Bruges 2010

# Effect of Coating Defect Size, Coating Defect Geometry, and Cathodic Polarization on Spread Resistance:
## - Consequences in relation to AC Corrosion Monitoring

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## Abstract

The spread resistance ($R_s$) related to a coating fault plays a very important role in pipeline corrosion and cathodic protection aspects. Firstly, along with the DC current density, it determines the level the IR drop measured in DC potentials. Secondly, it determines the level of AC current exchanged between the soil and the pipe through the coating fault at a given pipe-to-soil AC voltage.

This paper discussed the effects of two factors on the spread resistance. One factor being the level of DC current (CP current) – the other factor being the size, shape and geometry of the coating defect and related elements like coating thickness , contact angle etc.

Regarding the level of cathodic protection current, it is experimentally shown that a threshold level for CP current density exists above which the spread resistance decreases due to the production of hydroxyl ions. The threshold level depends on the soil resistivity – the lower the soil resistivity – the higher CP current density is needed to decrease the spread resistance. For a soil resistivity above 100 Ω.m the threshold level is approximately 0.15 A/m2.

The effect of the coating defect size and geometry has been numerically simulated by the Finite Element Method incorporated in Elsyca CPMaster software and complex yet understandable effects of coating defect size, coating thickness, and coating contact angle on the resulting spread resistance is acknowledged.

The main conclusion from the work presented is:

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.

## Introduction

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

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

or

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

$R'_S$ 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 $\rho_{soil}$ is expressed as [see reference 1 p. 540]:

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

or

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

Substituting (3) into (1) gives:

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

Substituting (4) into (2) gives

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

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 AC voltage and the density of the AC current exchanged between the pipe and the adjacent soil through this coating defect.

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

Since the AC voltage is easily measured with a simple voltmeter (or datalogger) between the pipeline and a reference electrode placed in remote earth, whereas the measurement of the current density requires a coupon connected to the pipeline and buried next to the pipeline, the simplest way to judge the AC corrosion likelihood would be simply by measuring or logging the pipe to earth AC voltage.

However, the above rationale is not feasible – the reason being two-fold:

1. The very nature of the AC 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 guide the level of AC current (almost) regardless of the soil resistivity.

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

The above mentioned effects will be discussed hereafter.

## 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 AC current density at constant AC voltage.
2. Decrease the spread resistance – leading to an increase in the resulting AC current density at constant AC voltage.
3. No influence – this case is not discussed.

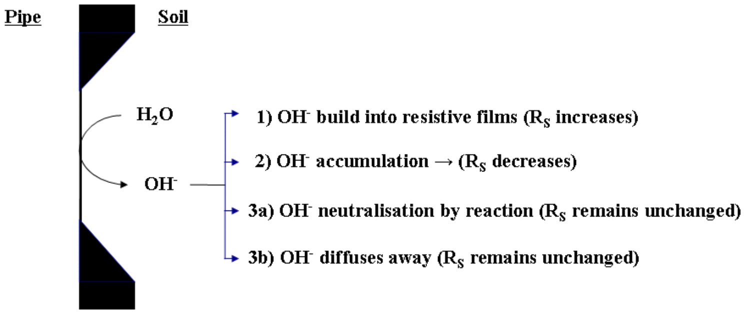


*Figure 1. Schematic illustration of the modification of the spread resistance due to the production of hydroxyl ions through the electrochemical cathodic protection processes.*

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. This effect has been described in literature previously – e.g. [2].

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 AC current density at the same level of AC voltage according to equation (2).

Figure 2 illustrates an example established in a soil box with environment having non-scale forming capability. A coupon having area of 1 cm2 was increasingly polarized in the environment and the spread resistance measured simultaneously. The decrease in spread resistance is observed to occur when the cathodic DC current density exceed a threshold of 0.15 A/m2 in this environment.

