APPLICATION OF COUPONS AND PROBES FOR CATHODIC PROTECTION MONITORING PURPOSES

Working group B
Chaired by Lars Vendelbo Nielsen, MetriCorr (Denmark)

Final version – April 2013 .

Foreword

This working document shall be taken as an initial tool for CEOCOR internal discussion on the application of coupons and probes for cathodic protection monitoring. The document will be modified according to the best knowledge and the latest best practice experiences of CEOCOR members.

Table of Content

1 Scope

This document covers the application of coupons and probes for cathodic protection and monitoring purposes. These are particularly useful for IR free potential measurements and for monitoring the cathodic protection effectiveness in areas with d.c. or a.c. interference as specified in EN 12954, EN 13509, EN 50162, and EN 15280.
The document seeks to give advice on several factors considered important for the successful application of coupons and probes; including issues like selection of test sites, parameters to be measured, design and geometries, installation procedures, and commissioning.

2 Normative references

1. EN 12954, Cathodic protection of buried or immersed metallic structures – General principles and application for pipelines
2. EN 13509, Cathodic protection measurement techniques
3. EN 13636, Cathodic protection of buried metallic tanks and related piping
4. EN 50162, Protection against corrosion by stray current from direct current systems
5. EN 14505, Cathodic Protection of Complex Structures
6. EN 15280, Evaluation of a.c. corrosion likelihood on buried pipelines – application to cathodically protected pipelines.

3 General – definition of coupons and probes

According to the EN standard [6] the definition of a Coupon is a representative metal sample with known dimensions. A coupon may be electrically connected to the pipeline. A probe is defined as a device incorporating a coupon that provides measurements of key parameters to assess the corrosion risk.

According to the ANSI/NACE Standard RP0104-2004 (The Use of Coupons for Cathodic Protection Monitoring Applications) a Coupon is merely a metal specimen made of similar material as the structure under investigation, whereas a Cathodic Protection (CP) coupon is a coupon that is connected to the external surface of, and immersed in the electrolyte adjacent to, the structure being protected by cathodic protection.

Special kinds of probes and coupons – examples of which are given in the annexes – are also considered part of the coupon definition (hence covered by this document) to the extent that they are intended to reflect pipeline coating defects, and thus act as a representative metal sample used to quantify the extent of corrosion or the effectiveness of applied cathodic protection.

Whenever the term “coupon” is mentioned in this document all aforementioned test probes are also addressed.

4 Terms

The terms and symbols used in this Document correspond to those used in EN 12954 and EN 13509.

5 Parameters

The following parameters can be measured by the use of coupons.

5.1 On-potential and off-potential (IR free potential)

The traditional coupon concept has been used to verify the cathodic protection potential. There are several situations where the use of coupons for this purpose seems a feasible alternative since off-potential measurements on the pipeline itself is problematic:

- In areas with stray currents and telluric currents
- When dealing with the cathodic protection of complex structures
- Interference caused by multiple pipelines sharing the same right-of-way
- Interference between two different pipelines in case of crossing or proximity,
- Interference between both parts of an isolating joint for one pipeline protected on both sides by two different CP systems
- Effects from equalizing currents from adjacent coating defects – the coupon may be regarded as one single coating defect exposed in the chemistry of the soil exactly where the coupon has been buried, whereas measurements on the pipeline may cover large areas of pipe with a range of coating defects exposed in individual soil chemistries leading to the formation of a mixed potential.
- In areas where the CP is applied using galvanic anodes, and it is not possible to turn off the CP instantly.

The CEN standards [1-5] allow for the use of coupons in such instances.

5.2 D.c and a.c current and current densities

Unlike real coating defects, the coupon concept allows for measurement of the current uptake.

The d.c. current consumed by a coupon is primarily utilized in the assessment of the significance of d.c. stray current interference [3]. Annex D (informative) in EN 50162 describes a procedure from which a high risk of corrosion can be identified. The procedure involves measuring the d.c. current throughout a period of typically 24 hours. From these measurements a period is defined in which no interference is present (e.g. silent hours during night). This period is used as a reference criterion and a measure of the baseline current under normal CP. Another period is defined where the worst interference is identified. The current measured in the worst period is then compared with the baseline CP current.

Apart from the risk of corrosion due to d.c. stray current interference, the d.c. current density is also important in the evaluation of a.c. corrosion likelihood [6]. Excessive CP d.c. current may produce alkalinity near a coating defect to the extent where this electrolysis (leading to the production of current conducting OH^- ions) considerably increases the conductivity of the soil adjacent the coating defect, thus lowering the spread resistance of this coating defect.

The a.c. current density has become a significant tool in the determination of the a.c. corrosion likelihood. Essentially, the a.c. current density related to a coating defect is conducted by the a.c. voltage on the pipeline in the position of the coating defect divided by the spread resistance of the coating defect. As the spread resistance and the a.c. current density cannot be measured in coating defects on pipelines, it has been recommended in the prEN 15280 [6] - (currently under revision) – to make use of a 1 cm^2 coupon for measuring the coupon current density for evaluation of the a.c. corrosion likelihood.

5.3 Spread resistance

According to [6] the spread resistance is the ohmic resistance through a coating defect to remote earth. In relation to coupons, the spread resistance is the ohmic resistance from the exposed metallic surface of the coupon towards remote earth. This is the resistance which controls the d.c. or a.c. current through a coating defect for a given d.c. or a.c. voltage.

The spread resistance of a coupon having a circular coating defect is in the simplest form given by:

$$R'_S = \frac{\rho_S}{2 \cdot d} \ (\Omega) \qquad (1)$$

where ρ_s is the specific soil resistivity of the soil adjacent to the coating defect, and d is the diameter of the circular coating defect. In the case of a.c. the current measured in ampere will be given as the ratio between the a.c. voltage and the spread resistance R'_S. As observed, the larger the coating defect diameter (d) the lower the spread resistance – merely telling that larger coating defects will cause higher current at the same level of a.c. voltage.

When normalising with respect to the area, the equations become:

$$R_S = \frac{\rho_S}{2 \cdot d} \cdot (½ \cdot d)^2 \cdot \pi = \frac{\rho_S \cdot d}{8} \ (\Omega \cdot m^2) \qquad (2)$$

Hence, the normalised spread resistance will decrease with decreasing coating defect area, and the a.c. current density (for a given a.c. voltage) will increase with decreasing size of the coating defect. Further considerations have been given in annex 2.

5.4 Corrosion rate measurements

Various types of coupons and probes have been designed for the purpose of quantifying corrosion and corrosion rate. Examples are weight loss coupons, perforation probes and electrical resistance probes. Refer to annex 1.

6 Design considerations

The coupon should be designed for the purpose e.g. general assessment of cathodic protection efficiency, d.c. interference, risk of a.c. corrosion as discussed in section 7.

The information obtained with coupons depends on the geometry and size of the coupon. As a consequence, attention should be paid to these influencing parameters. The fundamental concept of a coupon is the mimicking of a coating defect in the pipeline. These coating defects can have various shapes and sizes. Therefore the coupon geometry should be adapted to assumed coating defects geometry present on the pipeline. The relevant parameters are discussed in the following sections.

Geometry of the defect

The case of a pore in the coating is shown in Fig. 1 a. This represents the case where the coating was locally damaged resulting in parallel walls going through the coating. The resistance of the soil in the pore gives a contribution to the spread resistance and results in a homogeneous current distribution on the metal surface. This type of coupon is least sensitive to the total surface area since the current density is independent on coupon surface. This is especially true when the coating thickness is larger or in the same range as the coating defect – see annex 2. The calculated average current density is identical with the current density on the edges of the coupon.

