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Corrosion Rate as a Substitute for Electrical Fingerprints such as Off-Potential in the Evaluation of Cathodic Protection Effectiveness?

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Historically the most important criterion for cathodic protection is the IR-free potential, also known as Off-potential or polarized potential. Alternative ways of producing an Off potential include measurements on the pipeline itself with synchronized rectifier switching, and methods using coupons connected to the pipeline with local switch-off from the CP of the pipeline or other means of IR compensation.

Challenges in terms of the "modern" threats to pipeline integrity such as electrical interference from either DC- or AC power systems have called for other criteria, for instance based on current densities measured on coupons. Alternatively, also the corrosion rate can be used in the determination of safe operation. But can it stand alone as the sole parameter?

The answer to such a controversial question is of course "NO". But perhaps it will be a value adding parameter when combined with the range of other electrical fingerprints such as DC potential, IR free potential, DC- and AC current densities, AC voltage as well as the geometrical/environmental fingerprint better known as "spread resistance".

This paper does nevertheless seek to give a support to the use of the corrosion rate approach through a combination of personal pocket philosophies regarding the current standards in the field, hand-picked noticeable citations from a few CeoCor presentations through recent years as well as examples of the applicability of the concept used on pipelines.

1 - GENERAL BACKGROUND

The European Standard EN 12954 [1] – Cathodic protection of buried or immersed metallic structures – General principles and application for pipelines – defines in section 4.2 the criteria of cathodic protection as follows:

The metal to electrolyte potential at which the corrosion rate is < 0,01 mm per year is the protection potential, E_P. This corrosion rate is sufficiently low so that during the design life time corrosion damage cannot occur. The criterion for cathodic protection is therefore:

$$E \leq E_P$$

The protection potential of a metal may depend to some extend on the corrosive environment (electrolyte), but is mainly dependant on the type of metal used…

The protection potential criterion applies at the metal/electrolyte interface, i.e. a potential which is free from IR drop in the corrosive environment.

Some metals may be subject to corrosion damage at very negative potentials. For such metals, the potential shall therefore not be more negative than a limiting critical potential E_l. In such cases the criterion for cathodic protection is:

$$E_l \leq E \leq E_P$$

Some general guidelines are given in table 1 of said standard. For non alloy and low alloy Fe materials with yield strength ≤ 800 N·m2, these criteria are (all potentials measured versus a $Cu/CuSO_4$ reference electrode):

- E_P = -0,65 V in aerated sandy soil with resistivity higher than 1000 Ω·m
- E_P = -0,75 V in aerated sandy soil with resistivity between 100 and 1000 Ω·m
- E_P = -0,85 V in normal aerobic condition (T<40ºC)
- E_P = -0,95 V in normal aerobic condition (T>60ºC - interpolate between 40ºC and 60ºC).
- E_P = -0,95 V in anaerobic soil

2 - CHALLENGES IN THE ESTABLISHMENT OF A PROTECTION POTENTIAL

The above citation from the standard leaves behind some relevant observations. Some of these are:

1. The cathodic protection criterion is tied to a corrosion rate (maximum 0,01 mm per year).

2. The suggested protection potential, E_P, is tied to the knowledge on the actual environment in which the steel is exposed. This has as a consequence that site condition surveys that include soil resistivity and soil sample analysis must be conducted for the selection of a proper cathodic protection potential.

3. The suggested protection potential refers to a condition free from IR drops in the environment. This has as a consequence that a reliable method for eliminating the IR drop must be applied. The method should be simple and comparable across various environments, electrical condition (including interference), and operator independent.

4. The suggested protection potential refers to a measurements made with respect to a certain reference electrode placed in the surrounding soil. This has as a consequence that
    - The applied reference electrode should be stable and have a well-defined potential irrespectively of the soil condition – in particular if it is to be used as a "permanent"

reference electrode e.g. for remote monitoring purposes. A regular calibration process is required.

- The applied reference should be placed in a position in the soil with due consideration to disturbing effects like static or fluctuating interference currents.

In addition to the above concerns, interference issues (DC as well as AC) complicate the establishment and the sound interpretation of a (IR free) potential.

2.1 Which potential to reach?

What happens at the metal/electrolyte interface when cathodic protection is applied? What does this all means in terms of the protection criterion? This was the questions discussed by Dr. S. Leeds in a recent review paper (CeoCor 2013 [2]). Leeds refers to studies that tie together the corrosion rate (weight loss measurements) and exposure conditions (potential and environment) – among these were 12 different experiments conducted at various conditions, compared by weight loss, film analysis, CP current density and exposed potential. In an overall impression Leeds makes a statement which is effectively underlining the complexity and necessity of knowing the environmental factor (observation 2 above):

"Selecting which potential to use as the criterion for protection is not an easy decision. In some circumstances as seen in this work, applying -0.85 V (CSE) was not enough to stop corrosion. However, in other circumstances it is more than enough. Ewing […] found that "in well drained and rather dry soil, the protective potential was -0.7 V (CSE)". Barlo even reports values as positive as –0.6 V (CSE). In other soils –1.1 V (CSE) was required. This suggests that an understanding of the water/soil conditions that the structure is exposed to should be one of the most crucial parameters for the control of corrosion. These include pH, oxygen content and resistivity (corrosivity) of the electrolyte. Further research work is needed to cover a range of soil conditions, particularly acid soils, to determine the current density requirements that will produce sufficient alkali for film formation. All these conditions should be recognized and better defined by International Specifications and Standards as a guide for improved control of corrosion through the application of CP".

2.2 How to account for IR drops?

As with regard to the 3rd observation (IR free potential) there are several approaches to how this is obtained. Some of these are related to measurements directly on the pipeline, and some of these are related to the application of a coupon. The current working group D in Commission 2 of CeoCor is dealing with Guidelines for off-potential measurements on cathodically protected pipeline. In the DRAFT working document [3] (it is underlined that the document is a draft at the time of writing the current paper), it is noticed that:

"These last thirty years, cathodic protection operators have developed and adopted several IR free potential measurement techniques. Often one single technique may also be applied differently (e.g. time delay before measuring on coupon). As those techniques differ from each one, the obtained potential values are obviously unequal. The choice by an operator of one particular technique is based on individual experiences (or habits in the company),... "

Among the techniques presented are:

- Measuring on/off by synchronized switching off all DC current sources specific to the CP system – pipeline measurement which also include close interval potential survey.

- Switching off a coupon. This can be both a permanent and non-permanent coupon.
- Extrapolation of the ON-potential to the potential at zero current – using a coupon.
- Direct IR compensation using a coupon and measuring the spread resistance (R) and the DC current (I) that accounts for the IR drop.
- IR reduction by placing a reference electrode "very near" the coupon surface.

Different values will be measured depending on:

- Whether all current sources are effectively witched off,
- The period after switching off until the off-potential reading is made,
- The magnitude of balancing (equalization) currents between different coating defects on the pipeline,
- The measurements errors due to instrumentation, measurements technique and reference electrode.

Gomila reports results from a study using coupons for the determination of the off-potential [4]. The report was dedicated to illustrating the effect of the delay between switching off the coupon and making the off-potential reading. The comparison of delay times between 20 msec, 50 msec, and up to 1 sec as allowed according to EN 13509 (cathodic protection measurement techniques [5]) was made for 10 different examples. It was shown that the maximum difference between the 20 msec reading and the 50 msec reading was 110 mV, whereas the maximum difference between the 20 msec reading and the 1 sec reading was as high as 260 mV. It is recommended to evaluate these figures in view of a Tafel slope in the electrochemical corrosion process of 120 mV potential shift per decade of current!