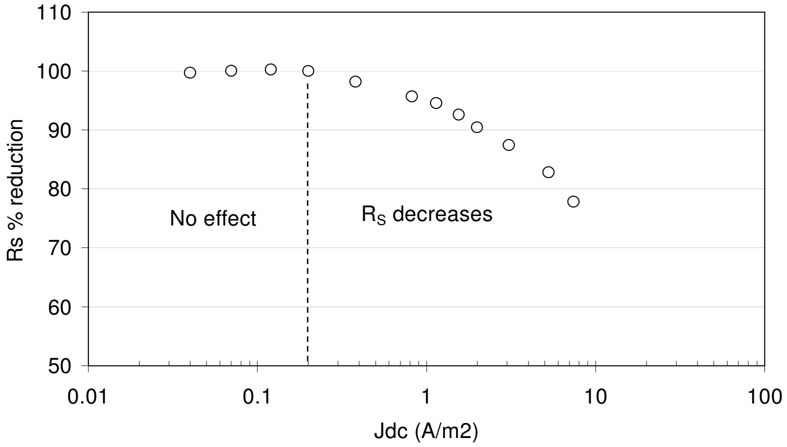


*Figure 2. Effect of the cathodic protection DC current density on the spread resistance – illustrating a threshold DC current density above which the spread resistance decreases.*

In a similar manner, the spread resistance in soil boxes with various soil resistivities (various concentrations of non-scaling solutions based on same chemical substances) was established [3] – figure 3.

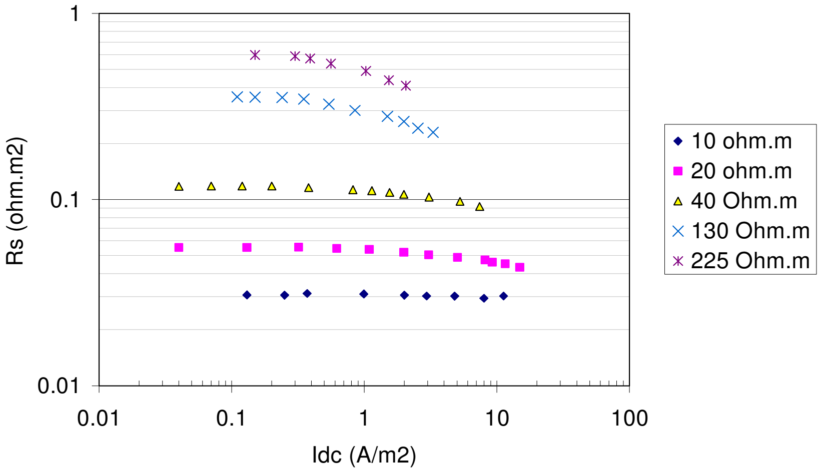


*Figure 3. Effect of the cathodic protection DC current density on the spread resistance – illustrating a threshold DC current density above which the spread resistance decreases.*

From these curves, the relative decrease in spread resistance was established – figure 4.

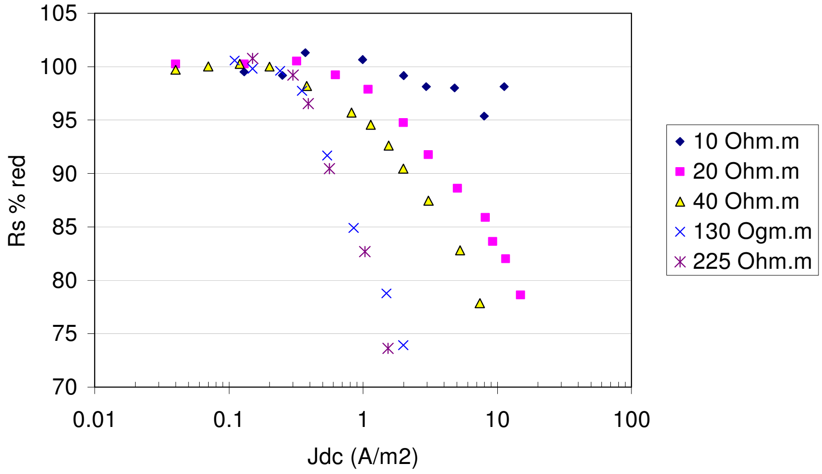


*Figure 4. Effect of the cathodic protection DC current density on the spread resistance.*

From these results assessment of the threshold cathodic protection current density – above which the spread resistance decreases – was established as a function of the soil resistivity – see figure 5.