In Fig. 1c another extreme example of a coating defect is shown. In this case the coating was sheared off and the metal surface is flat with the coating surface. In this case a high increase of the current density is observed at the edges of the coating, which can be as high as 10 times compared to the average current density. When high current densities are associated with high corrosion rates (e.g. a.c. corrosion) locally increased metal loss is observed resulting in a heterogeneous metal loss. The corrosion risk is significantly higher with this type of coupon compared to the pore situation shown in Fig. 1a and the calculated average current density underestimates the maximum current densities present at the metal surface. Similarly methods determining the average metal loss underestimate the corrosion rate taking place.

The case 1a is conservative for conventional Eoff measurements whereas case 1c is conservative for a.c. corrosion investigations, since it results in the lowest possible spread resistance and highest local current densities. Figure 1b illustrates a compromise that may be used in all cases.

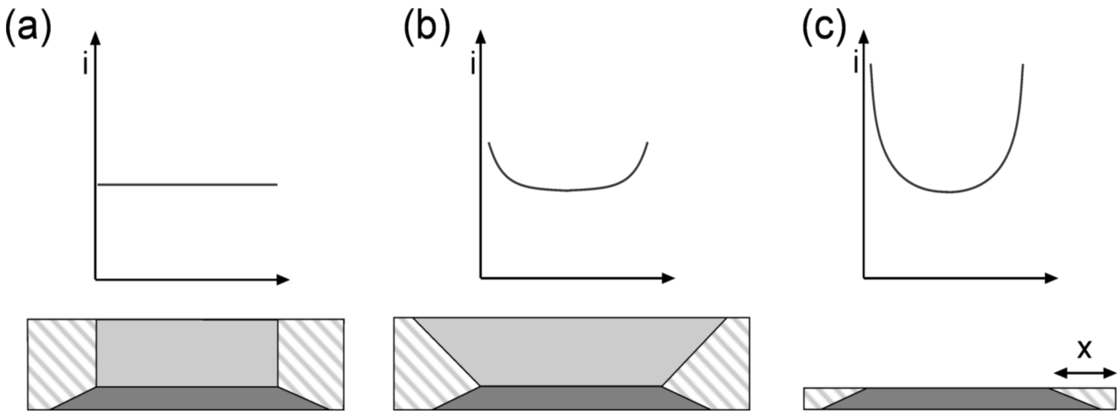


Fig. 1: examples of different coupon geometries and the corresponding current distribution. The dark grey represents the metal, the bright gray represents the sidewalls of the damaged coating and the pattern represents the cross section of the coating. The lateral extension of the insulating part of the coupon is marked with x. (a) Pore in the coating resulting in a parallel current distribution (b) hole in the coating with angled coating edges resulting in increased current densities at the edges (c) sheared off coating resulting in a flat transition from the metal to the coating.

In the examples in Fig. 1 the current distribution is discussed based on a two dimensional distribution. In the case of coupons with a square surface compared to a round one, the current density in the edges of the coupon types in Fig. 1 b and c is further increased. However, it is expected that the configuration in Fig. 1a is least sensitive to the shape of the coupon.

Dimension of the coupon base plate

The lateral dimension of the coupon base plate is relevant for the spread resistance and correspondingly for the current density. In Fig. 1c x represents the length of insulated coupon surface adjacent to the bare steel surface. In the case of a defect on a pipeline this length x would correspond to the coating extending around the defect. This value is typically quite large. Detailed analysis (Nielsen Ceocor 2010 - see annex 2) showed that the distance x is negligible as long as it is three times larger than the diameter of the coupon. If it is smaller, the current density on the coupon will be increased compared to that of an identical coating defect on the pipeline.

Surface area of the coupon

Generally, increasing coupon size results in smaller average current density. As a consequence, the current density is typically underestimated when the coupon surface area is chosen larger than the maximum defect size present on the pipeline. For this reason in the case of a.c. corrosion the use of 1 cm^2 has been established as a standard dimension. Contrarily, the use of 5 to 100 cm^2 defects may be indicated for investigating the efficiency of the cathodic protection. The size of the coupon may be adapted to the coating defects expected on a given pipeline. It is important to note that it is not possible to prove the efficiency of a poorly coated pipeline with large coating defects based on a measurement on a 1 cm^2 coupon with a defect geometry represented in Fig. 1c, since the current density will be significantly increased compared to the situation on the pipeline.

7 Monitoring purpose - selection of installation sites

The selection of the installation sites may include the following issues:

- General verification of the cathodic protection effectiveness
- Verification of the corrosion risk due to d.c. interference
- Verification of the corrosion risk due to a.c. interference.

7.1 General verification of CP effectiveness

For general verification, the coupons may be installed in locations that may have different soil resistivity, soil chemistry, moisture content, current density, coating condition, and temperature [1]. Examples of such locations are:

- the top of a dry, rocky hill,
- low-lying wet valley,
- mid-span between CP current sources,
- suction and discharge of compressor stations,
- casings.

Coupons should be placed in each environment to help identify the effectiveness of the impressed current system in that specific environment. In any case the coupons should be electrically connected to the pipeline. In order to ensure that the protection criterion is met, it can be useful to install coupons in locations where the access of the cathodic protection current may be difficult.

Typically these are areas where the protection criterion can be difficult to obtain: in high or very low soil resistivity, within protection tubes, in presence of high d.c. stray current, etc.

To validate the achievement of the cathodic protection criteria indicated at standard EN 12954 Table 1, IR free potentials shall be measured to avoid the ON measurement error.

According to standard EN 13509 Table 1 using an external potential test probe is a valid technique in all cases for measuring these IR free potentials.

At common “Instant OFF” measurements by interrupting the CP using a switch at the rectifier, CP current is interrupted but in some situations, as the ones specified in chapter 5.1 this is not always enough to verify compliance with the criteria. This problem could be solved by using external potential test probes.

The coupon should be located close to the pipeline to assure that the soil conditions are similar in the coupon and in the nearby pipeline coating defects. If the coupon fulfills the protection criteria under these conditions, it can be concluded that all corresponding coating defects on the pipeline with similar or smaller surface are protected as well.

For measuring IR free potentials at the external potential test probe, an interrupter is installed at the coupon-pipe cable and then cyclic interruptions are carried out. At the switch opening moment “Instant OFF” no current can enter or exit from the coupon; therefore the IR error created by the equalizing or stray currents is annulled.

The reference electrode shall be located as close as possible to the coupon to avoid or to minimize the IR error created by the current that circulates along the soil even if it doesn´t enter or exit from the probe. This current is the result of the existing potential gradients in the soil due to CP currents, stray currents, equalizing currents or galvanic currents.

The period of time between the Instant OFF and the moment in which the reading is performed, shall be short enough to avoid a reading after an excessive coupon depolarization and long enough to avoid an error due to the measurement devices equipped with a.c. filters.

7.2. Verification of CP effectiveness under d.c. interference conditions.

For the evaluation of the risk of d.c. stray current corrosion, the coupons should be placed at any location where the criteria for unacceptable d.c. stray current is present. Refer to reference [4].

In the presence of stray currents created by d.c. traction systems, the influences produced over the pipeline could importantly change during the design life.

To avoid any corrosion risk at cathodic protected pipelines due to stray currents, Standard EN 50162 establishes as criterion that CP criteria from Standard EN 12954 Table 1 shall be permanently achieved.

According to chapter 6.1 using ON-OFF potentials readings from external potential test probes, the above mentioned criterion could be confirmed. To validate these results the readings shall be performed during a sufficient period of time (e.g. typically 24 hours). Thus sufficient period of time must cover all normal variations created by stray currents influences due to a daily d.c. transit system schedule.

