D.c. stray currents corrosion : evaluation of the relevance of the risk assessment criterion proposed by the European Standard EN 50162

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Summary

Under normal operating conditions, electrical d.c. influences on buried, coated and cathodically protected steel pipelines from foreign electrical d.c. systems sharing closed rights of way can cause external localized corrosion. This corrosion results from the exchange of currents through the surrounding electrolyte, the soil, between the exposed metal of the pipeline, at coating defects, and a foreign electrical d.c. system.

The main sources of these electrical perturbations are due to d.c. traction systems (e.g. streetcars) and are mainly located in urban areas.

The European standard EN 50162 proposes a criterion based on d.c. current level to evaluate the risk of corrosion due to d.c. stray currents.

The ENGIE Lab – CRIGEN (Center of Research on Gas and New Energies), in association with a French gas' operator GRTgaz, performed a parametric study based on corrosion tests in soil boxes on X70 steel samples (weight loss coupons and ER probes) subjected to d.c. current perturbations in order to evaluate the relevance of the EN 50162 criterion.

1 Introduction

1.1 Factors enhancing d.c. stray currents corrosion

Some important corrosion issues can occur on buried, coated and cathodically protected pipelines due to d.c. stray currents involved by d.c. electrical systems (such as d.c. traction systems, railways…). This type of corrosion can lead to high corrosion rates and affects usually small localized coating defects.

This phenomenon depends on many factors such as:

- duration and frequency of d.c. stray current perturbations;
- surface area and shape of the coating defects;
- intensity of the d.c. perturbation;
- cathodic protection (CP) parameters: d.c. polarization potential and d.c. cathodic current density on the exposed metal, resulting from the CP protection system;
- and also the composition of the soil as well as the soil solution.

These numerous factors must be taken into account to fully predict the behavior of pipelines subjected to the d.c. stray current corrosion.

As corrosion rates could be high, it is necessary for pipelines' operators to identify as well as possible the risk of corrosion. For improving the monitoring of d.c. stray current corrosion, a criterion is given in the European Standard EN 50162 to assess the effectiveness of the cathodic protection and the associated d.c. corrosion risk. However, this criterion (detailed below) is specific to d.c. stray current issues and its first postulate is based on the European Standard EN 12954.

1.2 d.c. stray current criterion of the European standard EN 50162

The European standard EN 50162:2005 proposes a criterion based mainly on the d.c. current measurement and the risk assessment proposed is made of 4 steps:

1. Measurement of the d.c. current during a period without any d.c. perturbation (for example, the night). It is assuming this d.c. current allows to respect cathodic protection criteria as defined in EN 12954. This current, named the reference current, corresponds to the period A in the Figure 1 below;
2. Measurement of the global d.c. current (corresponding to the CP current + the d.c. stray currents) during a continuous period of time (typically 24 hours);

3 Choice of the period of time (1 hour) with the highest probe current reductions for the risk assessment as it is illustrated by the Figure 1 below corresponding to the period B;