The concern mentioned in the DRAFT working group document [3] seems to be quite valid: "The IR-Free potential measurement is an essential measurement in the CP assessment process and in the process of adjusting CP potential level. As different techniques exist, how does one know which technique fits to handle the situation?"

2.3 The significance of the reference electrode

The reference electrode position and performance clearly is an important issue in the (off) potential measurement. Working group E of Ceocor commission 2 is dedicated to developing a document covering various aspects of reference electrodes, such as calibration, installation, and minimum performance requirements [6]. Being a draft document, the stability performance requirements are still to be finally settled, but values in the range +/- 10 mV calibration before installation, +/- 20 mV after installation, and +/- 30 mV deterioration over time are mentioned. These figures are in contrast to figures given by Wyatt in a Technical Note on significant inaccuracies among 50 reference electrodes being part of a comparative study [7]. A full survey was undertaken to compare their electrode potentials with those of a clean, calibrated, portable $Cu/CuSO_4$ saturated electrode. Many electrodes were presenting potentials >30 mV from their theoretical potential, and some >100 mV. Within months the greatest error was >200 mV.

2.4 DC interference

DC interference is covered by European Standard EN 50162 – Protection against corrosion by stray current from direct current systems [8]. According to this standard, the criteria for stray-current interference for structures with cathodic protection are as follows:

“Structures protected against corrosion by cathodic protection shall be deemed to be exposed to unacceptable stray current interference if the IR potential is outside the protective potential range (see EN 12954).

To evaluate the acceptability of stray current interference, the installation of test probes and coupons should be considered.

In situations with fluctuating interference current probe measurements as described in Annex D can also be used to evaluate the acceptability of interference.

If in special situations (e.g. under d.c. traction influence) there are reasons to doubt the accuracy of the measurement method used other measurement techniques (e.g. weight loss coupons) can be used to establish that the structure is cathodically protected.

Measurements should be carried out during a period of normal operation of the interfering system”.

It is mentioned that the referred Annex D is concerned with the use of current probes to evaluate fluctuating stray current interference on cathodically protected structures. The probe currents in the worst hour of interference are compared with a reference level with low or no interference. It is (for instance) stated that unacceptable interference exists if anodic current is present in more than 3.6 seconds per hour (in the worst hour) or in 0.1% of the time.

It seems that the DC interference situation is very well suited for something else than potential criteria. K.C. Lax states on the front page of his CeoCor 2014 paper (Application of cathodic protection under severe stray current interference and verification of the effectiveness [9]) that:

“There is some advice available in the standards to assist in the application and evaluation of the effectiveness of cathodic protection applied in areas of stray current interference by the measurement of pipe-soil-potentials. It is the author’s view that although this advise is given with good intentions it is seldom of much use.

Simply measuring potentials is unlikely to provide the assurances required that the structures are not at risk from corrosion.

This case study of a project in a European City details how critical structures were cathodically protected and the effectiveness validated by the use of electrical resistance (corrosion) probes”.

2.5 AC interference

Criteria for acceptable AC interference levels are given in EN 15280 (Evaluation of a.c. corrosion likelihood of buried pipelines applicable to cathodically protected pipelines) [10]:

- As a first step, the AC voltage on the pipeline should be decreased to a target value, which should be 15V rms or less. This value is measured as an average over a representative period of time (e.g. 24 h).

and

- As a second step, effective AC corrosion mitigation can be achieved by complying with criteria defined in EN 12954:2001 table 1 (i.e. the usual CP criteria)

and

  - maintaining the AC current density (rms) over a representative period of time (e.g. 24 h) to be lower than 30 A/m^2 on a 1 cm^2 coupon or probe

or

- maintaining the average cathodic current density over a representative period of time (e.g. 24 h) lower than 1 A/m^2 on a 1 cm^2 coupon or probe if AC current density (rms) is more than 30 A/m^2.

or

- maintaining the ratio between AC current density (J_{AC}) and DC current density (J_{DC}) less than 5 over a representative period of time (e.g. 24 h).

Effective a.c. corrosion mitigation can also be demonstrated by measurement of corrosion rate.

These above criteria are normative. A set of informative criteria based on AC voltage versus DC ON-potentials are also given in the annex E of the standard.

The lesson from the above is that one can use a range of electrical fingerprints for the evaluation of AC corrosion, or one is allowed simply to use a corrosion rate measurement.

Special challenges are present when the IR free potential must be measured under AC interference conditions:

A. Effect of capacitive AC grounding devices. If measured on the pipeline by switching rectifiers, the capacitive grounding devices, which are often mounted to drain AC current from the pipeline, will introduce a time constant in such a way that the reading of an instant off value is made difficult if not impossible. Kioupis [11], and Blotzki & Quast [12] however have suggested restrictions and modifications to allow for an instant off value.

B. The depolarization effect of AC on the DC polarization curve [13]. This means that the AC will influence the DC potential, and therefore the application of the switching off of a coupon will include a potential error since the coupon DC potential (when switched off of the pipe) will lose the effect of the AC voltage present solely on the pipe. A direct IR compensation method has been suggested to compensate for this by enabling the coupon to be connected to the pipeline throughout the measurement period [3,13].

C. The effect of Faradaic rectification [13-16) – meaning that the IR free potential versus I_{DC} curve (the polarization curve) will exhibit an odd behavior and in some cases the potential becomes no longer a true function of the current density (a reading of the IR free potential can be the same at low DC as well as high DC current densities).

The IR free potential is particularly difficult to quantify under conditions of AC interference.

Generally, the above summary concerning the applicability of the IR free potential illustrates that although this very fundamental parameter is here to stay it has numerous drawbacks and uncertainties attached to it. These have become accepted by the industry – and can be overcome by the CP professional by having the limitations in mind. Besides, the potential is what it is – a potential for something to happen. No guarantees given.

3 - THE ELECTRICAL RESISTANCE TECHNIQUE FOR CORROSION RATE MEASUREMENTS

The Electrical Resistance technique for corrosion rate measurements has been described previously [10, 13, 17, 18], but will be repeated here for convenience.

This technique utilizes that the electrical resistance of a metal probe element increases when corrosion diminishes the thickness of the element. Referring to simple plate geometry for a metal element with dimensions as given in figure 1, the electrical resistance of the element can be expressed by:

$$R = \rho_m (T) \cdot \frac{L}{W \cdot d} \tag{1}$$

where L is the length of the element, W is the width of the element, and d is the element thickness.

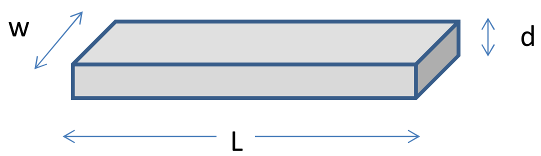


Figure 1. Rectangular metal element with thickness d..

The specific resistivity of the metal ρ_m is given by an equation like:

$$\rho_m (T) = \rho_m (T_0) \cdot (1 + \alpha)^{T - T_0} \tag{2}$$

It is observed that the specific resistivity is a function of the temperature, and therefore the resistance of the metal element not only depends on its dimensions, but also the temperature of the element (equation 1). For corrosion rate measurements by the ER technique, the temperature effect has to be compensated. Usually, therefore, a reference metal element is incorporated in the ER probe (figure 2).

