

Detection and mitigation of AC induced corrosion in pipelines

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Abstract

Concepts for detection and mitigation of AC induced corrosion are discussed. Regarding detection systems, it is recommended that direct measurements of corrosion rate using buried probes electrically connected to the pipeline are included in the detection procedure. Based on characterisation of the mechanisms leading to alkalisiation of the local environment at a coating defect it is justified that detection procedures based solely on measuring of electrical indicative parameters are insufficient for adequate reliability. Mitigation procedures involve to a large extent grounding of the pipeline via capacitors, and an intelligent switch device is presented that allows for significantly time saving procedures for CP surveys, since the device recognises the on/off pattern of the timer mounted on the rectifier and disconnects the otherwise disturbing capacitors when the timer is active.

Keywords: Pipelines, AC induced corrosion, mechanisms, standards, monitoring, AC corrosion detector, mitigation, intelligent switch device (ISD).

Introduction

Buried pipelines for transmission of natural gas are often paralleled with overhead high-voltage power lines in so-called energy corridors. The paralleled structures may result in induction of AC voltage along the pipeline which creates a voltage from pipe to remote earth. This voltage is added to the DC potential of the pipeline, which most often is controlled by sacrificial anodes or impressed current from a rectifier system to produce cathodic protection (CP) of the pipe (figure 1). The AC voltage causes an AC current to flow between the pipe and earth through coating defects. The magnitude of the induced voltage is determined by factors such as the length of the paralleling, the distance between the structures, the pipeline coating resistance and the level of current flowing in the overhead power transmission line. For at certain pipeline, the paralleling length, the distance between structures and the coating resistance are fixed and the magnitude of induced AC is controlled by the power transmission – figure 2 shows an actual measurement from the Danish gas grid system. Corrosion may result from such AC induction despite cathodic protection requirements are met, and this problem receives increasing attention from the gas transmission business. The present paper aims to give an overview of mechanistic recognitions achieved through years of laboratory research and field investigations, and on this basis give a discussion on applicable monitoring and mitigation devices. The discussion will be based on an electric equivalent circuit diagram.

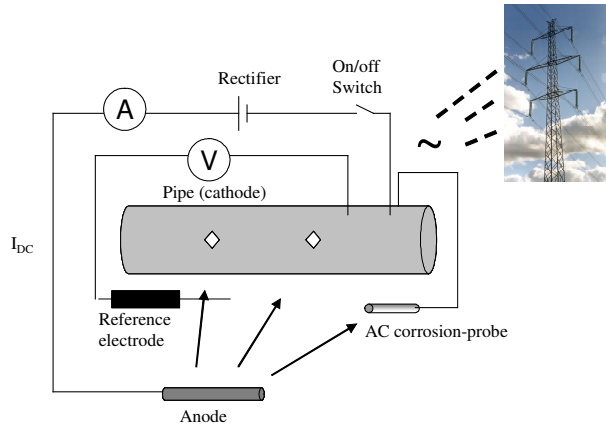


FIGURE 1 – Cathodic protection of pipeline by impressed current from rectifier system.

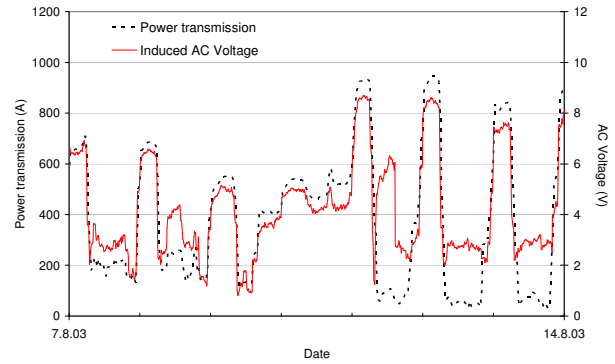


FIGURE 2 – Induced AC voltage compared with transmission current in paralleling high-voltage power line.

Electric equivalent circuit diagram

Figure 3 shows an electric equivalent circuit applicable for the AC corrosion case [1]. Between the pipe and the soil (remote earth) a number of voltage generating elements are presented, and the current passes via impedance elements present at the pipe/soil interface.