For this purpose a data logger and an interrupter are installed at the external potential test probe to obtain ON-OFF potential readings from the coupon and also the current that circulates during ON periods.

To avoid coupon depolarization due to long interruption periods the switch installed between the coupon and the pipeline is programmed in such a way that the ON period is very much longer than the OFF period (e.g. 59 sec. ON – 1 sec. OFF).

In some cases anomalies, which present insufficient CP periods at the coupon, have been encountered only during weekends, due to a different traction transit system schedule than the existing one at week days. This condition is difficult to verify therefore two options are available: at site potential recording during the entire weekend or having a remote monitoring system capable of measuring Instant OFF potential several times a day including weekends.

7.3. Verification under a.c. interference conditions.

For the evaluation of a.c. corrosion likelihood, the coupons should be installed anywhere the criteria for a.c. corrosion likelihood need to be evaluated. It is recommended that a.c. analysis and a.c. modeling software is used prior to or in connection with the selection of sites. Also in the case of a.c. interference the corrosion risk may be high in areas with low soil resistivity since the corrosion risk is a result of high current densities. The current densities typically increase with decreasing defect size. As a consequence the surface of the coupon should exhibit a surface area of 1 cm^2. Additionally, the access of the current to a small defect is influenced by its geometry. As a consequence, the surrounding coating, its thickness and the geometry of the coupon should reflect the expected defect geometry on the pipeline to obtain the most representative results. The coupon should be installed on the lower part of the pipeline, since there the humidity of the soil is higher and, therefore, the soil resistivity is logically lower. During installation special care has to be taken to make sure that the coupon is embedded in the very same soil as the pipeline.

8 Installation procedures

8.1 General considerations for permanent coupons

The installation of coupons should be made in such a manner that the representative behaviour is maintained to the greatest possible extent. The following are points that should be considered in this context:

A. The coupon should be installed in the same soil or backfill as the pipeline itself.

B. The coupon geometry and consequent spread resistance should reflect the purpose of the monitoring.

C. The coupon should not cause or receive any electrical interference from adjacent coupons or coating faults unless being part of the purpose of monitoring.

D. The coupon should have and maintain an effective electrical contact to the surrounding soil – unless lack of contact is part of the purpose of monitoring.

Good electrical contact must be maintained between the coupon surface and the surrounding environment. During the installation process, the soil around the coupon shall be compacted to prevent settlement and air voids forming around the coupon. These voids could result in loss of full contact between the coupon surface and the surrounding soil. The possible loss of contact because of soil movement caused by freezing or subsidence of the backfill material around the coupon shall be considered and minimized during installation.

CP coupons may be installed by a number of different methods, including:

- Excavation activities during structure investigation,
- Installation of the coupon during construction of the structure under investigation.
- Hand digging,
- Auguring,
- Vacuum excavation,
- Use of casing to limit excavation work for easier installation and later removal of coupon.

The installation method selected depends on site access, the type of soil to be excavated, the cost involved, and the availability of an electrical connection to the structure [1].

8.2 Considerations when excavating (pipeline is unexposed)

To better ensure that the coupon is embedded in the same soil as the pipeline (and not arbitrary soil from the excavation) it is advisable to arrange the excavation in such manner that a wall of original soil is left behind in which the coupon can be arranged. See figure 2–right.

In this case it may be possible to arrange the coupon flush with the pipe wall giving ideal conditions for reproducing the draining effect that the pipeline itself may produce, thus providing a best practice for reproducing the conditions experienced by a true coating defect. See figure 2 – left.

Figure 2: Left: Rod type ER probe embedded in sleeve for the purpose of providing a better integration with a pipe surface. Right: Illustration relating to the installation during excavation procedures. In order to ensure installation in original backfill (or same soil as the pipeline) make the excavation in such manner that an original wall of soil is left behind in which the coupon is installed (white arrow indication)

8.3 Suggested procedures when auguring

The following is a typical procedure for the installation of coupons by auguring:

Locate and mark all buried structures including piping, tanks, and cabling prior to the installation. Select a point to auger - take proper precautions so as not to damage the coating or structure when auguring. Preferably, the backfill zone is known in advance (see figure 3). Make a mark (for instance on the test post) defining a depth of zero – if the depth of the coupon position is desired (advisable).

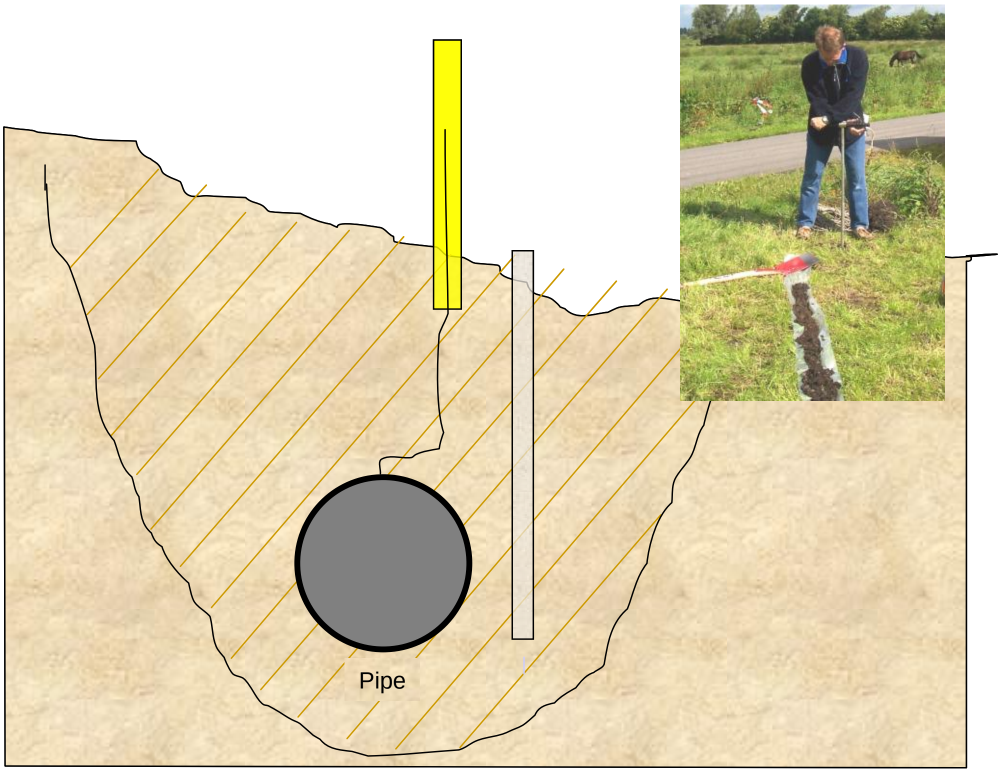


Figure 3. Sketch of a pipeline embedded in original backfill. Picture illustrating the auger process. Soil is arranged carefully on a plastic sheet in order to fill back and compact in the same row as excavated.

For characterizations of the soil, it can be advised to use some excavated soil to perform resistance test in a soil box, to observe humid content, to make acid droplet test for presence of calcium carbonate or to sample for further analysis back in laboratory. Keep strict record. Push the coupon in position using an auger fitting – see figure 4.