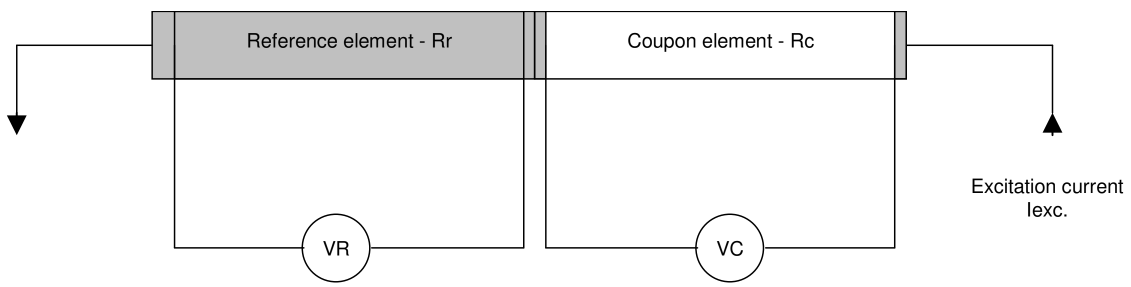


Figure 2. Conventional circuit for ER probe techniques.

The resistance of this reference element measured along with the element being exposed to the corrosive environment. Assuming that the two elements share the same temperature, the thickness of the exposed element can be quantified by:

$$d(t) = d\,(t=0) \cdot \frac{R_R(t)}{R_C(t)} \cdot \frac{R_C(t=0)}{R_R(t=0)} \tag{3}$$

Under conditions where a current (especially AC) passes through the spread resistance of the coupon element, the heating of the coupon part is expected to be greater than the heating of the reference part where the a.c. discharge is not taking place. Therefore ER measurement for corrosion risk evaluation must be designed with temperature compensating means that take this specific temperature effect into account.

These above features are built into a corrosion rate probe which is placed in the same backfill and close to the pipeline - just like a traditional coupon, and using the same kinds of guidelines for the application of coupons for cathodic protection monitoring purposes [19]. Besides the corrosion rate and accumulated degree of corrosion, the probe can also be used just like traditional coupons; for the measurements of AC and DC current densities, OFF potential (or IR free potential more generally), spread resistance etc.

Some questions which are both critical and constructive have been raised regarding the use of corrosion rate probes over the years in particular by Büchler and particularly in relation to AC corrosion [14, 20] – such as:

1. The ER probe does not represent the pipeline because the geometry facilitates current pick-up from a full sphere ("the whole world" as opposed to a semi sphere as defined by a small coating defect embedded into the pipe wall).

2. The ER probe – being essentially a rectangular shape – does not cope with findings that AC corrosion is usually ball-shaped in nature.

3. Due to the heating effect of the AC current at the ER probe surface, the ER probe is heated significantly more that a coating defect in a pipeline because of the heat sink effect of the pipeline steel wall.

4. The corrosion rate will be overestimated in thin element ER probes because corrosion will increase the surface area, hence increase the spread resistance of the defect. High corrosion rates on thin coupons observed in field tests are typically not found in pipelines. The increase of the surface with increasing corrosion depth significantly decreases the current densities and therefore the corrosion rate over time.

5. What happens on a coupon represents only the coupon itself.

The above reasonable questions are dealt with in the following sections.

3.1 Effect of the coupon geometry

The effect of the coupon geometry has been extensively studied in terms of both modeling and testing, the report of which was made at CeoCor 2010 [21] – part of which has been adapted for the CeoCor publication on the application of coupons [19]. The modeling was in the form of numerical simulations using the Elsyca CPMaster software package. CPMaster is based on the Finite Element Method (FEM). The studies had the following scope:

i. Evaluate the significance of the following factors relating to the coating defect (see figure 3):

   a. The effect of the thickness, t, of the coating

b. The effect of the angle, α, between the coating and the bare metal of the coating fault,
c. The effect of the extension, L_c, of the carrier plate – especially when the difference of the size of the carrier plate and the coating fault becomes little – like in coupons.

ii. Prepare the same evaluation as above, however for a rectangular coating defect having length L and width W. Focus on the effect of the length to width ratio of this coating defect and discuss of the spread resistance of rectangular defects versus circular coating defects.

iii. Prepare the same evaluation with infinite carrier plate.

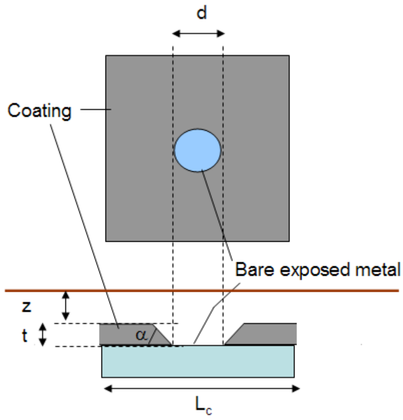


Figure 3. Illustrations of a circular coating fault and its related parameters.

Figures 4 and 5 were some of the results from these studies, which among a range of other things concluded that:

- It is generally simulated that the spread resistance increases with increasing defect size. It is further observed that rectangular geometries exhibit reduced spread resistance compared with the circular shape – for instance the spread resistance of the 10:1 rectangular shape is about 80% of the circular equivalent whereas the scratch-like 1000:1 rectangular shape is less than 20% of the circular defect having equivalent size.

- The spread resistance increases with increasing coating thickness. This effect of this phenomenon is increasing with decreasing defect size. For large coating defects (+100 cm2) the effect is very small.

- The above effect weakens when the contact angle between the defect and the coating opens.

- The effect of the size of a carrier plate when designing coupons seems to be insignificant as long as the carrier plate is 3 times larger than the coating defect.

- The formulas and spread sheets provided by the simulation can be used to further detailing the answers to the questions addressed within this paper, and interested parties are encouraged to apply for a copy of these tools.

- The approach that when the soil resistance is known, then the AC current density resulting from a certain level of AC voltage can be assess by a simple formula is wrong and misleading for at least two reasons:

- The CP current density will affect the spread resistance by modifying the chemical environment close to the coating fault. This is an important aspect of the AC corrosion mechanism.

- The shape, size and geometry of the coating fault system will significantly influence the spread resistance.

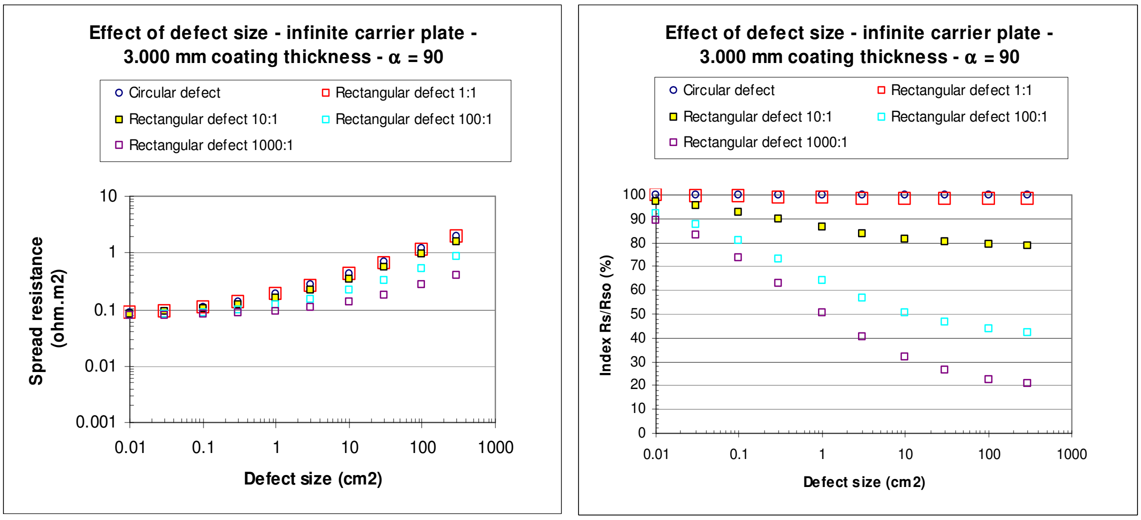


Figure 4. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is 3 mm thick with a contact angle 90 degrees.

