dimension (soil resistivity). However without being stated clearly in the standard the on-potential criterion very much depends on the coating quality and defect size. This was thoroughly discussed in the work of Buechler et al. (Büchler, Collet, & Angst, 2017) by experimentally proving and simulating CP within large defects. Bigger defects in the range of 100 cm^2 might exist on old bituminous coated pipelines. Increased risk of a not effective CP originates from the fact that heterogenous polarization of a defect in well aerated soils leads to formation of galvanic cells within the defect. Under this condition an on-potential -1.2 V is not sufficient to compensate the potential differences on the surface. Surprisingly this might apply to one excavation result out of four presented here where relevant corrosion rate was found. The other three were found under anaerobic conditions in ground water. The soil resistivity in these cases was below or close to 100 Ω m. It is unlikely that under such conditions a substantial aeration cell might form. This leads to two further important parameters besides the defect size: water hardness and convection. The combination of soft and flowing water with a large coating defect will increase the difficulty of getting a protection through concentration polarization. Conclusively also for this condition a much more negative on-potential than -1.2 V is needed.

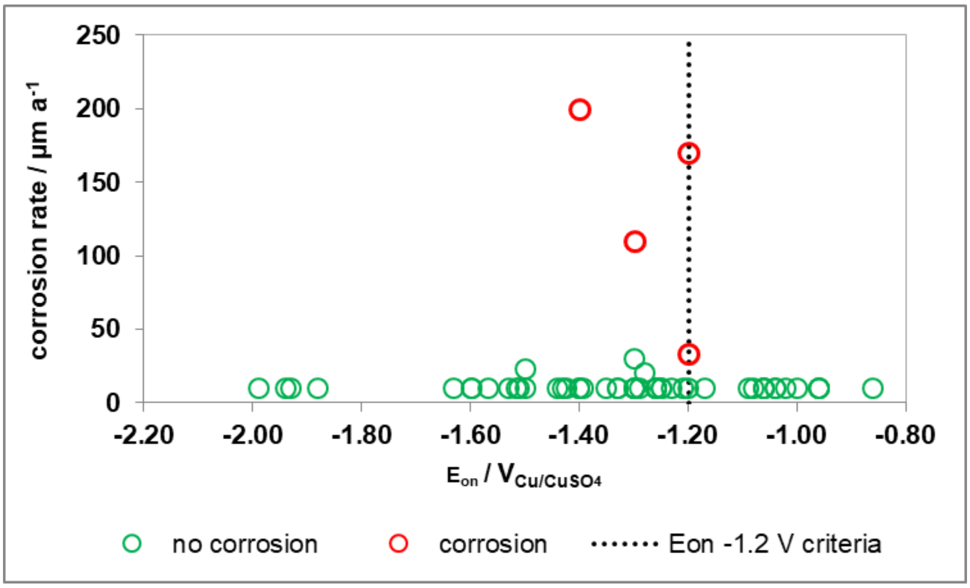

Figure 7: Calculated corrosion rate from excavations as a function of remote on-potential to evaluate the data according to the on-potential criteria according to EN 14505.

This means if it is known that the buried pipelines on a compressor station have old bituminous coatings with a high probability of larger defects and soft ground water, than other additional methods need to be considered to determine the effectiveness of corrosion protection.

Analyzing the data with current density criteria

The conclusion of previous analysis shows that the use of IR-free potential criteria in combination with aeration and soil resistivity is a very conservative approach for determining the effectiveness of cathodic protection. Application of the on-potential criteria according to EN 14505 without the knowledge of aeration, water chemistry (hardness) and defect size will result in misinterpretation and safety issues. As stated previously effectiveness of cathodic protection needs to be analyzed multi-dimensionally. A proposal from SGK within the framework of Working Group H “potential criteria” combines the use of on-potential with parameters as shown in table 2. To be precise the proposal suggests the use of current density criteria, which can be directly transferred to an on-potential according to

$$|E_{on}| = \frac{J\,\pi\,\rho\,d}{8} + |E_{ir-free}| \quad (1)$$

where E_{on} is the minimum on-potential needed for an individual defect, J the current density to achieve $E_{ir\text{-}free}$ or better the protection potential, d the defect diameter, ρ the soil resistivity and $E_{ir\text{-}free}$ is the IR-free potential according to ISO 15508-1 for the corresponding aeration and soil resistivity.