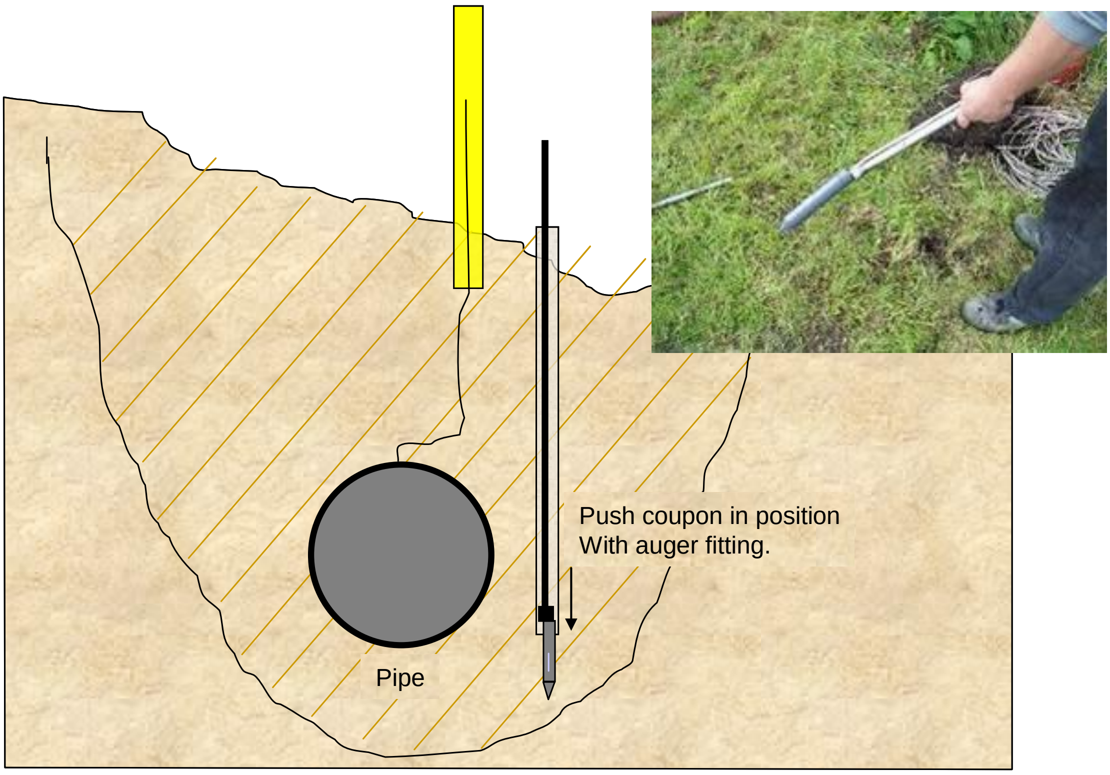


Figure 4. Push coupon in position with auger fitting.

If the soil is soft / sandy push the coupon an additional step down through the undisturbed native soil/backfill. In this case, the soil usually fills out and compacts around the coupon and provides good electrical connection. Fill back the soil in the drilled hole in the same row as uncovered and compact each small amount of backfill.

If the soil is harder, it may be necessary to form a cake of soil from the desired coupon depth and form a “cake” around the artificial coating defect of the coupon – mixed with a bit of distilled water prior to positioning in the soil. Fill back the soil in the drilled hole in the same row as uncovered and compact each small amount of backfill.

Arrange the coupon test leads in the test post.

8.4 Considerations in urban areas

In urban areas there may be restrictions in positioning the coupon due to other installations. Therefore it may be necessary to deviate from the requirements in section 8.1. However, the significance of the obtained results may be compromised due to this deviation.

9 Commissioning

9.1 Preliminary checking

Before connecting the coupon to the pipeline, the following measurements should be performed:

- Free corrosion potential of the coupon
- Potential of the permanent reference electrode (if present) against a portable reference electrode
- Spread resistance of the coupon (resistance of the coupon to remote earth).
- If it is an ER probe – the Initial values of the electrical resistance of the build-in metal elements.
- Resistance of the pipe to remote earth.
- Soil resistivity near the coupon.

9.2 Start up

- Coupon a.c. current
- Coupon d.c current
- ON potential
- Coupon OFF potential – against the internal reference electrode (if present) and against an external reference cell.
- If it is an ER probe – the Initial values of the electrical resistance of the build-in metal elements – under influence of the a.c. current
- Checking of the remote monitoring system – if applied.

9.3 Verification of the settled parameters

Once the coupon has sufficient ground contact and after a suitable polarization period, the coupon parameters (9.2) should be checked.

9.4 Installation and commissioning documents

After successful installation of the coupon, the following documents should be prepared

- Installation date as well as documents detailing the type of coupon and the dimensions of the coupon parameters.
- As built layout drawings with indications of the position of the coupon relative to the pipe and if possible relative to the backfill.
- Details of equipment operation and adjustment
- Results of all measurements carried out before and after commissioning
- Description of the installation with details and references to materials as well as information useful for the correct operation and maintenance – e.g. frequency of system checks.

The final data are the basis for subsequent system checks to be performed on the coupon arrangement and therefore need to be filed and retained.

Annex 1

Special types and procedures of coupons and probes

A1.1 Coupons for determination of weight loss and pitting

The coupons are produced from steel plates that are marked, degreased and weighed. After connection of the cable the surface is coated except for the area simulating the coating defect, see figure A1.1 below. Until installed it should be stored in a sealed plastic bag containing a drying agent.

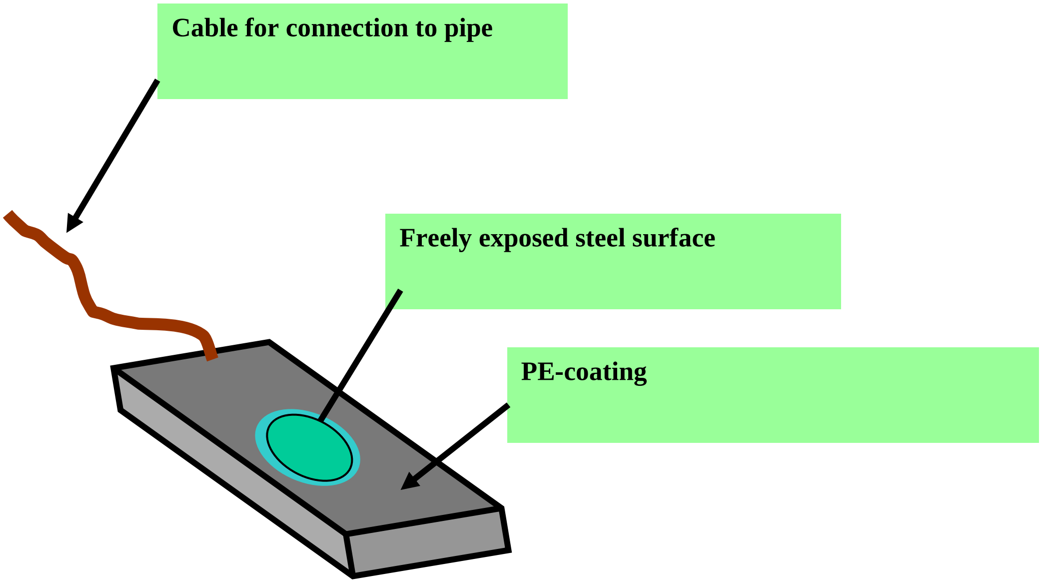


Figure A1.1. Sketch of a weight loss coupon.

When the coupon is excavated for evaluation it is advised to collect a sample of the surrounding soil for determination of soil type and resistivity. Before cleaning the exposed steel surface a photo should be taken. The coupon is cleaned with fresh water, dried and placed in a plastic bag with drying agent.

The coating is removed and the cable dissembled. The weight loss is determined by pickling in Clarkes solution (20 g Sb_2O_3 and 60 g $SnCl_2$ x $2H_20$ per litre concentrated HCl), in accordance with ISO 8407. The pickling is performed in several steps with weighing in between. The mass loss for each pickling is transferred to a graph, see figure A1.2 below.