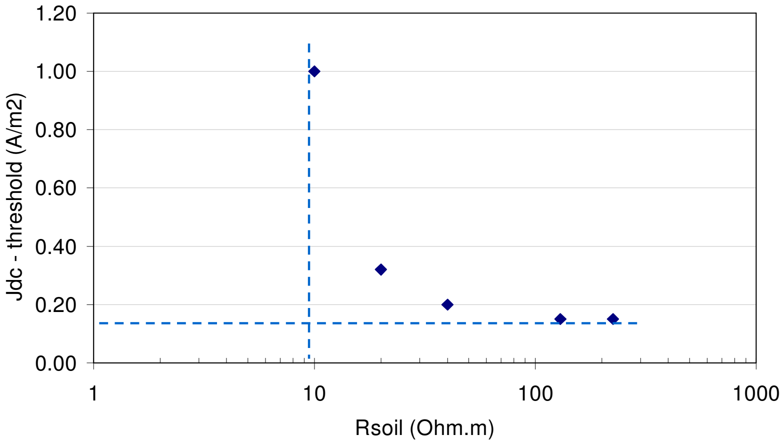


*Figure 5. Threshold cathodic DC current density above which the spread resistance decreases – as a function of the soil resistivity.*

As observed from the figures, the experiments show that in this non-scaling environment the cathodic protection current density will reduce the spread resistance if the current is higher that a threshold level.  This cathodic protection current density threshold level increases with decreasing soil resistivity – figure 3 and 4,

The spread resistance in very low resistivity soil seems unaffected by the cathodic protection current whereas it seems that cathodic protection current densities below 0.15 A/m2 do not affect the spread resistance in the present type of soil – figure 5. Due to the above effects it is not possible to define a reliable level of AC voltage as a criterion for evaluation of AC corrosion risk.

## Effects of coating fault geometry on the spread resistance

The objective of this study was as follows:

1. The usual calculations of the spread resistance of a coating fault (at least for AC corrosion purposes) are based on a circular coating fault with diameter 1 cm2 with a coating thickness approximately zero (yet effectively providing infinite resistance). This coating fault is located on a surface (for coupons: a carrier plate) with infinite extension. For this situation, re-confirm that equation (3) is obeyed.

2. Evaluate the significance of the following factors relating to the coating defect (see figure 6):

    a. The effect of the thickness, t, of the coating
    b. The effect of the angle, $\alpha$, 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.

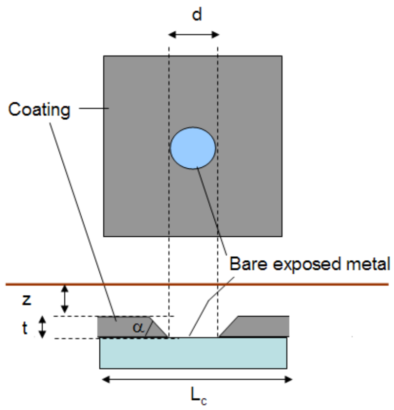


*Figure 6. Illustrations of a circular coating fault and its related parameters.*

3. 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.

These questions were answered by numerical simulations using the Elsyca CPMaster software package. CPMaster is based on the Finite Element Method (FEM) and is fully integrated in the 3D CAD package SolidWorks®. This offers the possibility to calculate potential and current density distributions on complex 3D structures. Full details on the mathematics behind CPMaster are presented in reference [6]. More information on the software is provided in reference [7].

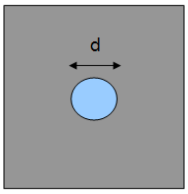
Details of this study can be seen in reference [5].

The following formula and correlations were provided by the simulation:

The total spread resistance $R_s$ of a coating fault as presented in figure 6 is given by the following formula:

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

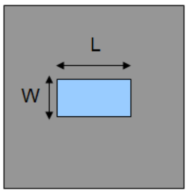
$R_{s1}$ and $R_{s2}$ for a circular coating defect are given by:



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

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

$R_{s1}$ 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 parameters and units in the above equations 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 |
| $\rho_{soil}$ | Ωm | Soil resistivity |
| $\rho_{pore}$ | Ωm | Pore medium resistivity |

The above equations were loaded into a spread sheet application in order to further simulate the relative importance of the parameters and questions outlined in points 1-3. Note that the spread resistance has been expressed in Ω.m2 i.e. normalized with respect to the defect area.

## Effect of the size of the coating fault on the spread resistance.

Figure 7 shows the simulated effect of the size of the coating fault on the spread resistance. In this case the thickness of the coating is very thin and having a contact angle of 90 degrees. The soil resistivity in all simulations have been 25 Ω.m.