Table 2: Parameters for calculating the protection current density (Büchler M. , 2019)

Defect surface	*[cm²]*	*<1*	*1-10*	*10-100*
a	*[A/m²]*	0.01	0.03	0.1
Aeration (J_{O2})	*[A/m²]*	*<0.01*	*0.01 - 0.1*	*0.1 - 1*
b	*[A/m²]*	0.01	0.1	1
Hardness	*[°fH]*	*0-15*	*15-25*	*>25*
c	[-]	1	0	0
Flow	*[m/day]*	*<0.1*	*0.1 - 1*	*>1*
d	*[A/m²]*	0	0.1	1
Bedding size	*[mm]*	*< 1*	*1-10*	*> 10*
e	*[A/m²]*	0	0.1	1

The current densities from table 2 were used to calculate the overall current density according to

$J = a + b + c\ (d + e)$ (2)

The data were re-analyzed by applying the proposed method as shown in figure 8 and 9. It needs to be mentioned that under presence of groundwater always a flow rate of 0.1 – 1 m/day corresponding to 0.1 A m^{-2} additional current density was chosen.For clarity of how the current density was chosen three examples are presented in following:

Example 1: Bituminous pipeline with clay as bedding material. No ground water.

Factor	a	b	c	d	e
Selected parameters	0.1 A/m^2	0.01 A/m^2	1	0	0

Overall current density needed: 0.11 A/m^2 (clay as bedding material leads mostly to anaerobic conditions)

Example 2: PE coating with sand as bedding material soft ground water.

Factor	a	b	c	d	e
Selected parameters	0.03 A/m^2	0.01 A/m^2	1	0.1	0.1

Overall current density needed: 0.24 A/m^2 (Ground water leads to anaerobic condition)

Example 2: Bituminous coating with sand bedding. No ground water.

Factor	a	b	c	d	e
Selected parameters	0.1 A/m^2	0.1 A/m^2	1	0	0.1

Overall current density needed: 0.3 A/m^2

The diagram summarizes the measured E_{on} as a function of calculated minimum on-potential needed to achieve the current density. The diagram is divided by the line were the ratio of the calculated and measured E_{on} corresponds to one. Above that line the ratio is > 1 indicating possible corrosion risk and if the ratio is < 1 the cathodic protection is effective. On the first glance some of the calculated values seem to be unrealistically negative. This is due to the fact, that as mentioned previously larger defect sizes in combination with high aeration might give rise to heterogeneous polarization (Büchler, Collet, & Angst, 2017).The proposed current densities in Table 2 for these cases represent a very conservative approach that demonstrates the required on-potentials for meeting the -0.85 VCSE protection criterion. The above data clearly demonstrate that this is not required. Based on these data effective cathodic polarization does not require such negative E_{on} values under these conditions. A further reason for this high values are the soil resistivity which are mostly over 1 kΩ m (the highest one is more than 4 kΩ m). Even though the risk of corrosion might be hinted by calculation, no corrosion was found in the field. Conclusively the method seems to deliver conservative results for such conditions, which is relevant for ensuring safety. A closer look at the potentials between -0.8 to -2.4 V (figure 9) shows that three out of four data were predicted correctly as corrosion issues.