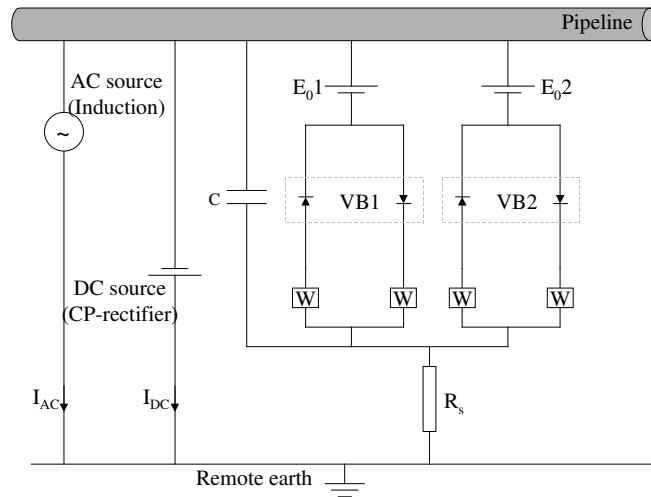


FIGURE 3 - Equivalent circuit for AC induced corrosion.

The external voltage generating elements of the diagram constitute the induced AC voltage and the DC voltage imposed by the CP. The DC voltage from the rectifier system should be used to displace the natural (open circuit) potential of the pipeline being controlled by the active electrochemical processes. Elements of two such processes are illustrated e.g. iron dissolution and H^+ reduction. Each process defines an equilibrium potential (E_0 – Nernst equation). At a pipe potential different from E_0 , the DC currents from the processes will be following characteristic functions, e.g.

exponential behaviour with respect to degree of polarisation described by the Volmer-Butler (VB) equations (represented as diodes). Forward and reverse processes have different characteristics and a diode symbol is indicated for both the forward and the reverse reaction. These so-defined VB elements are analogies to - or more general cases of - the polarisation resistance in EIS equivalent circuits. Diffusion impedances (Warburg elements) are connected to each of the semiconductor processes, since by limited diffusion conditions, the electrochemical processes are inhibited. In all, the electrochemical charge transfer processes may define a replacement impedance, Z_F , controlling the faradaic current flow. In parallel with the elements describing the above electrochemical charge transfer processes, the interfacial capacitance is positioned. In the case of AC induced corrosion this element becomes quite important since the impedance of the capacitor is inversely proportional to the frequency. At the frequency of the induced voltage (50Hz is dominating in Denmark), the impedance of the capacitor (Z_C) usually is magnitudes lower than the faradaic impedance Z_F .

Thus the AC current is transferred between the pipe surface and remote earth primarily as a capacitive current, the magnitude of which is almost entirely determined by the AC voltage divided by the so-called spread resistance, R_s . This resistance becomes then a very important parameter, since for a given induced AC voltage, the spread resistance will determine the magnitude of the AC current density. In turn, the magnitude of the AC current density will conduct the degree to which the electrochemical processes (including iron dissolution) are influenced by the AC. Further, the spread resistance will be determining the amount of IR drop when performing CP potential measurements.

Presently recommended monitoring and mitigation principles

General principles and application of cathodic protection for pipelines are described for example in standard EN 12954 [2]. Cathodic protection measurement techniques are described in EN 13509 [3]. Table 1 gives the criteria according to EN 12954 in the form of a protection potential below which the structure is cathodically protected.

Medium		Protection potential (off), V CSE
Water and soil Aerobic conditions	Normal condition	-0,85
	Aerated sandy soil $100 < \rho < 1000 \Omega \cdot m$	-0,75
	Aerated sandy soil $\rho > 1000 \Omega \cdot m$	-0,65
Water and soil Anaerob. conditions		-0,95

TABLE 1 - Protection potentials in soil and in fresh and salt water according to EN 12954 [2].

NACE standard RP0169 [4] and NACE standard TM0497 [5] are pendants to the above defined EN standards, however, with a slightly different selection of potential criteria. None of the above standards deal in detail with the AC interference problem. In the EN 12954 standard the AC corrosion problem is dealt with only in very brief terms stating that structure to electrolyte potential measurements should be performed

using suitable equipment to ensure that potential criteria of Table 1 are met in the presence of AC current on the structure. Also that corrosion likelihood may be negligible if alternating current density referred to a 1 cm² bare surface (e.g. an external test probe) is lower than 30 A/m² and the structure to electrolyte potential meets the cathodic protection criteria. On cathodically protected structures and in the presence of alternating current the protection current density may need to be higher to meet the protection potential, and finally that structures with a small number of small holidays may present a higher risk of corrosion due to alternating current.