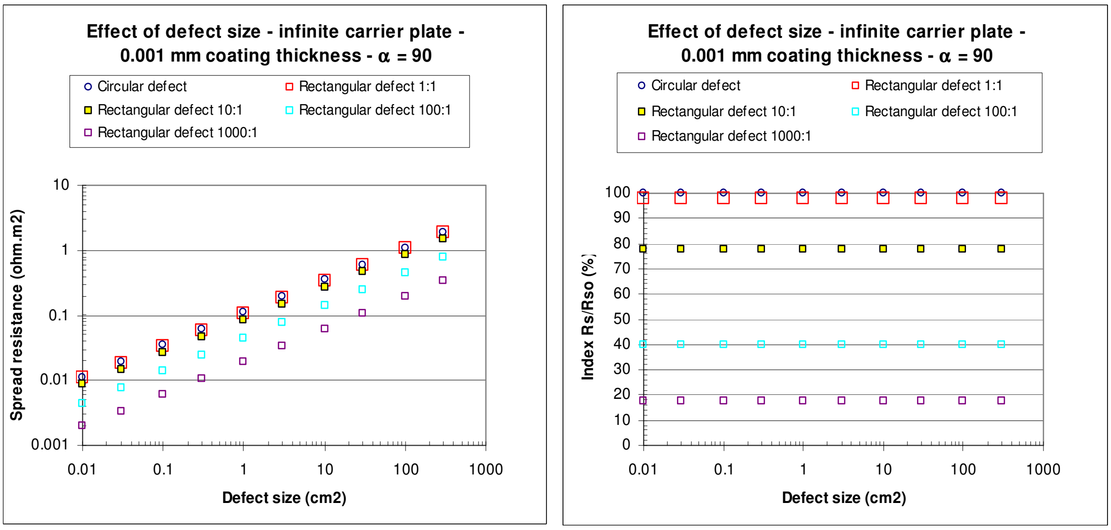


*Figure 7. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is very thin (1 micrometer).*

Figure 7 (left) shows the spread resistance as a function of the defect size. This has been calculated for a circular defect as well as for rectangular defects with length to width ratio ranging from 1:1 to 1000:1 (scratch-like shape). It is generally observed that the spread resistance increases with increasing defect size. As already generally adapted the AC current density will therefore increase with decreasing area – given the same AC voltage level. It is further observed that rectangular geometries exhibit reduced spread resistance compared with the circular shape.

This has been illustrated further in figure 7 (right). In this figure, the spread resistance of a circular shape has been indexed = 100. For each calculated area, the spread resistance of the rectangular coating defect has been compared with the circular. As observed in this manner a square (L:W = 1:1) coating fault exhibits approximately the same spread resistance as a circular spread resistance – regardless of the area of the coating fault. Increasing the length to width ratio of the rectangular coating defect gradually decreases the spread resistance compared with the circular having equivalent size. Accordingly, 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.

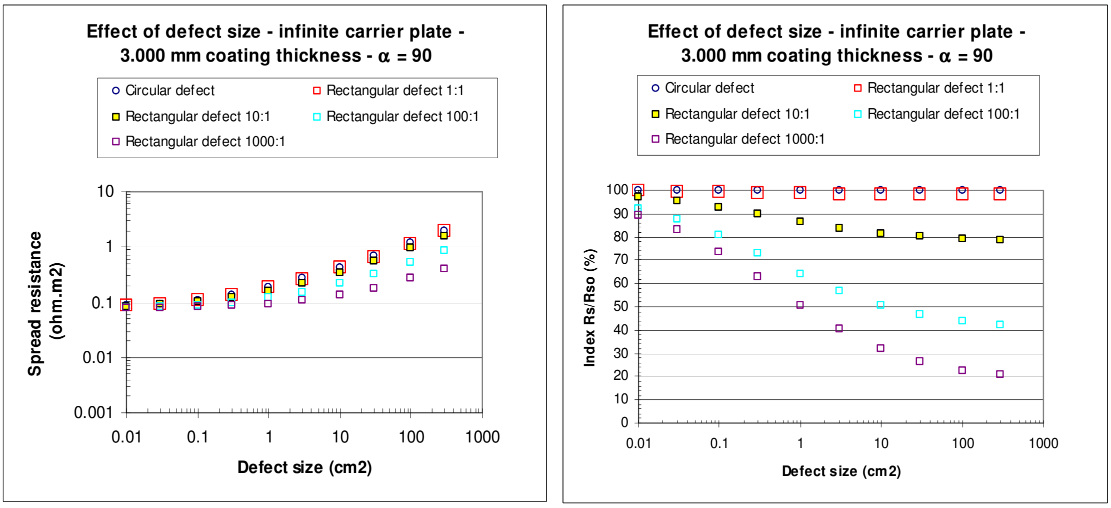


*Figure 8. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is 3 mm thick with a contact angle 90 degrees.*

Figure 8 shows the same simulations as presented in figure 7, only in this case the coating thickness is increased from “insignificant” to 3 mm. The contact angle between the coating and the pipe is 90º.