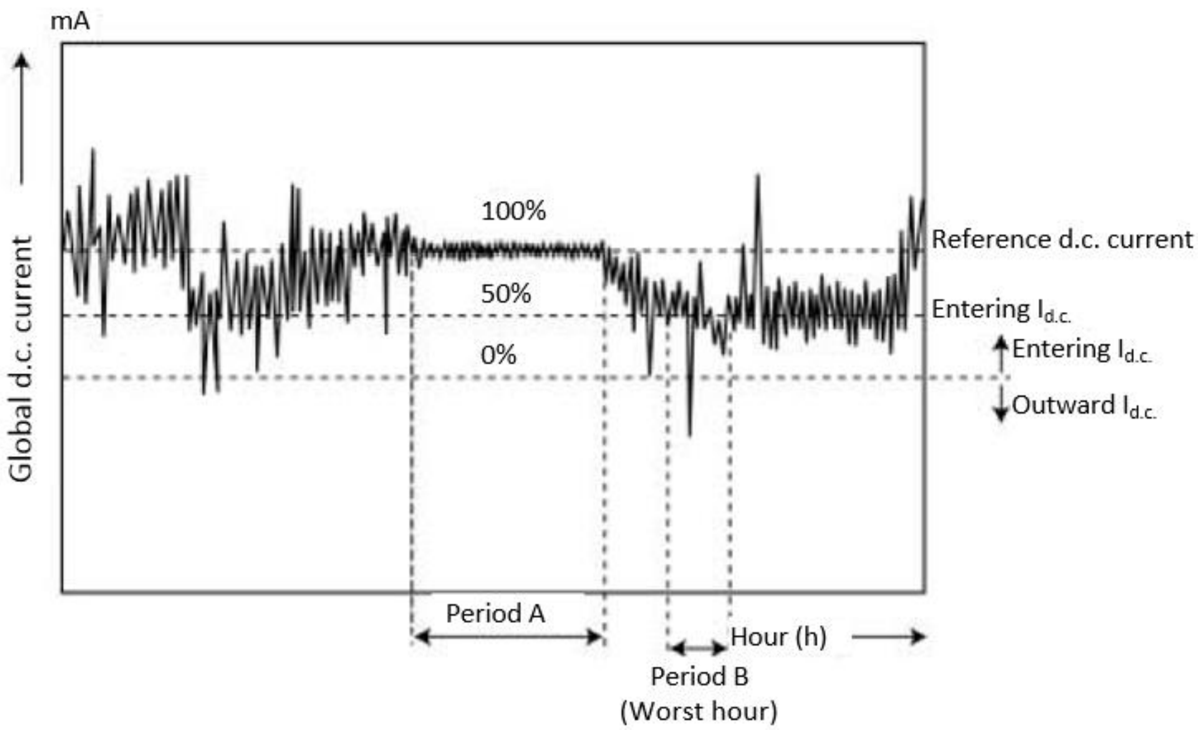


Figure 1. Representation of a 24 hours measurement on a probe submitted to d.c. stray current interferences

4 Evaluation of the d.c. stray current corrosion risk based on the Table 1 below.

Percentage of global $I_{d.c.}$ by reference $I_{d.c.}$	Maximum acceptable occurrence period	
	Percentage on the worst hour	in secondes
> 70	Unlimited	
< 70	40	1 440
< 60	20	720
< 50	10	360
< 40	5	180
< 30	2	72
< 20	1	36
< 10	0.5	18
< 0	0.1	3.6

Table 1. d.c. stray current corrosion risk assessment : maximal acceptable occurrence period of d.c. stray current per worst hour depending on the percentage of global current by reference current

For operational maintenance, this criterion:

- **is quite difficult to apply**, mainly because the choice of the worst recorded hour is often subjective. In fact, the occurrence of fluctuation of the global current due to d.c. stray currents is very important and the highest probe current reductions do not always correspond to the “worst” hour period;
- **is not really accurate**, as some parameters, which could have an influence on d.c. stray current corrosion, are not precisely defined:
    - d.c. anodic current intensity (outward currents);
    - reference current intensity (corresponding to a low or high CP level);
    - duration and frequency of d.c. stray currents (threshold on global time of perturbation is proposed by the criterion but, for example, would a single perturbation (which would last for a certain amount of time), or 10 different perturbations (having the same global duration) have the same consequences on the steel corrosion rate ?);
    - Metallic exposed area of coating defect.

As a conclusion, based on experience, CP operators consider this criterion to be too conservative.

1.3 Objectives of this work

ENGIE Lab - CRIGEN performed a parametric study in order to:

- better appreciate the impact of d.c. stray currents on corrosion phenomenon;
- and evaluate the relevance of the criterion of the European standard EN 50162.

Laboratory tests were performed in soil boxes to evaluate the impact of several main parameters on d.c. stray currents corrosion, in particular, the impact of:

- cathodic protection potential;
- anodic d.c. stray currents intensity;
- duration of application of the d.c. interferences.

The experimental conditions of the tests, presented in this article, were focused on the worst threshold values of the European standard criterion (EN 50162), in order to evaluate its relevance.

2 Experimental Study

2.1 Experimental setup

The four experiments, presented here, were carried out in a glass electrochemical corrosion cell, as shown in Figure 2. This test cell is filled with pure sand of small size (grain diameter from 0 to 2 mm) wetted by a Na_2SO_4 aqueous solution in the amount of 10 g/L which is controlled such as to get a soil resistivity of about 15 Ω.m. The humidity of the soil is around 60% relative to the water saturation of the soil.

The experimental setup is presented in Figure 2 and comports:

- A three-electrode cell including:
    - a steel working electrode present as a sample or as an Electrical Resistance Probe (ER-Probe) depending on the test performed;
    - a $Cu/CuSO_4$ reference electrode;
    - and a Mixed Metal Oxide grid (made of tantalum and iridium oxides) counter electrode;

- Two galvanostats : one for applying a fixed cathodic protection level and the other one for applying d.c. interferences to the working electrode. The galvanostats fully control (i) the d.c. currents applied, (ii) the instant ON-potential and (iii) the IR-Free potential (versus the reference electrode). Those parameters are regularly measured all test long;

- An oscilloscope was used (i) to check the applied signal, (ii) to perform a fast speed recording of the ON potentials of the working electrode during d.c. perturbation and (iii) to determinate regularly the IR-Free potential on samples.