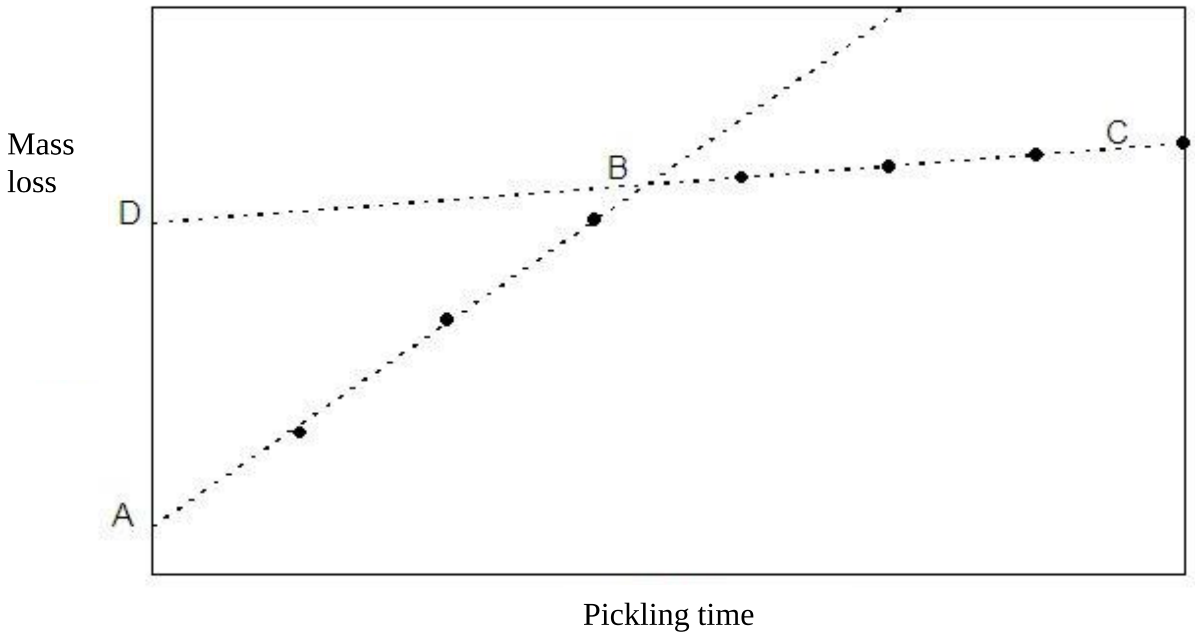


Figure A1.2. Mass loss curve.

The line AB represents the removal of corrosion products. The pickling is repeated until three points on the, close to horizontal line, BC is achieved. Until point B corrosion products are still remaining on the surface. At point B the surface is clean from corrosion products and the points between B and C represent the attack on the base metal. The mass loss is extrapolated to the point D on the y axis which represent the mass loss due to corrosion. The difference in mass loss between the points D and C is a compensation for the mass loss of the base metal during the pickling.

After each pickling the coupons are rinsed in water, dipped in ethanol and dried in warm air. When the coupons are dry and have achieved room temperature they are weighed. The pickling is performed at room temperature and each and at periods between 1 and 10 minutes depending on how heavily attacked the coupons are.

The deepest pit within the exposed area should be determined using optical microscope.

A1.2 Coulometric oxidation procedure

Based on the ac-corrosion mechanism an accumulation of corrosion products occurs in front of the metal surface. The cathodic protection current results in an increased pH value and in a reduction of parts of the Fe^{3+} to Fe^{2+}. The overall content of iron ions accumulated due to corrosion can be estimated by coulometric oxidation of Fe^{2+} to Fe^{3+} [1]. As a consequence, the amount of charge is proportional to the amount of corrosion products formed over time. The coulometric oxidation can be performed with all types of coupons installed in the field and connected to a cathodically protected pipeline.

By separating the coupon from the pipeline, a constant anodic current can be applied and the resulting potential can be recorded. The ohmic potential drop can be numerically corrected or the off-potential can be determined by periodically interrupting the current flow. The amount of charge required to polarize to coupon to 0 V CSE is used for estimating the mass loss on the coupon [2]. The advantage of the technique is the possibility of determining the corrosion that occurred in the past. Moreover, the further increase of corrosion can be determined by means of repeated coulometric oxidation. The results of the measurement are only reliable, if all the corrosion products are electrochemically accessible and if the cathodic protection current is sufficiently high to reduce the corrosion products.

A1.3 Perforation probes

The perforation probe can be used as a conventional coupon for regular measurements but its primary purpose is to give a warning when the deepest corrosion pit reaches a predestined value. The key advantage is the simple handling and especially the information about the corrosion depth. Hence, information about the depth of the corrosion is provided independent of the corroding surface. This is especially important in cases of very local corrosion that penetrates rapidly, but with little mass loss. The monitoring of the perforation coupon can be readily integrated into the conventional inspection routine and also remotely controlled.

There are different types of perforation probes but they are built on the same principle idea. When corrosion penetrates a thin steel plate, this can be detected by a physical measurement.

In the following, two examples of penetration coupons are described, one based on electrical measurements (conductive type) and one on pressure surveillance.

The conductive type consists of a thin steel plate and an internal electrode, see figure A1.3. When corrosion perforates this steel plate humidity will penetrate into the gas tight coupon and form a conductive electrolyte between the electrode and the thin plate. By a simple resistance measurement between the electrode and the thin plate the perforation of the coupon can be detected by means of conventional resistance measurement devices.

Figure A1.3. Conductive perforation coupon.

The pressurised perforation probe based on pressure surveillance is shown in figure A1.4. It consists of a steel tube connected to a flexible copper tube. Both tubes are covered with a shrinkage tube except for the defect on the steel tube, see figure 10 (right). The copper tube is fitted into a junction box. To the same box a valve and a manometer are connected enabling pressurization the copper/steel tube as well as monitoring the pressure. This packaged is placed within a plastic container which is mounted within the test post. When the deepest pit penetrates the wall of the exposed steel surface the pressure falls and this is indicated on the manometer.

Figure A1.4. Pressurized perforation coupon.

A1.4 ER corrosion rate coupons/ probes

The ER coupon technique can be applied for corrosion rate assessment as an alternative to the weight loss coupon. Unlike the weight loss coupon, the ER coupon technique does not require excavation and weighing procedures since a mass loss is assessed by electronic means. Other coupon quantities such as a.c. current density, d.c. current density, spread resistance etc. can be measured as well on ER coupons.

The ER technique consists in measuring the change of the resistance of a metal element formed as a coupon. When the metal element suffers from metal loss due to corrosion the electrical resistance of the element increases. Since the resistance of the element also changes due to temperature variations, a second element which is coated in order to protect it from corrosion is utilized for temperature compensation. The element exposed to the corrosive environment constitutes the coupon part element whereas the element protected from corrosion by the coating constitutes a reference element (see figure A1.5).

When current is exchanged between the exposed element and the soil, the ER technique should provide means for temperature compensation due to heating of the exposed element by the current exchange.

The resistance values of the two individual elements are usually measured by passing an excitation current through the elements and measuring the voltage generated over the element length caused by the excitation current.