Regarding mitigation of the AC interference, a NACE standard recommended practice RP0177 [6] on mitigation of alternating current and lightning effects on metallic structures and corrosion control systems covers personnel safety and protection of equipment rather than deals with the corrosion problem itself. This standard is therefore not considered to be relevant for the detection of AC induced corrosion, but may be useful when the problem has been encountered and measures for mitigation of the problem should be implemented.

In conclusion to the above, neither NACE nor the EN standards cover satisfactorily the AC corrosion problem. CP criteria are based on potential measurements and these are inadequate for coping with AC interference effects on corrosion.

A set of papers and guidelines that most directly focuses on the AC corrosion problem is the so-called CeoCor Booklet on AC corrosion on cathodically protected pipelines (guidelines for

risk assessment and mitigation measures) [7]. In this publication, various terms and parameters are discussed regarding their applicability for the AC corrosion detection. Three specific measurement methods are recommended for the evaluation of the AC corrosion risk (table 2).

No.	Measurement	Diagnose
1	Measuring pipe to soil potential using an instrument inserted in between a steel coupon installed into the soil and electrically connected to the pipeline to undergo the CP and the AC as the pipeline. The instant off potential (coupon to soil) may be measured by disconnecting the coupon from the pipeline, measuring the potential without IR drop. Automated measurements disconnects the coupon then measures the off potential 1 ms after disconnecting, then re-connects. Together with the on potential the current to the coupon is measured. Approximately 20 ms afterwards, the cycle is repeated. Due to a desynchronisation of the measuring cycle from the AC interference, the measurements will be taken at any time within the (e.g. 20 mS) AC interference period, including peak values.	Using this measuring technique, the pipeline is considered protected from AC corrosion if the coupon to soil off potential is at any moment more negative than the protective potential range (table 1).
2	Measuring AC current density on a coupon	Safe if the RMS AC current density is lower than 30 A/m ²
3	Measuring AC and DC current density on a coupon and defining the current density ratio (J_{AC}/J_{DC}).	The risk is low if the ratio is lower than 3, medium if between 3 and 10, and high if above 10.

TABLE 2 – Measurement recommendations according to the CeoCor booklet [7].

During the Danish research activities, instrumentation have been developed for reliable detection of AC induced corrosion in field as well as in the laboratory. Further, a device for mitigation has been developed. These instrumentations and devices are now implemented as routine tools to be used particularly for coping with the AC corrosion problem. Both sets of instrumentations are designed to fit into standard measuring posts (figure 4). The instrumentation for detection of AC corrosion is based on an instrument that controls a number of buried probes electrically connected to the pipeline. A number of such instruments arranged along a pipe section may give adequate information on the corrosion risk.



FIGURE 4 – Devices for AC corrosion detection and mitigation installed in standard measuring posts (left), and the probe used for AC corrosion detection (right).

The concept is based on a sensitive ER system measuring the decay of the thickness of an element build into the probe (figure 4) by comparing the electric resistance of the element with a twin element also build into the probe but covered from exposure to the corrosive environment [8,9]. The AC corrosion detector system then measures directly if corrosion occurs, not just indicative variables as the ones defined in tables 1 and 2. Besides this,

any of the electrical measurements defined through the CeoCor booklet (statements 1-3 in table 2), can be measured on the probe. The AC corrosion detector measures and stores automatically corrosion, AC voltage, AC current density, and spread resistance, and uses these parameters to determine the AC corrosion risk [10] – see e.g. figure 5. The mitigation device developed through the Danish activities makes use of a traditional grounding via a capacitor that allows for AC drainage but blocks the DC so as to keep the CP of the pipeline.

Highly AC interfered pipelines may need such grounding with a few kilometers distance in order to adequately bring down the AC voltage to acceptable limits.

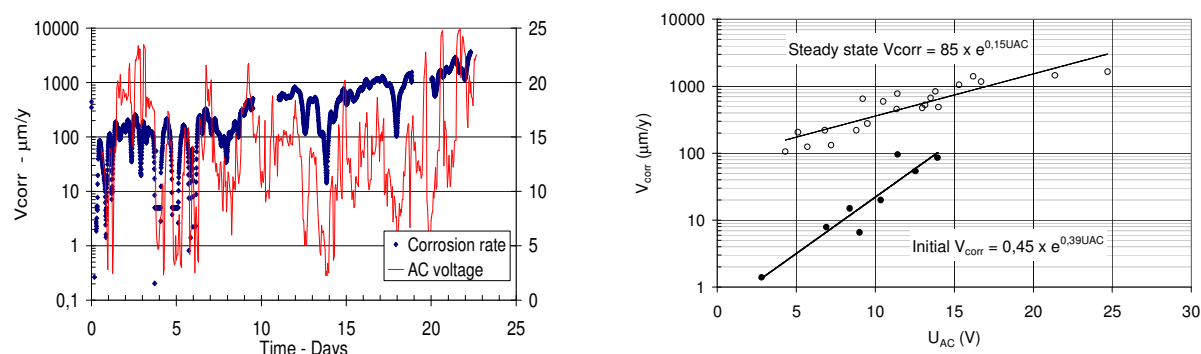


FIGURE 5 – Example of corrosion rate measurement compared with AC voltage on the pipe (left) and described as a function of the AC voltage (right).