For large coating defects (+100 cm2) the pattern is exactly the same as the previous case with a coating with insignificantly small thickness. However, when gradually decreasing the coating defect size, the effect of the coating thickness becomes increasingly more important. For all cases, the spread resistance asymptotically approached 0.1 Ω.m2 regardless of the shape. In this way it is demonstrated that the tunnel effect created by the coating is controlling the spread resistance rather than the size of the coating defect. Regarding the index presented in figure 8 (right), it seems that when gradually decreasing the defect area, the effect of the coating thickness also becomes increasingly important. The relative effect becomes increasingly pronounced with increasing length to width ratio. A 1 cm2 scratch (1000:1) exhibits a 50% reduction in spread resistance compared with a 1 cm2 circular defect.

Figure 9 shows the same simulations as presented in figure 8 (3 mm coating) only in this case the contact angle between the coating and the pipe is reduced to 45º - i.e. opened up against the surrounding environment. The effect of this is best illustrated from figure 9 (right) showing the index. Where the 90º contact angle caused a very significant effect particularly at small defects, the 45º angle loosens up on this effect again.

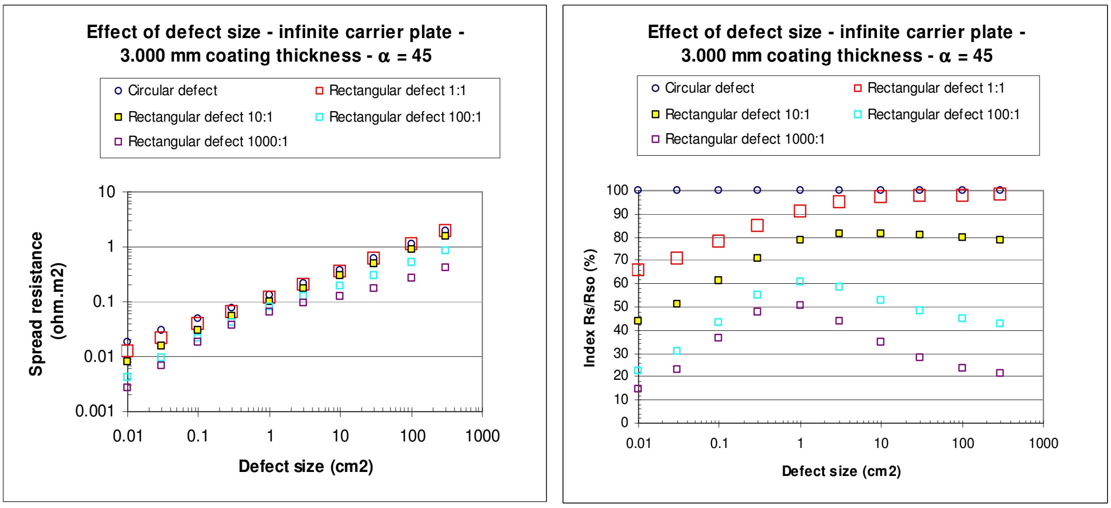


*Figure 9. The effect of the size of the coating fault on the spread resistance – circular shape as well as rectangular shapes with various lengths to with ratios. The adjacent coating is 3 mm thick with a contact angle 45 degrees.*

Figure 10 addresses a different question.

A small coating defect present on a pipe is generally expected to receive current flux from a hemisphere of volume whereas a single point (not shielded by the pipeline) is expected to receive its current from the whole sphere.

For coupon design purposes, this becomes an important question when trying to design the coupon as representative as possible of a pipeline coating. For this reason, a series of simulations have been made where the coating fault is mounted on a carrier plate. The effect of the relative sizes o the coating fault and the carrier plate was simulated. Some results can be seen in figure 10.