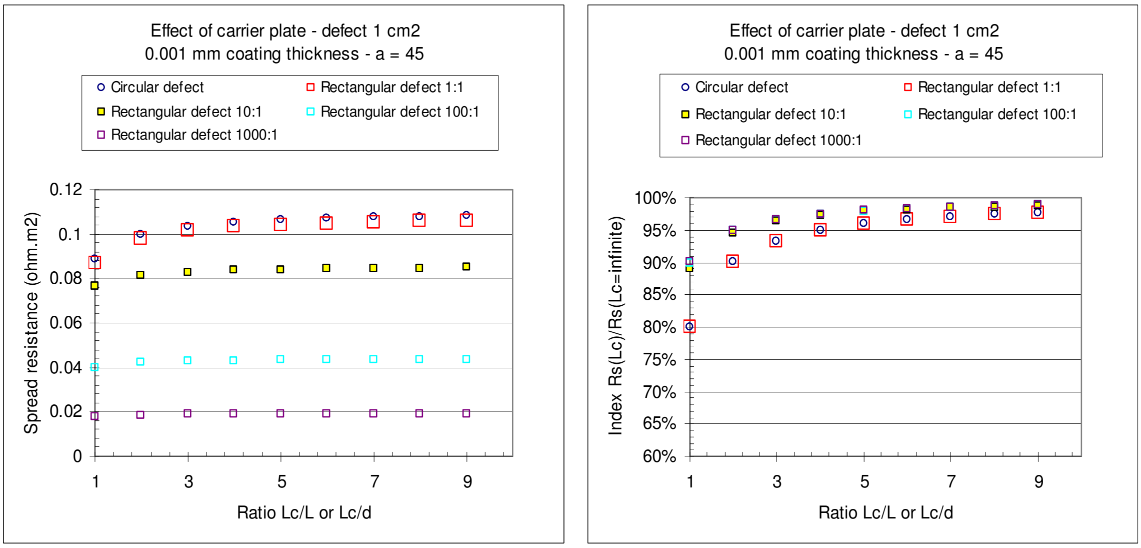


Figure 5. The effect on the spread resistance of the ratio between coating defect size and the size of the carrier plate. For a 1 cm2 coating defect with 3 mm coating layer and a contact angle of 45 degrees.

These detailed investigations have been the basis for the development of MetriCorr ER probes, and – as mentioned – the investigations have been recognized adapted for the CeoCor coupon document. They were initiated to get a scientific approach – rather than intuitive – to the whole discussion concerning pipe wall geometry versus coupon geometry.

3.2 Effects due to heating of the coupon by AC current

The effect of the coupon geometry has been extensively studied in terms of both modeling and testing, the report of which was made at CeoCor 2012 [18]. The scope of work for that study was as follows:

Scope of work

The following primary questions were discussed with regard to coupons in general:

i. What is the expected dependency of soil resistivity on the soil temperature?

ii. What is the (maximum) effect of AC current density on the temperature rise of the exposed part of a surface of a metal coupon?

iii. What maximum impact on the spread resistance (hence impact on the level of AC current density) will the elevated coupon temperature have in comparison with a real pipeline coating defect assuming no temperature rise for this.

iv. What can be done regarding the design of the coupon in case question 3 above points out a problem?

v. In addition, the following has been briefly discussed regarding corrosion rate measurements using ER (Electrical Resistance) probes:

- What impact will the temperature rise caused by the AC current density have on thickness measurements and corrosion rate measurements using ER probes for the quantification of AC corrosion etc?

- What can be done to compensate for the above effect?

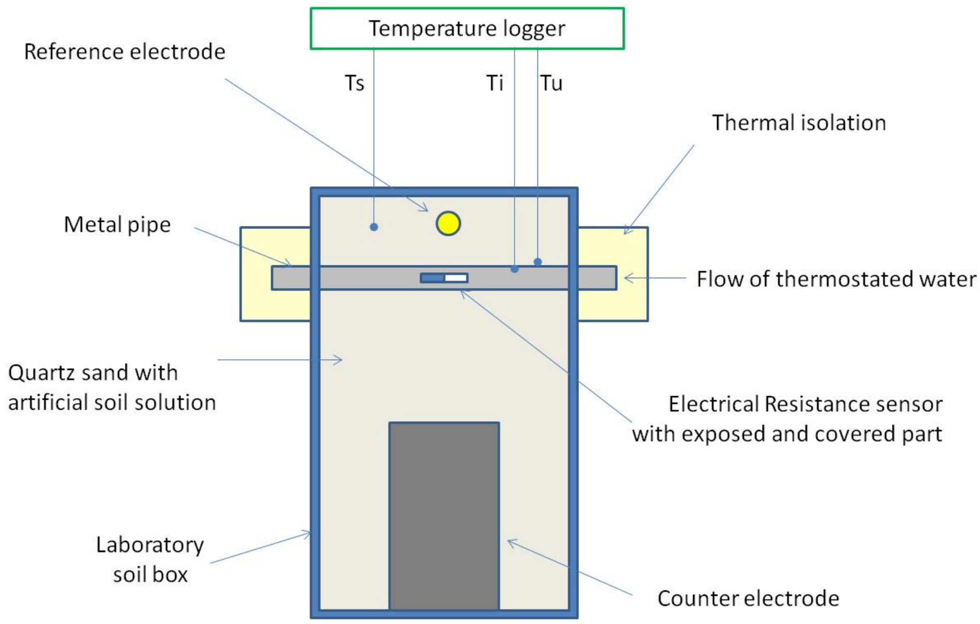


Figure 6. Sketch of the setup used to make a correlation between temperature and ER data.

The study was utilising that the ER probe can be used as a thermometer itself due to equations (1) and (2). Figure 6 shows a setup where ER probe elements are glued onto the outer surface of a pipe system in which thermostatically controlled fluid can heat the probe from the inside – enabling for a study of the effect of heating on the probe responses. This was compared with the responses resulting from creating very high AC currents under non-corrosive conditions hereby enabling for a simple verification of the above questions.

The following conclusions were drawn concerning the questions initially raised (scope of work) [18]:

- By measuring the soil resistivity in a 4 point Wenner soil box during natural cooling of a sand / pore solution environment, it has been shown that the soil resistivity decreases by approximately 2% per °C

- By use of the ER technique for temperature measurements, it has been shown that during a.c. charging the temperature of the surface may increase in the order of 1 °C per 100 A/m2 a.c. current density.

- Simultaneous measurements of the spread resistance and other electrical parameters have shown that the effect of the increase in probe surface temperature on the spread resistance is insignificant compared with the effect of the d.c. charging (d.c. current density) on the spread resistance. Therefore no immediate risk exists that coupons in this respect will create artificially low spread resistance and behave more sensitive towards a.c. corrosion compared with the pipe surface itself.

- No particular effort seems necessary to diminish the risk that coupons generate higher a.c. current densities compared with the pipeline – given the same coating fault geometry and size.

- Regarding corrosion rate measurements using ER (Electrical Resistance) probes the following was concluded:

- A local heating of the coupon part respective to the reference part of an electrical resistance probe may have detrimental effects on the accuracy of the ER probe. Artificial metal loss of up to 0.3 µm per 100 A/m2 may occur due to poor design.