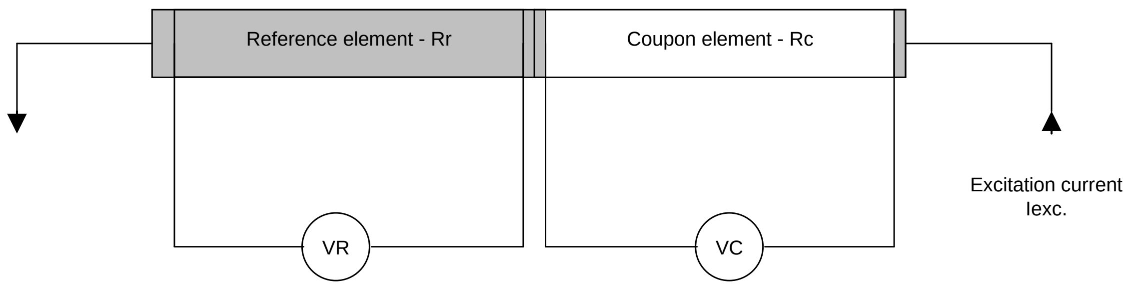


Figure A1.5. Principle of ER probe with excitation current and voltage measurement.

The thickness of the coupon element at time t can be assessed throughout time using the sketched circuit principle. The coupon element thickness at time t is then quantified by a mathematical algorithm, for instance:

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

where (t = 0) refers to initial probe conditions. The slope of a thickness versus time curve can be used for simple assessment of the corrosion rate.

Further reading:

***Possible temperature effects on a.c. corrosion and a.c. corrosion monitoring**, Paper presented at CeoCor 2012 Lars Vendelbo Nielsen.*

Annex 2

Effect of coupon geometry and d.c. current density on spread resistance

For the monitoring of a.c corrosion risk, it has been a common discussion whether the pipe to earth a.c. voltage or the a.c current exchanged in coating defects would be suitable as monitoring parameter. The correlation between these two parameters is given as:

$$U_{AC}(V) = R'_S\,(\Omega) \cdot I_{AC}\,(A) \qquad (1)$$

or

$$U_{AC}(V) = R_S(\Omega \cdot m^2) \cdot J_{AC}\,(A/m^2) \qquad (2)$$

R'_S denotes the spread resistance in Ω whereas R_S denotes the spread resistance in $\Omega.m^2$.

Usually, the spread resistance related to a circular coating defect with area (A) and diameter (d) embedded in soil with a soil resistivity ρ_{soil} is expressed as [see reference 1 p. 540]:

$$R'_S\,(\Omega) = \frac{\rho_{soil}(\Omega \cdot m)}{2 \cdot d\,(m)} \qquad (3)$$

or

$$R_S(\Omega \cdot m^2) = \frac{\rho_{soil}(\Omega \cdot m)}{2 \cdot d\,(m)} \cdot A\,(m^2) \qquad (4)$$

Substituting (3) into (1) gives:

$$U_{AC}(V) = \frac{\rho_{soil}(\Omega \cdot m)}{2 \cdot d\,(m)} \cdot I_{AC}\,(A) \qquad (5)$$

Substituting (4) into (2) gives

$$U_{AC}(V) = \frac{\rho_{soil}(\Omega \cdot m)}{2 \cdot d\,(m)} \cdot A\,(m^2) \cdot J_{AC}\,(A/m^2) \qquad (6)$$

At a given location – providing that the soil resistivity as well as the geometry and dimensions of the coating defect of matter are fixed values in equations (5) and (6), both equations suggest that there is a well defined constant correlation between the pipe to earth a.c. voltage and the density of the a.c current exchanged between the pipe and the adjacent soil through this coating defect.

In such case, it wouldn't matter which parameter (a.c. voltage or a.c. current density) is chosen to assess the a.c. corrosion risk – provided that the sol resistivity and the coating defect geometry and size are known and constant. In this context, it must be noted that

1. The very nature of the a.c. corrosion process involves a modification of the resistivity of the soil in the close proximity of the coating defect – particularly through the production of hydroxyl ions from water through by the cathodic protection current – which will lower the spread resistance and determine the level of a.c. current.

2. The spread resistance depends significantly on the size and geometry of the coating defect.

A2.1 Effects of the cathodic protection current density on the spread resistance

The electrochemical processes resulting from cathodic protection may influence the resistivity of the soil close to the coating defect in three different ways:

1. Increase the spread resistance – leading to decrease in the resulting a.c. current density at constant a.c. voltage.

2. Decrease the spread resistance – leading to an increase in the resulting a.c. current density at constant a.c. voltage.

3. No influence – this case is not discussed.

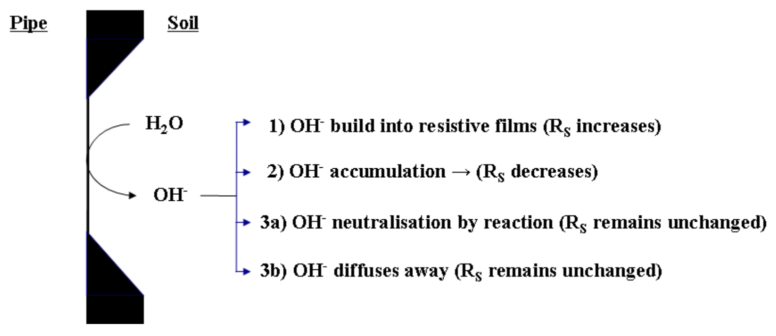


Figure A2.1. Schematic illustration of the modification of the spread resistance due to the production of hydroxyl ions through the electrochemical cathodic protection processes.

Case 1 (increase of the spread resistance) Due to the cathodic protection processes, alkalinity (OH^-) is produced at the bare steel surface at the coating defect. If the soil contains earth alkaline cations like Ca^{2+} and Mg^{2+}, the alkalinity production will lead to precipitation of calcium- or magnesium hydroxides. This scale forming process will form resistive layers on the steel surface, and the spread resistance will increase regardless of a constant soil resistivity in the bulk. The process may increase the spread resistance by 2 orders of magnitude.

Case 2 (decrease of the spread resistance) relates to the accumulation of the hydroxyl ions (OH^-) produced by the cathodic protection processes.

If produced in sufficiently large amounts – with a certain reaction rate – hydroxyl ions will accumulate at the surface and contribute to the conductivity of the soil close to the steel surface. Besides an increase in pH, the accumulation will lower the spread resistance and cause increase in the a.c. current density at the same level of a.c. voltage according to equation (2) – see example in figure A2.2 and in figure A2.3 for various soil resistances used in test environment.

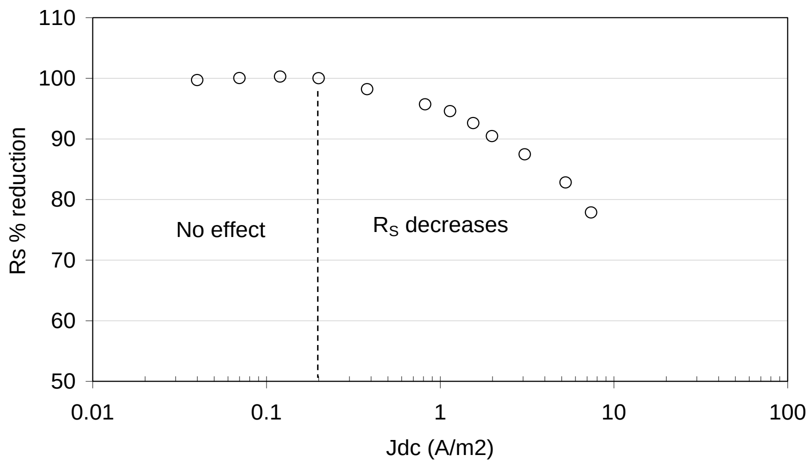


Figure A2.2. Effect of the cathodic protection d.c. current density on the spread resistance – illustrating a threshold d.c. current density above which the spread resistance decreases.