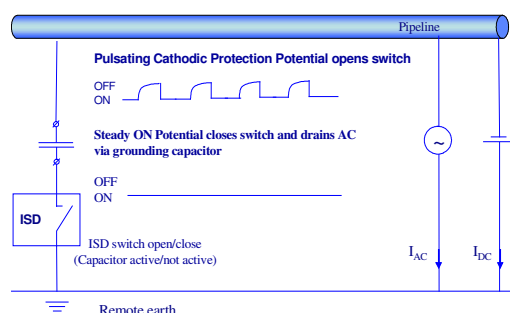


FIGURE 6 – At steady ON-potential the ISD drains the AC current through a capacitor. At regularly pulsating ON/OFF potential, the ISD disconnects the capacitor.

The capacitors however, prohibit the performance of CP surveys where the off potential is measured along the pipe. Measuring the off potential requires switching off the CP rectifier current and measuring the off potential immediately after in order to eliminate the instant IR drop but still maintaining the pipeline polarised. In practice, a timer is applied for regularly pulsating the rectifier, where after the operator is allowed to record the potential along the pipeline. If the pipeline is grounded via capacitors, the instant off potential value is not achievable since the capacitor introduces an extra time constant. Therefore, the capacitors should be disconnected prior to the CP survey.

At long pipelines this procedure (disconnection – survey – reconnection) may be very time consuming. The method of the mitigation device is therefore to recognize the pulsation of the rectifier and – in such case – automatically disconnect the capacitors [11, 12]. In this manner, two operator trips along the pipeline are saved for disconnection/re-connection of the capacitors.

Mechanisms

Monitoring and mitigation strategies are naturally based on the understanding of the mechanisms of the process or problem under consideration. A consensus is merging (see e.g. [7,13-16]) that AC induced corrosion is associated with a creation of an alkaline environment nearby the coating fault. This alkalisation is helped by the CP current, which is a direct in-situ source of OH^- (figure 7). In combination with an oscillation of the potential caused by the AC, the dangerous region becomes as the hatched area of the Pourbaix-diagram in figure 8. The (50Hz) oscillating potential means that the thermodynamic condition of the steel would be between immunity and passivity. In the immunity area, the oxides are reduced, whereas in the passive region, the iron dissolves as the first step then creates protecting oxides in the second.

It appears that the time constant for the second step is large, and that the passivation process for this reason cannot take place within the (<20 mS) period of the potential being in the anodic part of the oscillation. Eventually, if the CP current is high and the OH^- accumulates at the surface, the high-pH (>13) region in the Pourbaix-diagram showing general corrosion risk may be reached. Based on this mechanistic behaviour, the recommendations of increasing the DC protection current in order to avoid AC corrosion may not be advisable.

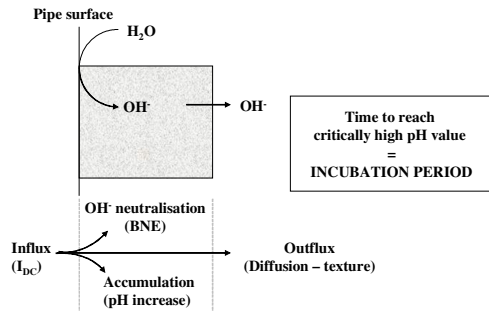


FIGURE 7 – Accumulation of OH^- at coating fault caused by CP current and blocked diffusion in the soil.

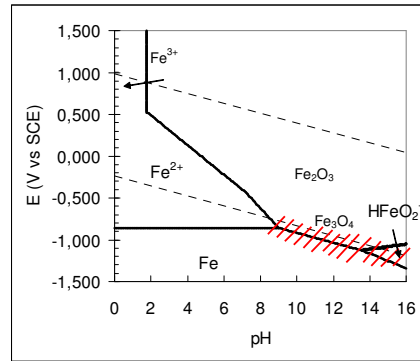


FIGURE 8 – Pourbaix-diagram showing dangerous region in respect to AC induced corrosion.