- The above effects must be effectively compensated for. This can be done in several ways, among these are

    a. Proper geometrical arrangement of the coupon element and the reference element.
    b. Use of effective means for heat sink – levelling out fast enough the temperature difference between coupon and the reference part.
    c. Shortly disconnecting the probe from the a.c. source (the pipeline) during measurements awaiting thermal balance.
    d. Others.

Proper combination of the above has been indicated to decrease the artificial metal loss to as low as 1 nm per 100 A/m2.

By the above study, the possible effects of heating were closed.

3.3 Effects due to increase of spread resistance with corrosion depth and possible overestimation of corrosion rates with ER probes compared with pipe, as well as the general difference between the pipe and a coupon.

This question has yet to be answered properly – but as per the date of writing this manuscript, the following statements can be made:

- We have at the MetriCorr laboratories performed initial comparative AC corrosion investigations using probes with element thicknesses 0.1 mm, 0.5 mm, 1.0 mm and 3 mm. The corrosion rates found on 0.1, 0.5, and 1.0 mm probes were consistent with each other, whereas the corrosion on the 3 mm thickness probe ceased after approximately a year of exposure. This has not since been reproduced. It is believed that the cease in corrosion rate on the thickest probe as a matter of exhausting the environment rather than a matter related to spread resistance. A Ph.D. study has been initiated with the purpose of further investigating the effect of soil type and environment, coating geometry, and steel type/composition on AC corrosion rates.

- It may be questioned if the observation that ER probes may over estimate corrosion rates made is at all valid. Very high corrosion rates are sometimes found on ER probes. True, but very high corrosion rates have also been reported for real pipelines – in excess of 10 mm per year with wall-through penetrations [22-25]. The reference by Büchler [14] was a comparative field study including both ER corrosion rate probes and magnetic flux ILI tools presented by N. Kioupis [26] who – rather than reflecting on the high corrosion rates –concluded that "Without disregarding the usefulness of MFL ILI technique, in terms of AC corrosion the results of such inspection must be treated with caution, as the weak accuracy of MFL method can be aggravated by the magnetic corrosion products and the fairly small dimensions of AC corrosion defects". Further - "The ER probes method turned out a valuable diagnostic tool which helped to clarify the types of AC corrosion. It also enabled identification of pipeline areas prone to AC corrosion while assisting in the assessment of the effectiveness of measures applied to mitigate AC corrosion risk".

3.4 The general difference between the pipe and a coupon.

Concerning statements that pipeline measurements and coupon measurements cannot be compared is indeed a true statement. It has been claimed that the use of coupons is fraught with certain problems, since the obtained results are determined to a large extent by the local soil conditions [26]. A coupon represents only itself and not the entire pipeline. YES, this is the whole idea of a coupon measurement – to isolate an artificial coating defect and to measure parameters on this that cannot be measured on the pipeline. The challenging part is to make this artificial coating defect as representative as possible of a similar true coating defect in the same soil and backfill, under the same electrical conditions – integrated at the pipe.

An opposite statement also exists: "The use of potential and AC values measured directly on the pipeline for the evaluation of the corrosion risk offers significant benefits, because the statement can be applied to the entire pipeline" {26]. Well, is this really a true fact? Measuring a potential directly on a pipeline will be a mixed potential resulting from the range of coating faults existing at the pipeline – and depending on the density of coating faults the relative weight of the response from the most critical coating fault may weaken out and drown in the big average picture provided by the pipeline measurement.

4 – THE PRACTICAL USE OF THE CORROSION RATE CONCEPT

In the practical application the corrosion rate sensors are used in combination with recording of a range of electrical fingerprints. The ER corrosion probe is installed near the pipeline, preferably in the same backfill and electrically connected to the pipe through a datalogger. Procedures for the position of the probe are alike those used for coupons [19].

Along with the logger and probe, a reference electrode is positioned for the measurements of potentials and AC voltage.

The following parameters are logged in the datalogger – see figure 7:

1. Probe element thickness for the processing of corrosion rate calculation
2. AC voltage between the pipeline and the reference cell
3. AC current density exchanged between the artificial coating defect embedded in the corrosion rate probe and the soil.
4. The spread resistance (R_S - a measure of soil resistivity very close to the coating defect).
5. DC-On potential (E_{ON}).
6. DC current density exchanged between the artificial coating defect embedded in the corrosion rate probe and the soil (J_{DC}).
7. IR compensated potential ($E = E_{ON} – R_S \times J_{DC}$).

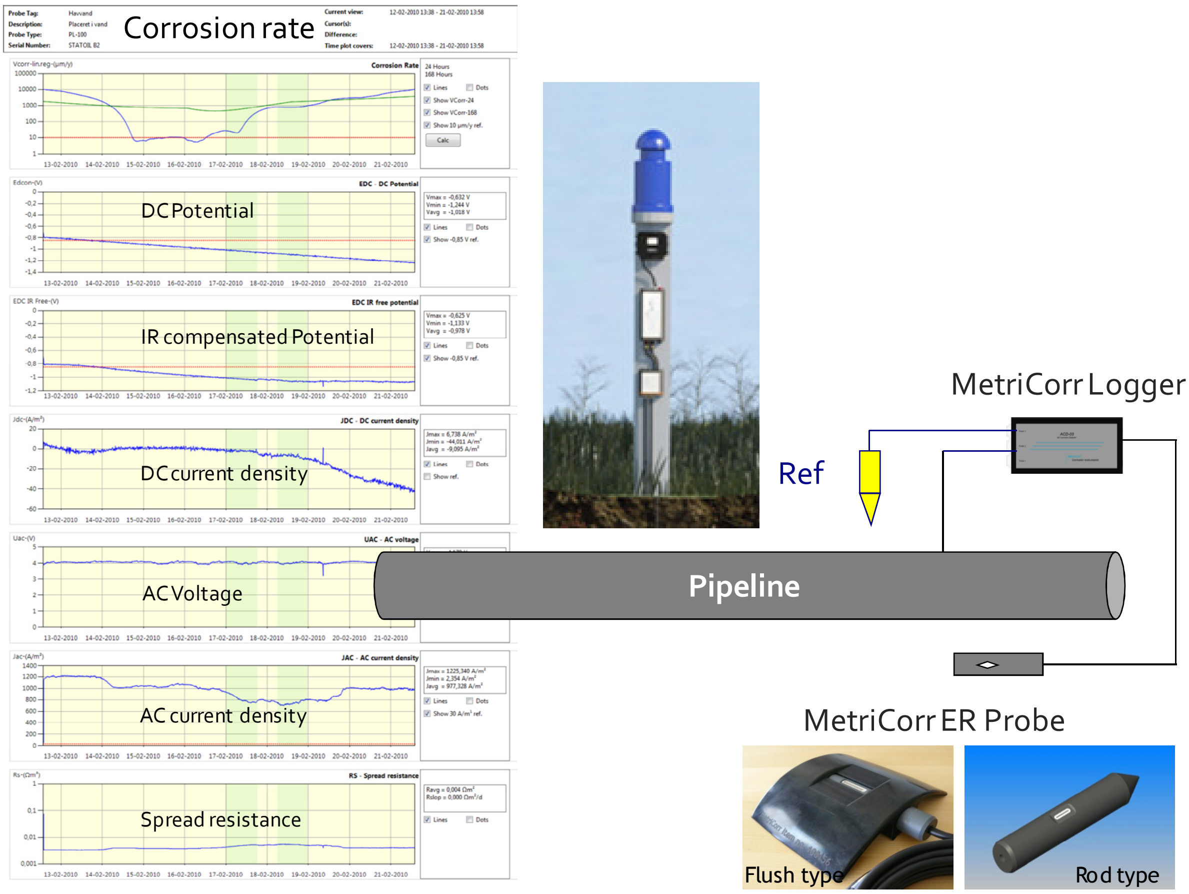


Figure 7. Illustration of the field application of the combined ER corrosion rate and electrical fingerprint concept.