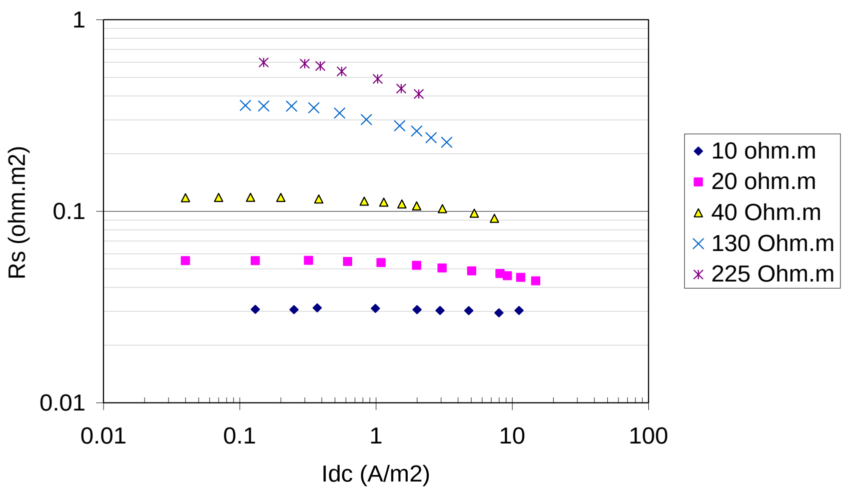


Figure A2.3. Effect of the cathodic protection d.c. current density on the spread resistance – illustrating a threshold d.c. current density above which the spread resistance decreases.

Figure A2.4 is an example of threshold cathodic protection current density – above which the spread resistance decreases – established in a quartz sand environment.

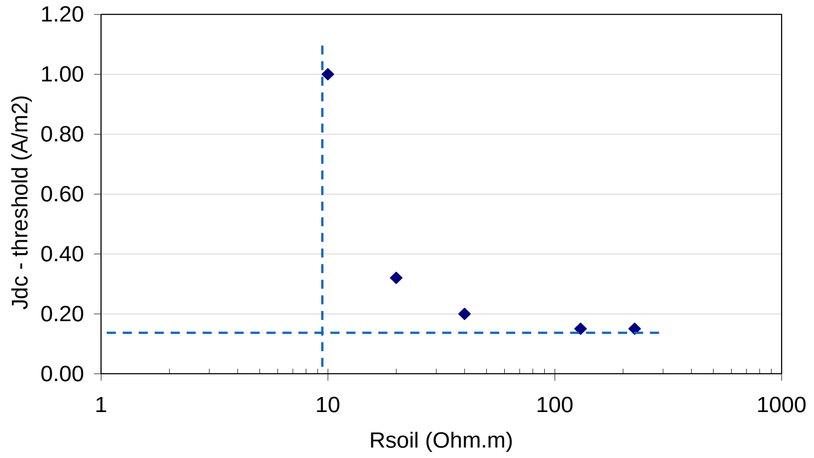


Figure A2.4. Threshold cathodic d.c. current density above which the spread resistance decreases – as a function of the soil resistivity – quartz sand environment.

A2.2 Effects of coating fault geometry on the spread resistance

The equations given in section 5.3 for the spread resistance of coating faults are simplified. Figure A2.5 illustrates the geometrical parameters related to a circular coating defect,

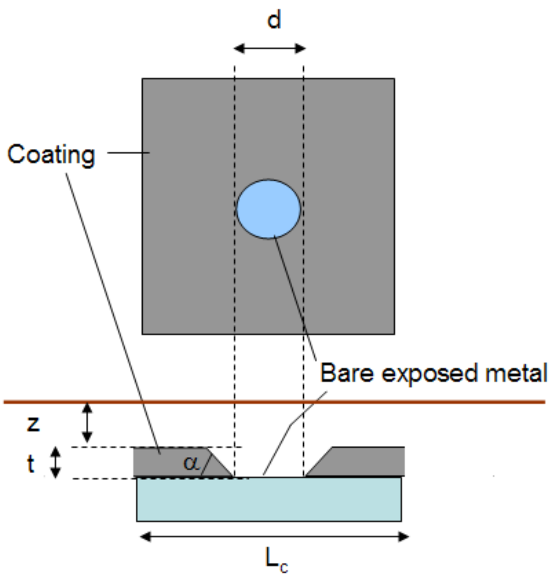


Figure A2.5. Illustrations of a circular coating fault and its related parameters.

The parameters influencing the spread resistance of circular and rectangular coating defects are given below.

Parameter	Unit	Description
d	m	Fault (pore) diameter – circular fault
L	m	Fault length – rectangular fault
W	m	Fault width – rectangular fault
t	m	Depth of pore (coating thickness)
L_c	m	Carrier plate length
α	degrees	Angle of the coating to coating fault gutter
ρ_{soil}	Ωm	Soil resistivity
ρ_{pore}	Ωm	Pore medium resistivity

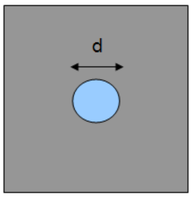
Numerical simulations based on the Finite Element Method for the above geometries have provided more exhausting and detailed correlations between spread resistance and the above parameters.

The following formula and correlations can be provided by the simulations:

The total spread resistance R_s of a coating fault as presented in figure A2.5 is given by the following formula:

$$R_s = \frac{R_{s1} R_{s2}}{R_{s1} + R_{s2}}$$

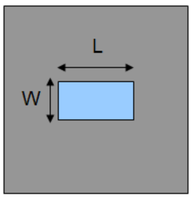
R_{s1} and R_{s2} for a circular coating defect are given by:



$$R_{s1} = \rho_{soil} \frac{1}{2d}\left(1 - \frac{d}{5L_c}\right) + \rho_{pore}\frac{4t}{\pi d^2}$$

$$R_{s2} = \left\{\rho_{soil}\frac{1}{2\pi t}\left(1 - \frac{d}{5L_c}\right) + \rho_{pore}\frac{2}{\pi d}\right\}\frac{1}{1-(\alpha/90)^{3/2}}$$

R_{s1} and R_{s2} for a rectangular coating defect are given by:



$$R_{s1} = \frac{\rho_{soil}}{\sqrt{\frac{36}{\pi}\left(L^2 + W^2\right)}} \ln\left(\frac{4L}{W} + \frac{4W}{L}\right)\left(1 - \frac{W+L}{10L_c}\right) + \rho_{pore}\frac{t}{LW}$$

$$R_{s2} = \left\{\rho_{soil}\frac{1}{2\pi t}\left(1 - \frac{W+L}{10L_c}\right) + \rho_{pore}\frac{2}{\pi(L+W)}\right\}\frac{1}{1-(\alpha/90)^{3/2}}$$

The following figures illustrate the above complex equations in terms of calculated spread resistance versus coating defects size for various geometries. See figure captions for details.

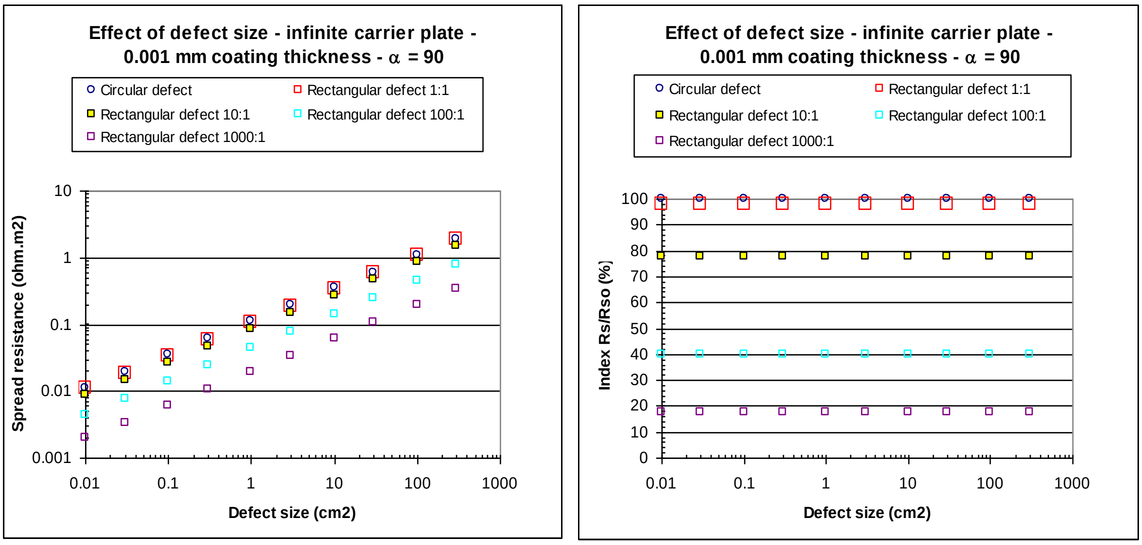


Figure A2.6. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is very thin (1 micrometer).