It can be shown from simple laboratory experiments that the superimposed AC depolarises the kinetics of the electrode system (figure 9) which is in agreement with practical field experience. In addition to (or perhaps as a result as) the effect of the AC current on the potential oscillation, the production of alkalinity increases with increasing AC current. Since the AC current density is approximately proportional to the induced AC voltage, and the proportionality factor is the inverse spread resistance, the spread resistance is a very important factor. It can be shown both mathematically [7] and experimentally (see figure 10) that the spread resistance (in $\Omega\cdot\text{m}^2$) decreases with decreasing area of the coating defect. In conclusion to this, small coating defects are more susceptible to AC corrosion than larger coating defects. As a consequence of the above, the standard AC corrosion probes have small coating fault areas, and the AC corrosion detector measures (as one diagnostic parameter) the spread resistance of each probe. This spread resistance is further an indication on whether ground water is present, as well as the local (initial) soil resistivity that turns out to be crucial. Presence of earth alkaline cations (Ca, Mg) increases the spread resistance by precipitating in the presence of alkalinity [7, 13].

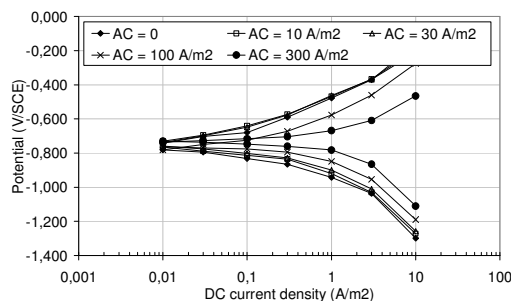


FIGURE 9 – Depolarisation of the kinetics shown by polarization curves in synthetic soil solution with different levels of superimposed AC current.

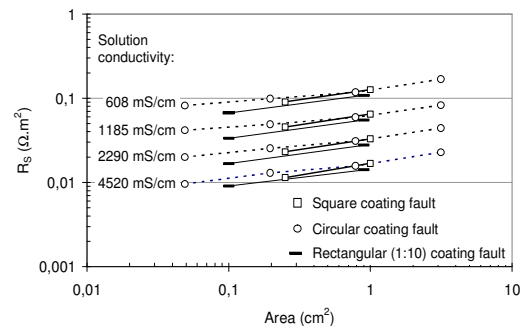


FIGURE 10 – Spread resistance as a function of the area of the coating fault. In synthetic soil solutions at four levels of solution conductivity.

A further example of evidence of the alkalisation mechanism is shown in figure 11. A probe buried in a non-corrosive type of soil was connected to a cathodically protected pipeline interfered with AC. A narrow pipe was inserted right next to the probe surface allowing for dosage of liquid to the local environment. Different types of liquids were then tested, and the figure shows the highly interesting response from the probe when 0.1 N NaOH was dosed.

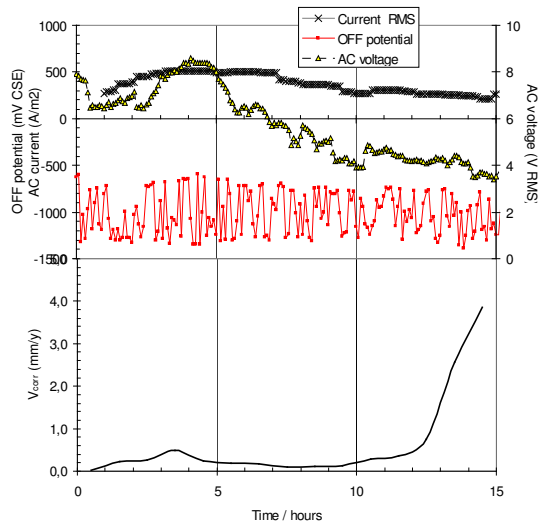


FIGURE 11 – Corrosion rate response during controlled addition of alkalinity to a buried probe.

dramatically. This shift in behaviour is not quite evident solely from the electrical parameters used in the guidelines to predict AC corrosion and shown in the upper graph. In conclusion to this, a direct measure of the corrosion rate should be incorporated in any monitoring strategy.