By graphically displaying corrosion rate and the electrical fingerprints throughout time, it is possible to make a statistical treatment of the data by dividing into time-based subsets. Electrical fingerprints in subsets with high corrosion rates are compared with electrical fingerprints in subsets with low corrosion rates. Hereby follows the possibility not only to detect unacceptable corrosion – if any – but also to make a simple analysis of the root cause. Remote monitoring and data presentation and analysis facilities via web are routine services. 5 examples of the use of the concept follows.

4.1 A simple example – inadequate IR free potential

As the first simple example figure 8 illustrates the use of the corrosion rate concept to illustrate safe operation despite inadequate IR free potential.

Figure 8. Illustration of the application of the concept to validate the effectiveness of the cathodic protection by showing corrosion rate less than 0.01 mm/year despite inadequate IR free potential.

4.2 DC interference

The second example has been created in the laboratory and concerns DC interference. As part of the GERG project 2.51 [27], soil box laboratory experiments were conducted where the DC potentials were continuously switched between a cathodic protection potential and an anodic “interference condition". Figure 9 shows an example of the corrosion rate measured as a result of two different situations:

A. A cathodic protection potential kept at -1250 mV for 300 seconds followed by an anodic "interference potential kept for the period t_A between 1 and 300 seconds (X-axis in figure 9).

B. A cathodic protection potential kept at -860 mV for 300 seconds followed by an anodic "interference potential kept for the period t_A between 1 and 300 seconds (X-axis in figure 9).

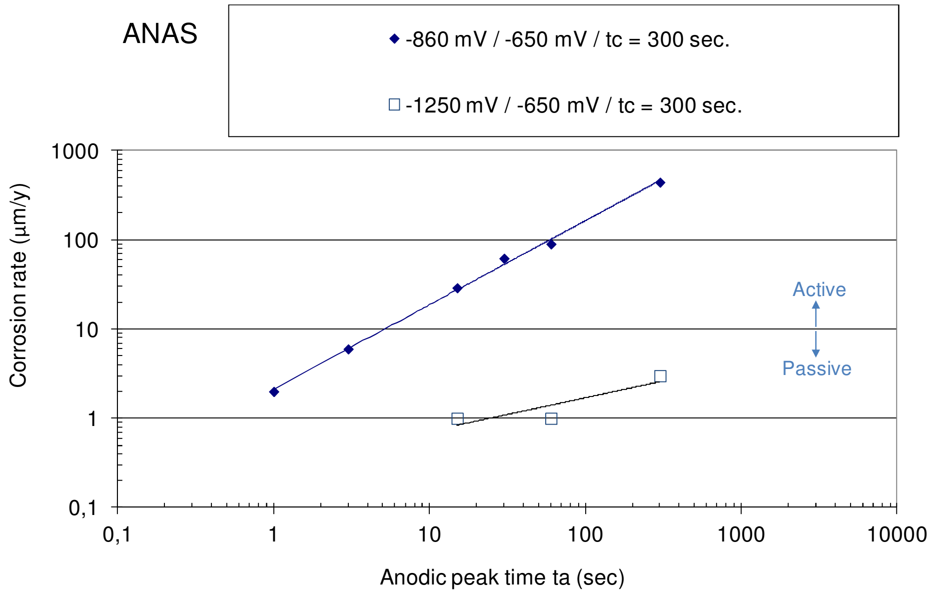


Figure 9. Corrosion rates resulting from well defined DC interference patterns established in the laboratory.

As clearly observed, even though both cases are characterized by equally unacceptable interference levels in terms of anodic potentials, the corrosion rates are very different dependent on the cathodic protection level when interference is absent.

4.3 AC interference

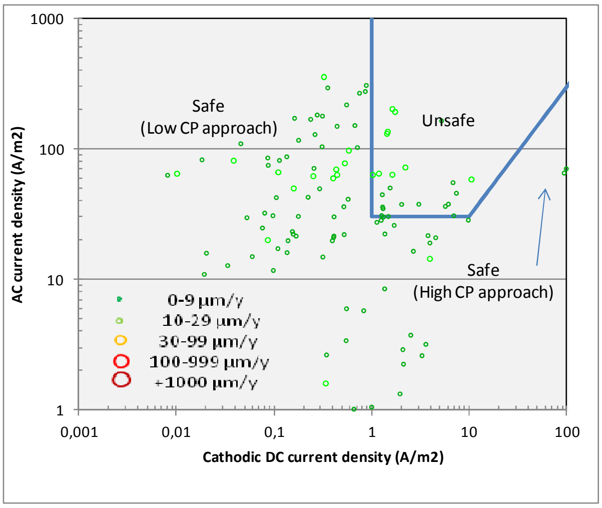
The third example relates to the AC corrosion criteria established in EN 15280 [10] using the corrosion rate / electrical fingerprint method. In all 218 sets of data from 31 pipelines located in USA, South America, Europe and Asia were established and analyzed in terms of corrosion rate versus electrical parameters.

Figure 10 shows an example where corrosion rate observations have been incorporated in the Current Criteria plot of EN 15280. The size of the dots illustrates measured corrosion rate; falling in 5 categories:

1. 0-9 µm/year
2. 10-29 µm/year
3. 30-99 µm/year
4. 100-9999 µm/year
5. 1000-.. µm/year

The first two of these categories (corrosion rates up to 30 µm/year) were considered acceptable whereas the last three categories (higher than 30 µm/year) were considered unacceptable corrosion.

The data are illustrated in figures 10 and 11.



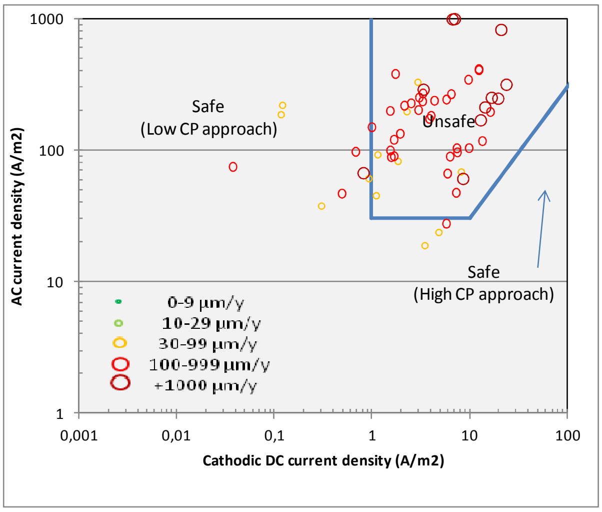
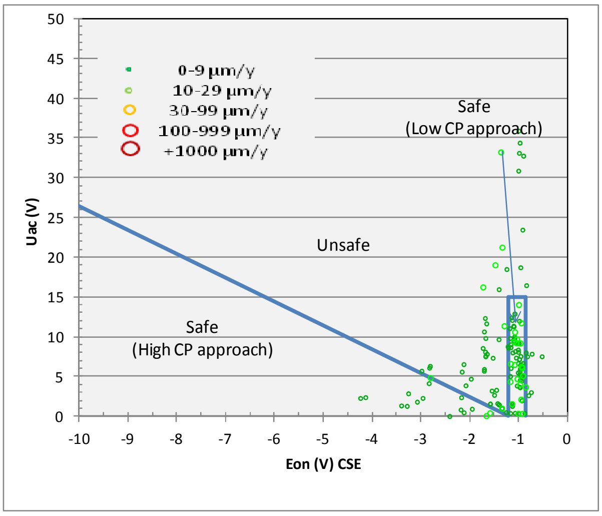


Figure 10. AC/DC current density criteria plots for AC corrosion evaluation. Left plot illustrated with low corrosion rates – right plot with high corrosion rates.