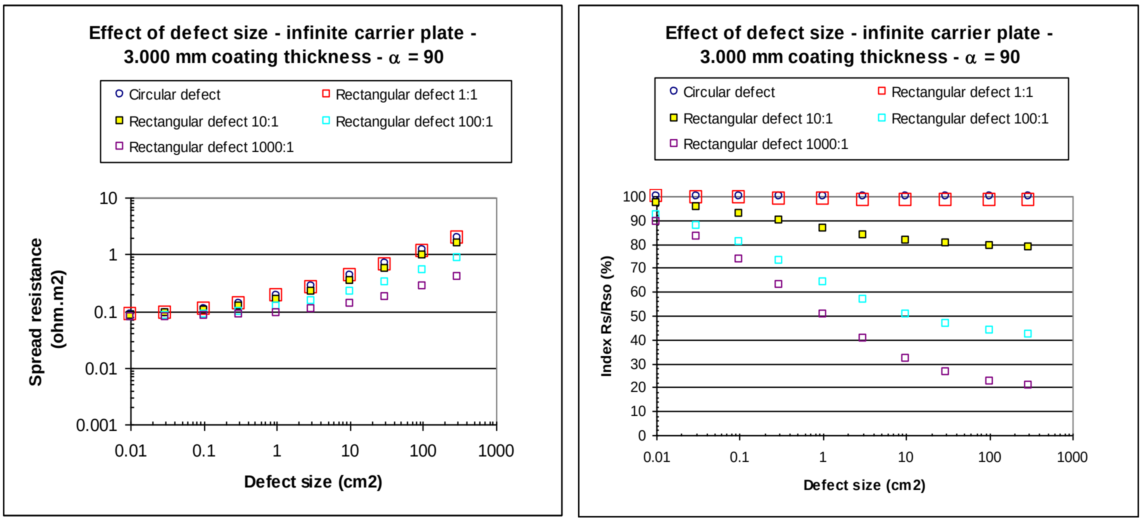


Figure A2.7. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is 3 mm thick with a contact angle 90 degrees.

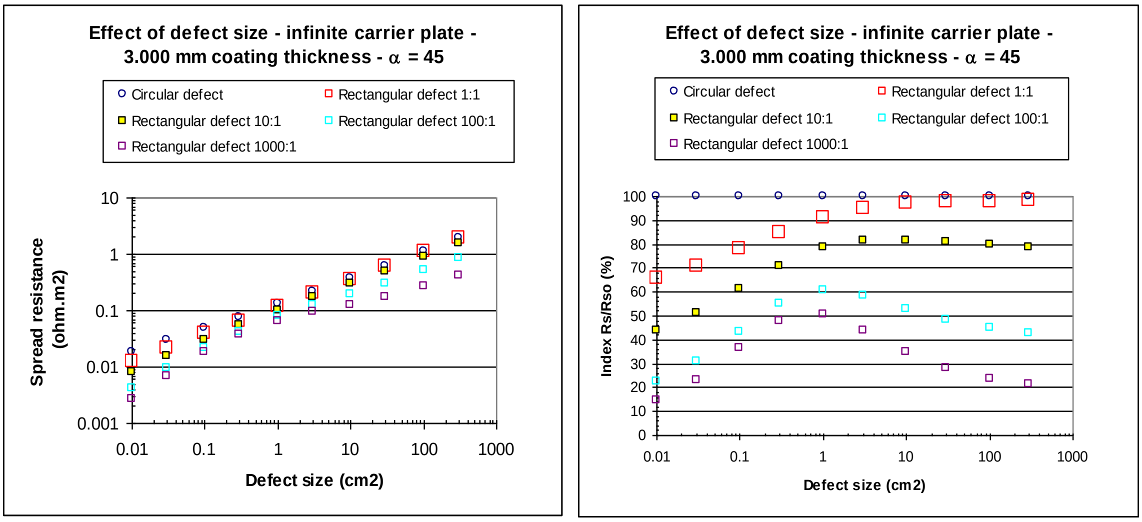


Figure A2.8. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is 3 mm thick with a contact angle 45 degrees.

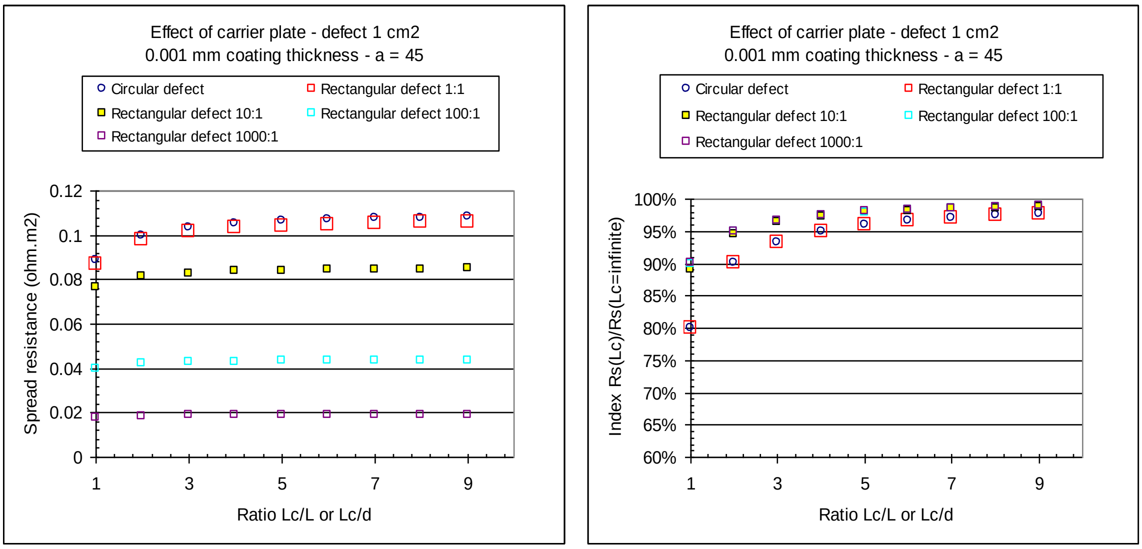


Figure A2.9. The effect on the spread resistance of the ratio between coating defect size and the size of the carrier plate. For a 1 cm2 coating defect with 3 mm coating layer and a contact angle of 45 degrees.

Further reading:

Effect of Coating Defect Size, Coating Defect Geometry, and Cathodic Polarization on Spread Resistance: - Consequences in relation to AC Corrosion Monitoring, Paper presented at CeoCor 2010 Lars Vendelbo Nielsen & Michael Berggreen Petersen (MetriCorr, Denmark), Leslie Bortels & Jacques Parlongue (Elsyca, Belgium).