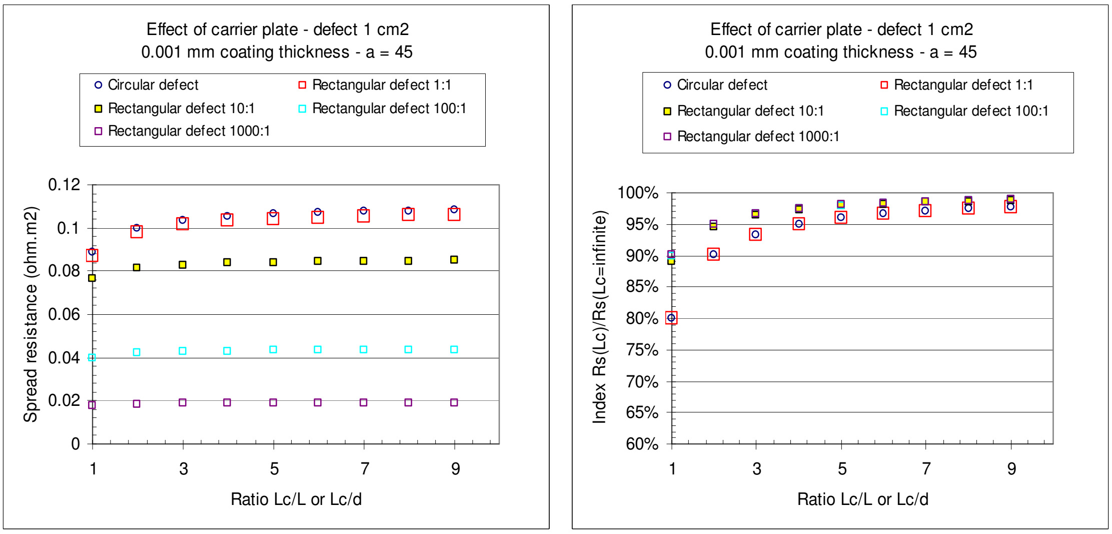


*Figure 10. The effect on the spread resistance of the ratio between coating defect size and the size of the carrier plate. For a 1 cm2 coating defect with 3 mm coating layer and a contact angle of 45 degrees.*

Figure 10 (left shows the spread resistance calculated for the different geometries as a function of the ratio between the size of the defect and the size of the carrier plate. A ratio of 1 indicates the spherical current distribution (receiving current from “the whole world”) whereas a large ratio indicates the hemispherical current distribution (receiving current from “half the world”). The defect size is 1 cm2 and the coating thickness is 0.001 mm whereas the contact angle is 45º.

In figure 10 (right) these calculation have been compared with a the spread resistance for a 1 cm2 coating defect placed on a 1 x 106 cm carrier plate – i.e. a modeling of the condition with current received only from the hemisphere (“half the world”). The questions answered is how big the carrier plate must be in order to detect a reasonable shielding effect from the carrier plate (when will the coupon stop receiving current from the whole world?).

In the case simulated, it seems that when the size of the carrier plate exceeds a factor 3 of the coating defect, the carrier plate will provide at least 90-95 % of the shielding effect and increasing the carrier plate further will not give any additional shielding.

Clearly, quite a number of other questions may be relevantly asked concerning the shape, size and geometry of the coating fault system. These could include:

- further illustrations of the effect of the coating contact angle
- further illustrations of the effect of the coating thickness
- Illustrations of the effects of the soil resistivity
- Illustrations of the effect of the resistivity of the chemistry within the pore in the coating defect.

Several others may exist.

A few random tests have so far been made in the laboratory for experimental verification of the simulations. However, these studies are comprehensive and costly. All interested parties are invited to receive the simulation report as well as the spread sheet tool for their own further evaluation. Further, any collaboration on the experimental verification will be met with a warm welcome.

## Conclusions

### 1. The effect of cathodic protection current density on spread resistance:

1. The spread resistance relating to a coating defect can be lowered significantly by a cathodic protection current density above a certain threshold level. This effect creates the autocatalytic nature of AC corrosion.

2. This cathodic protection current density threshold level – above which the spread resistance decreases - increases with decreasing soil resistivity.

3. The spread resistance in very low resistivity soil seems unaffected by the cathodic protection current whereas it seems that cathodic protection current densities below 0.15 A/m2 do not affect the spread resistance in the present type of soil.

4. Due to the above effects it is not possible to define a reliable level of AC voltage as a criterion for evaluation of AC corrosion risk.

**2. The effect of coating fault geometry on spread resistance:**

Among the conclusions are:

5. 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.

6. 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.

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

8. 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.

9. 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.

**3. General conclusion**

10. 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:
    a. 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.
    b. The shape, size and geometry of the coating fault system will significantly influence the spread resistance.

## Literature

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