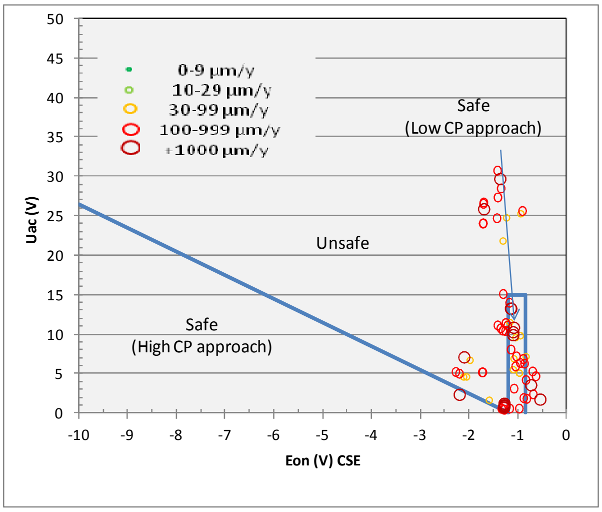


Figure 11. Voltage/potential criteria plots for AC corrosion evaluation. Left plot illustrated with low corrosion rates – right plot with high corrosion rates illustrating bad correlation between corrosion rates and the potential criteria.

Two types of disagreement exist between the corrosion rate data and the electrical fingerprint criteria:

A: No corrosion measured, but criteria for the electrical fingerprints suggest critical condition.

B: Corrosion measured, but criteria for the electrical fingerprints suggest non-critical condition.

Two types of agreement exist between the corrosion rate data and the electrical fingerprint criteria:

C: No corrosion measured, and criteria for the electrical fingerprints suggest non-critical condition.

D: Corrosion measured, and criteria for the electrical fingerprints suggest critical condition.

Figure 10 (left) shows all field observations with acceptably low corrosion rates plotted in the Current Criteria plot. As observed, a significant portion of these data points with low corrosion are present in the Unsafe zone according to the Current Criteria. Of the 156 data points plotted, 28 (18%) are located in the Unsafe zone despite low corrosion being measured. These are type A disagreements according to the above definitions.

Figure 10 (right) shows all field observations with unacceptable high corrosion rates plotted in the Current Criteria plot. As observed, a significant portion of these data points with unacceptably high corrosion rates are present in the Safe zone according to the Current Criteria. Of the 62 data points plotted, 12 (20%) are located in the safe zone despite high corrosion rates.

A similar analysis can be made regarding the Potential Criteria (which are only Informative as opposed to Normative in this standard). Figure 11 shows the equivalent data points embedded in the Potential Criteria plots. Disagreement in accordance with type A (no corrosion measured but in the Unsafe zone according to the Potential Criteria) exists in 45 out of 156 observations (29%) whereas disagreement in accordance with type B (corrosion measured, but voltage criteria suggest Safe operation) exists in 23 out of 62 observations (37%).

The above statistical observations have been assembled in table 1.

	Disagreement		Agreement	
Criterion	Type A	Type B	Type C	Type D
Current	18%	20%	82%	80%
Voltage	29%	37%	71%	63%

Table 1. Statistical observations – comparison of corrosion rate and electrical fingerprints.

4.4 Mixed AC and DC interference

A particular example has been illustrated in figure 12. A complex AC/DC pattern had been introduced to the pipeline by a mixture of AC voltage induced by overhead power lines, and a DC stray current situation caused by a DC railway system. The plot shows AC voltage and DC current density measured through a one-week period. The AC voltage changes on a daily basis from + 10V at night because of export of power to a neighboring country to a few volts during daytime. 10 V AC produced in this case AC currents above 500 A/m^2 because of a low spread resistance caused by excessive DC. The DC stray currents were predominantly cathodic in nature, and were vigorous during daytime but more silent during the night when no trains were active. A detailed analysis (figure 13) showed that the measured corrosion rate peaked when combined AC and DC stray current was present.

When AC decayed during daytime, there was still unacceptable corrosion, but at night when AC was high and DC stray currents were limited, it was possible to maintain a corrosion rate of zero even at 250 A/m^2 AC current density.

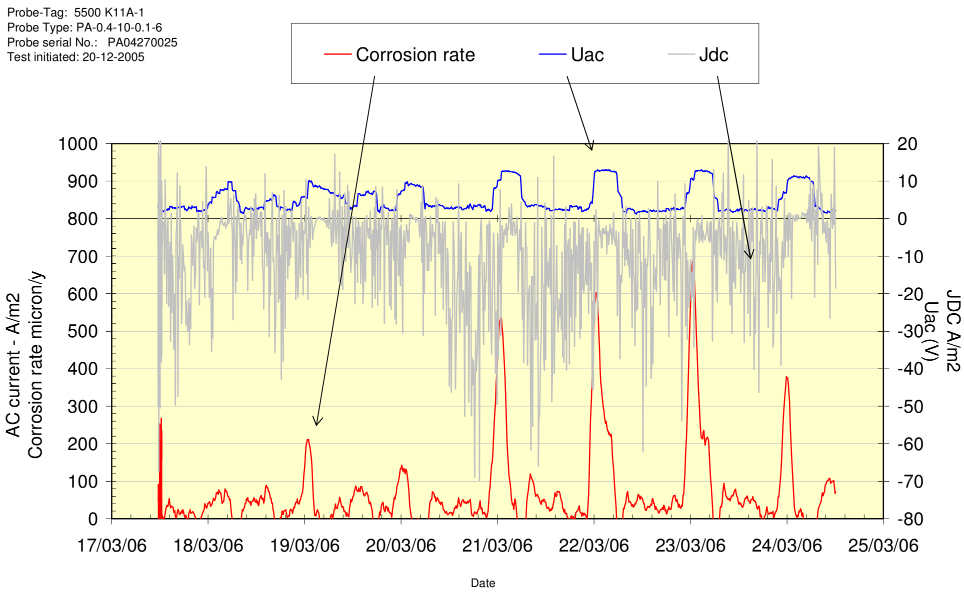


Figure 12. Complex AC/DC pattern at a site interfered with induced AC and DC stray currents. Corrosion rate measurements for the same.

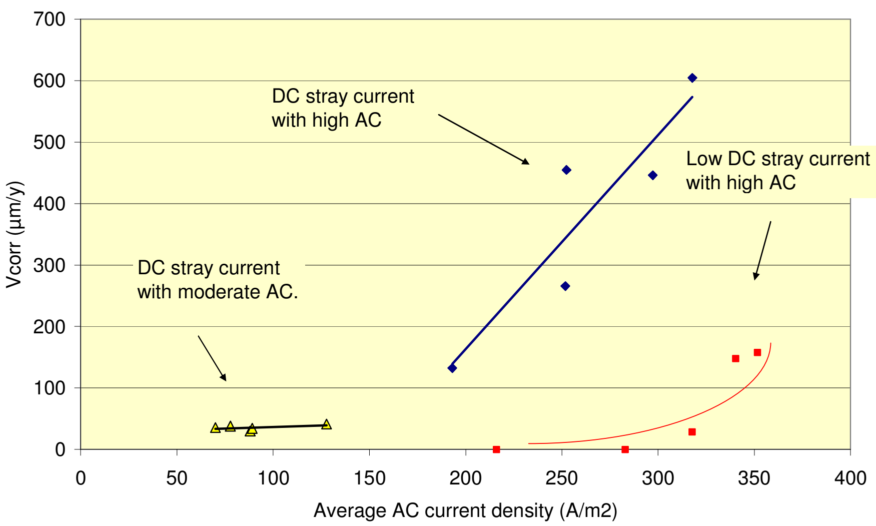


Figure 13. Detailed analysis of correlation between corrosion rate and electrical data.