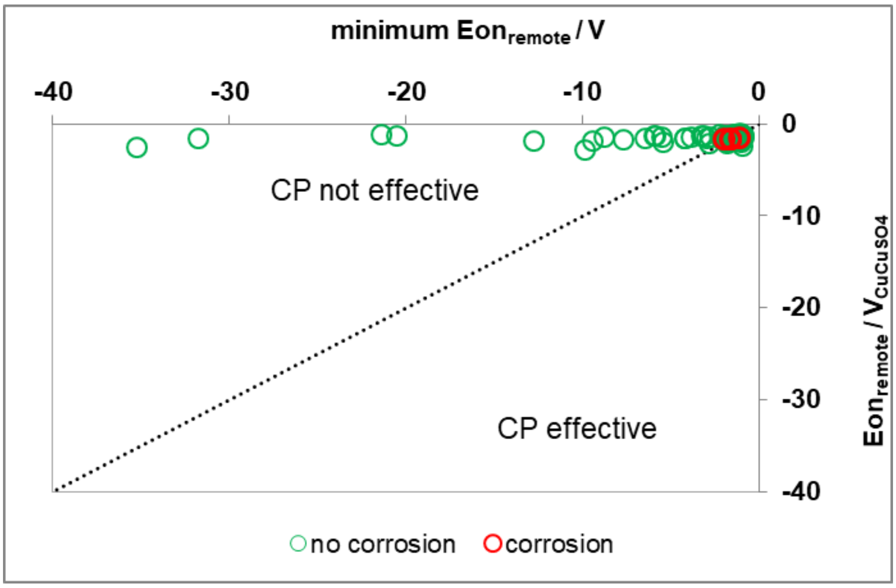

Figure 8: Calculated minimum remote on-potential as a function of measured on-potential

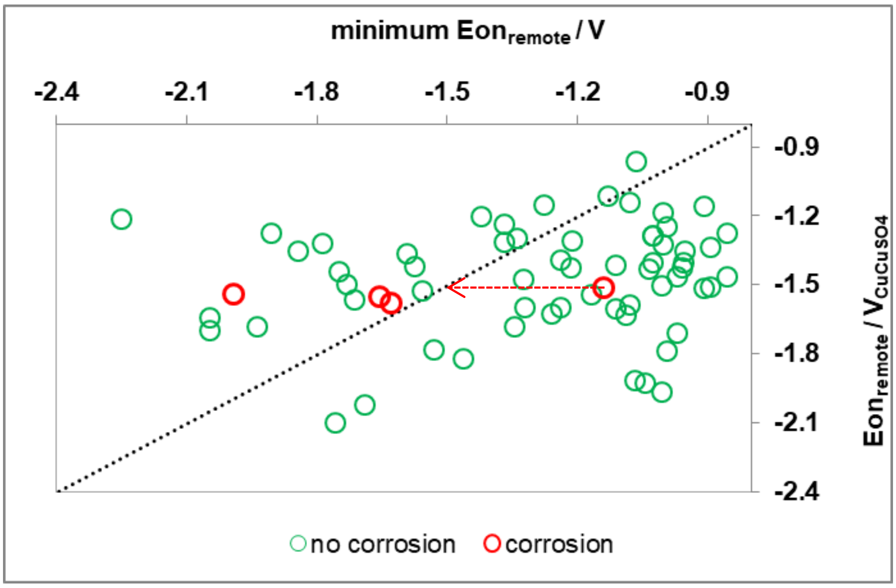

Figure 9: The same data as depicted in figure 8 with smaller range of potentials. The red arrow indicates the position of the red circle, if a calculation based on anaerobic condition is performed.

One data with corrosion issue was wrongly predicted as effective CP. Based on geological data the pipeline runs through a well aerated soil at this point and the soil resistivity is in the range of 60 Ω m. However excavation results revealed that the pipeline is in ground water, so that the condition might be more anaerobic. A recalculation considering the anaerobic condition, results in a minimum required on potential of -1.5 V indicated with an arrow in figure 9. Even this on-potential gives a ratio between calculated to measured on potential < 1 indicating effective CP at this point.

While the above mentioned data were plotted as a function of remote on-potential, figure 10 represents the same data with the on-potentials measured directly over the defect. Direct comparison of assessment with remote on-potential towards the assessment with the on-potential over the defect shows that the latter one is more conservative, as the number of data points with a ration >1 leads to 10 more excavations. If the one data with the corrosion issue is recalculated to the condition found at the excavation, the data point would be in the field indicating corrosion risk.