Throughout time, the AC current density, the AC voltage, the off potential oscillation (using method 1 described in table 2) as well as the corrosion rate was measured. It is evident from the figure that throughout the 15h period, the AC voltage peaked at 8 V after some 4 hours. At this time, the peak to peak off potential oscillation was 800 mV corresponding 280 mV RMS. Hence, the ratio between the AC voltage and the off potential oscillation would be around 30 - indirectly indicating the ration between the Faradaic impedance (Z_F) and the spread resistance at 50 Hz. From the corrosion rate measurement (lower graph in figure 11) it is evident than when the OH^- is allowed time to reach the probe surface in sufficient concentration, the corrosion rate increases

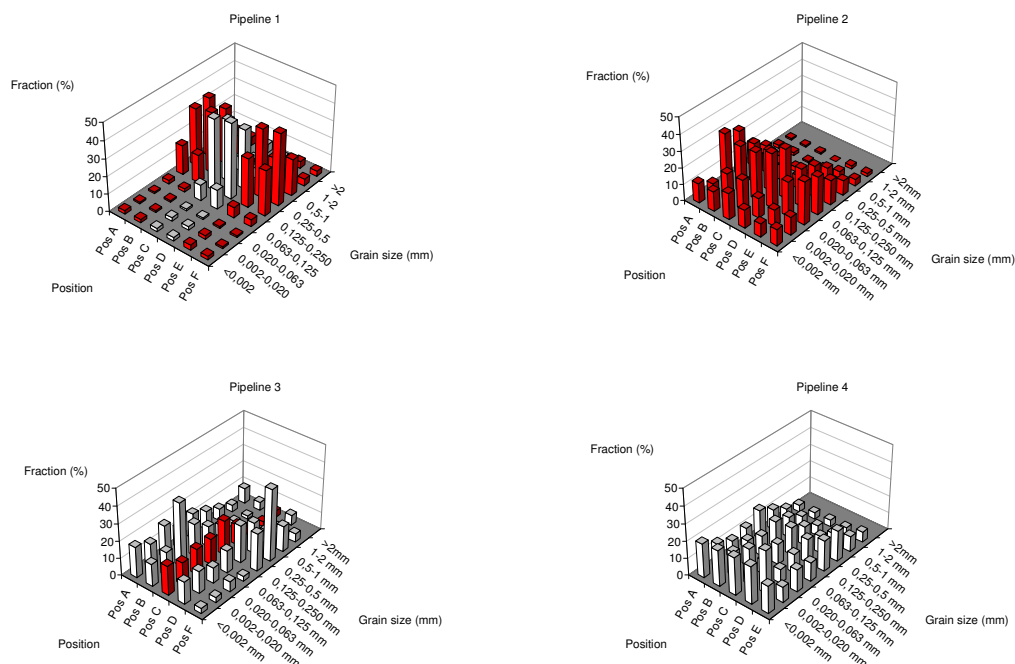


FIGURE 12 – Texture properties from soil samples collected at various positions along 4 different pipelines during AC corrosion surveys. Colored bars indicate that corrosion was possible, whereas no corrosion was detected at positions with white bars.

Further experiences from field measurements have included studies on the soil texture to find out if the grain size distribution makes a difference in the AC corrosion mechanism. The justification of this question arose from findings in a very corrosive soil in which a probe was inserted and corroding according to figure 5 though connected to the pipe CP system. Another probe inserted in an adjacent well (with open water in equilibrium with the soil, but with no soil particles) right next to the corroding probe didn't show any tendency to corrode. Hence, the soil particles was acting as diffusion barriers so and the OH^- generated at the probe surface was easily accumulated and a critical situation build up. In the open water, the OH^- was allowed to diffuse away from the probe surface, and no critical condition was established. The question was therefore if the particle size of the soil creates different diffusion coefficients for OH^- diffusion and therefore if the soil particle size has any impact on whether a sediment is characterised as AC corrosive or not. After several soil textural analyses and comparison with corrosion behaviours a conclusion is merging that though the physical presence of soil particles plays a key role, the grain size is less important. Figure 12 illustrates theses findings.

Conclusion

Concepts for detection and mitigation of AC induced corrosion are discussed. Regarding detection systems, it is recommended that direct measurements of corrosion rate using buried probes are included in the detection procedure. Based on characterisation of the mechanisms (involving alkalisation of the local environment at a coating defect) it is justified that detection procedures based solely on measuring of electrical indicative parameters are insufficient for adequate reliability. Mitigation procedures involve to a large extent grounding of the pipeline via capacitors, and an intelligent switch device has been presented that allows for significantly time saving procedures for CP surveys, since the device recognises the on/off pattern of the timer mounted on the rectifier and disconnects the capacitors when the timer is active.

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