The solution to the above problem was provided in a very simple way. The pipeline operator presented the data for the operator of the traction systems and asked if there was possible a fault in their traction isolation system. A short circuit was easily identified in an automated potential equalizer located at a railway station close by the test station. Switching this back in place not only limited the cathodic interference significantly, it also made sure that the spread resistance increased and the AC current density was kept below 250 A/m^2. The corrosion rate has been kept at zero ever since, and the cure for the corrosion problem was made at no cost to the pipeline operator besides the costs for the monitoring system.

4.5 Chasing the IR free potential while corroding the pipeline

The last example illustrates the clear effect of AC on the DC potential, and also the effect of excessive cathodic polarization on AC corrosion.

An operator had chosen the following strategy to safeguard against AC corrosion:

1. By extensive installation of mitigation wires, it should be assured that the AC voltage otherwise present at the pipeline should be mitigated entirely.

2. The above should be supplemented by effective cathodic protection.

The data throughout a period of approximately 6 months are given in figure 14. From the upper two graphs is observed that apart from a period of approximately one week (grayed on the graphs), the corrosion rate is zero. It is also observed that apart from the same grayed period, the AC voltage is mitigated to around 0V and low AC current density follows. The DC potential shows substantial cathodic protection, and the DC current density reached extremely high values with a very low spread resistance as the result.

The operator is obliged towards authorities to document the IR free potential is kept according to legislations – well below -850 mV CSE. Since the established grounding devices hinder the proper reading of the off potential when switching off the rectifiers, these devices are disconnected during the close interval potential survey performed to demonstrate the proper cathodic protection. The data resulting from this procedure are exactly those highlighted in the graphs by the grayed area.

It is observed that:

- The AC voltage increases in this one week period from zero to around 8-10 V.
- Due to the low spread resistance created by the excessive DC current density, the increase in AC voltage results in high AC current densities – around 650 A/m^2.
- This high AC current density causes a displacement of the IR free DC potential by approximately 100 mV. In other words, the IR free potential reported to authorities is different from the IR free potential under normal operation (with groundings connected).
- During this whole procedure, the high DC current density combined with the high AC current density causes a tremendous corrosion rate (approximately 6-10 mm/year during the survey period). If this procedure is repeated every year, the average yearly corrosion rate will exceed maximum level tolerated for a cathodically protected system.

In conclusion, the operator created for themselves a corrosion problem in their attempt to establish the IR free potential. In addition, the IR free potential established was not representing normal operating conditions.

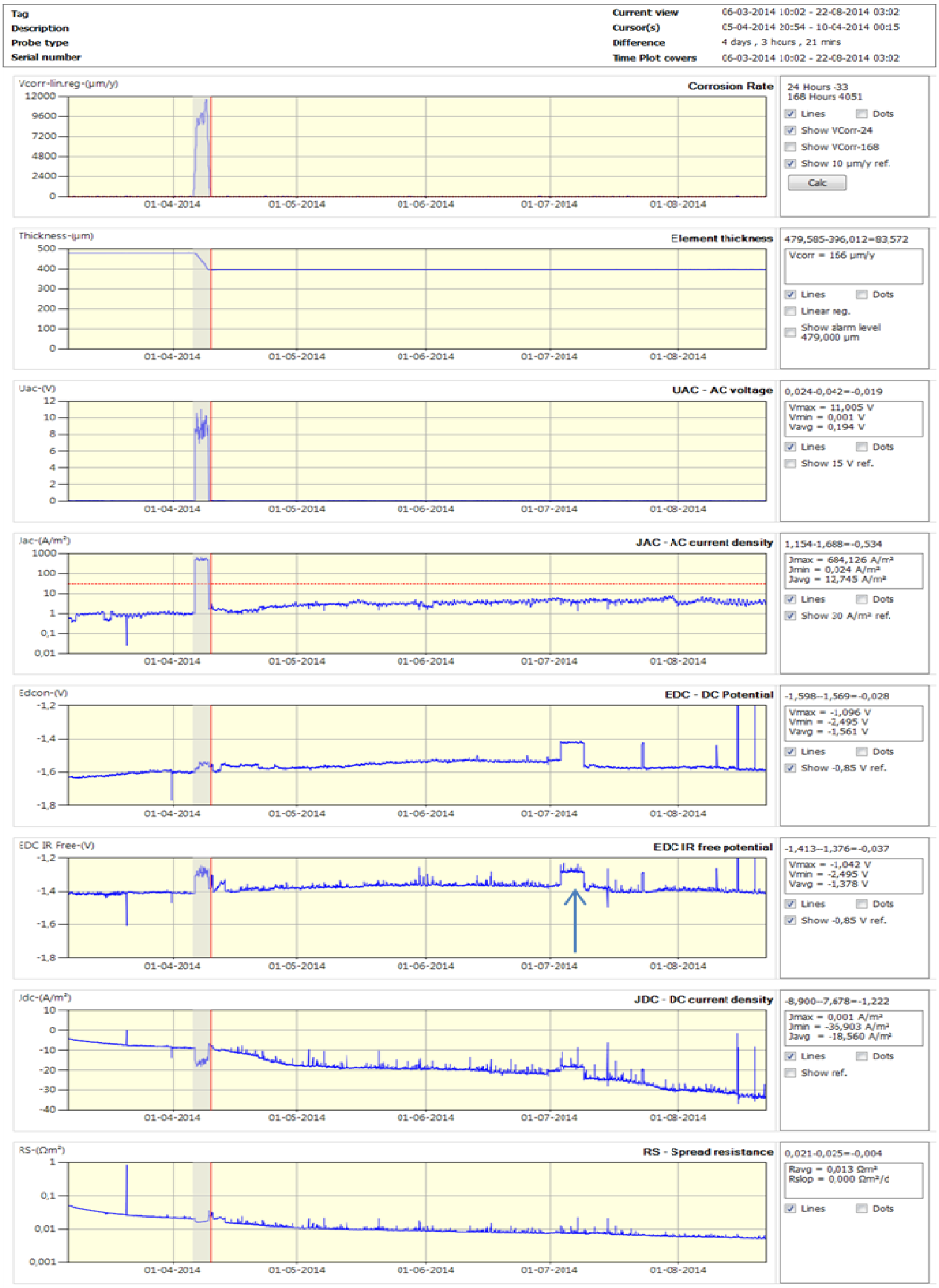


Figure 14. Corrosion event coupled to the disconnection of grounding devices in connection with a close interval potential survey.

5. CONCLUSIONS

Corrosion Rate as a Substitute for Electrical Fingerprints such as Off-Potential in the Evaluation of Cathodic Protection Effectiveness?

No!

…but in many cases the corrosion rate concept can be a significant support in the demonstration of effective cathodic protection, and it can be used in conjunction with the electrical fingerprints to diagnose root cause and correct protection measures in circumstances where corrosion is actually detected

6 - ACKNOWLEDGEMENTS

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