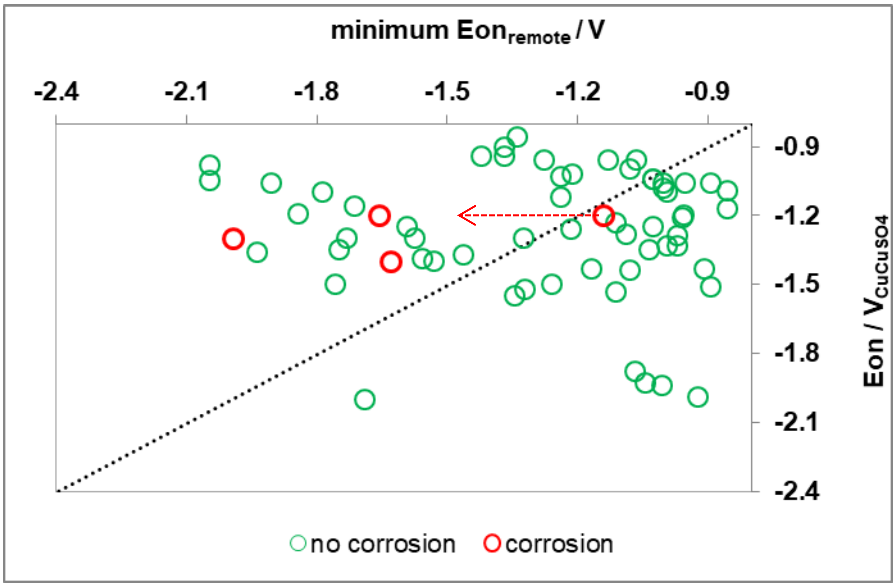

Figure 10: The same data as depicted in figure 9 changed with the on-potential measured directly over the defect. The red arrow indicates the position of the red circle, if the calculation would have been performed based on anerobic parameters.

From an economical point of view 40-50 % of the data with no corrosion issues would have been not excavated, which is comparable to the number of excavation results achieved from analyzing the data according to ISO 15589-1 considering the aeration and soil resistivity.

Conclusion

Within this paper the procedure to determine the effectiveness of cathodic protection according to ISO 15589-1, the off-potential criteria, EN 14505 and the proposed current density criteria from CeoCor Working Group H “Potential Criteria” were compared. Herein the excavation data resulting from intensive measurement techniques and operational excavations were used.

Analyzing the data by using the off-potential criteria of -0.85 V would have classified the points with not effective CP as wrongly as effective.

Strictly following the IR-free potential criteria according to ISO 15589-1 in combination with analyzing aeration and soil resistivity results in a conservative approach for determining the effectiveness of cathodic protection as numerous excavations were suggested, where no corrosion issue existed. In contrast to that applying solely the on-potential criteria from EN 14505 leads to clear underestimation of the corrosion risk, as only the soil resistivity and the on-potential are considered.

The newly proposed method by SGK within the CeoCor Working Group H “Protecion Criteria” defines how the on-potential criteria can be individually adapted by considering the parameters defect size (coating quality), aeration, water hardness, flow velocity and bedding size. Three out of four corrosion issues were predicted correctly, while one was wrongly stated as no corrosion issue. Taking the on-potential over the pipeline defect instead of the remote on-potential seems to be a more conservative and correct approach.

It can be concluded that using the on-potential criteria or current density criteria needs an extensive analysis of the input parameters itself (e.g. validation of soil resistivity measurements, measurement of aeration and bedding). It is believed that a multi-dimensional analysis and assessment of data might give a more detailed view on the effectiveness of CP. Within this work a ratio between calculated and measured on-potential values defining the effectiveness of CP is introduced. While a ratio < 1 indicates effective CP a ratio > 1 indicates possible corrosion. It is suggested that the ratio indicating corrosion needs a safety factor; e.g the ratio can be 0.9 (validity only for $CuCuSO_4$ reference electrode) above which corrosion is indicated. Another important point of discussion is the bigger coating defect in well aerated soil as the calculation provides unachievable high on-potential values. While this might be correct from a theoretical point of view, excavation results showed that under well bedded aerated soils (e.g. sand) with very high soil resistivity above 1000 kΩ m corrosion was not observed, despite the fact that the on-potential is not met. It is proposed that the probability in the formation of galvanic cells within a single defect might be very low for soils with high resistivity (Zhang, 2011).

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