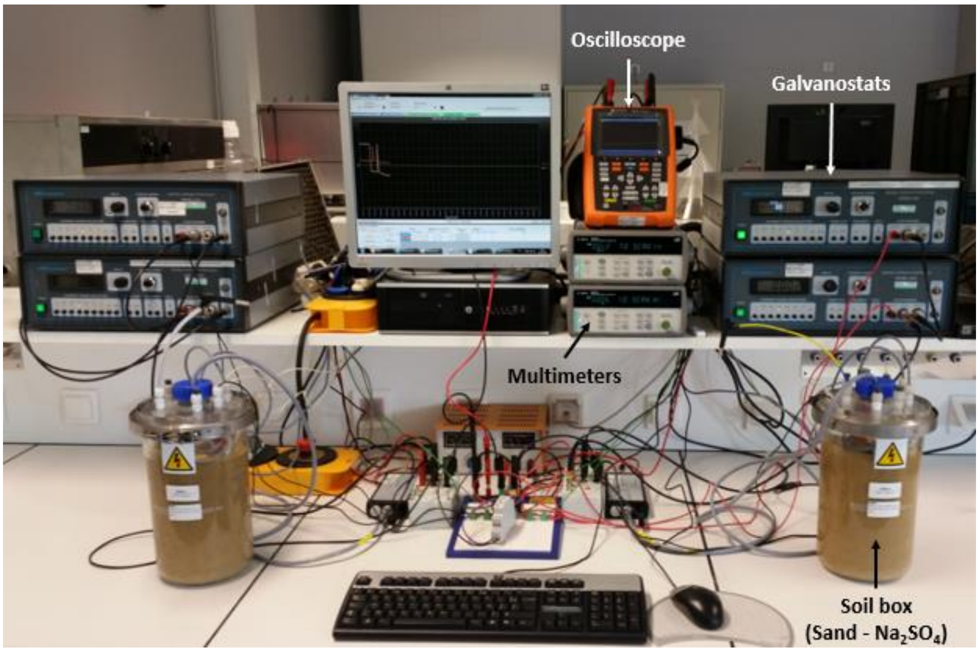


Figure 2. Experimental setup

2.2 Experimental procedure

The testing campaign gathers 4 experiments split into two different types of samples, sum up in the Table 2 below:

1- Two tests were carried out on ER-probes in order to identify the threshold values of d.c. stray currents leading to develop significant corrosion (all others experimental conditions were fixed). The d.c. stray current applied was increased each 8 days as long as the value of the instantaneous corrosion rate measured by the ER-probe was still lower than 10 µm/y. As a result, in these tests, the applied d.c. stray current density ranges from 50 µA/cm² to 1000 µA/cm². For each test, the CP level applied corresponds to an IR-Free potential of -910 mV_{CSE} (named “Low CP level”) or -1150 mV_{CSE} (named “High CP level”);

2- Two Weight Loss (WL) tests are conducted on steel coupons in order to validate the instantaneous corrosion rates measured on ER-probes at the highest d.c. stray current applied (1000 µA/cm²) at each CP level (low and high). These sandblasted samples were made of carbon steel (X70) and placed in a sample-holder with a rectangular opening area of 1 cm².

Test reference	Working electrode	IR-Free Potential linked to the fixed CP level	d.c. stray current density	Duration
T1	ER-probe	-910 mV_{CSE}	from 50 µA/cm² to 1000 µA/cm²	A minima 8 days for each anodic d.c. current fixed
T2	ER-Probe	-1150 mV_{CSE}		
T3	WL coupon	-910 mV_{CSE}	1000 µA/cm²	21 days
T4	WL coupon	-1150 mV_{CSE}		

Table 2. Main experimental and electrical conditions fixed for each test performed

As illustrated in Figure 3, the experiments were performed with the same procedure made of 2 common steps and 1 different step that depends of the test performed (see 3.a. and 3.b):

1) At the beginning of each experiment and before any polarization, the open circuit potential of the working electrode (WE) was measured until steady state and an electrochemical impedance spectroscopy (EIS) of the steel sample/soil interface was performed.

2) Then, the sample was polarized at least 24 hours in galvanic mode to reach the fixed IR-Free potential.

3) After step 2, d.c. stray current perturbations were applied to the steel samples and respected the schema of the Figure 3 below. Each day of perturbation was made of two different periods:
    - during 20 hours, an anodic d.c. perturbation with a rectangular shape signal was applied each 12 minutes during 2 or 5 seconds (depending on the type of tests defined below in a or b);

- during 4 hours no perturbation was applied, which corresponds to the night period (Period A, Figure 1).

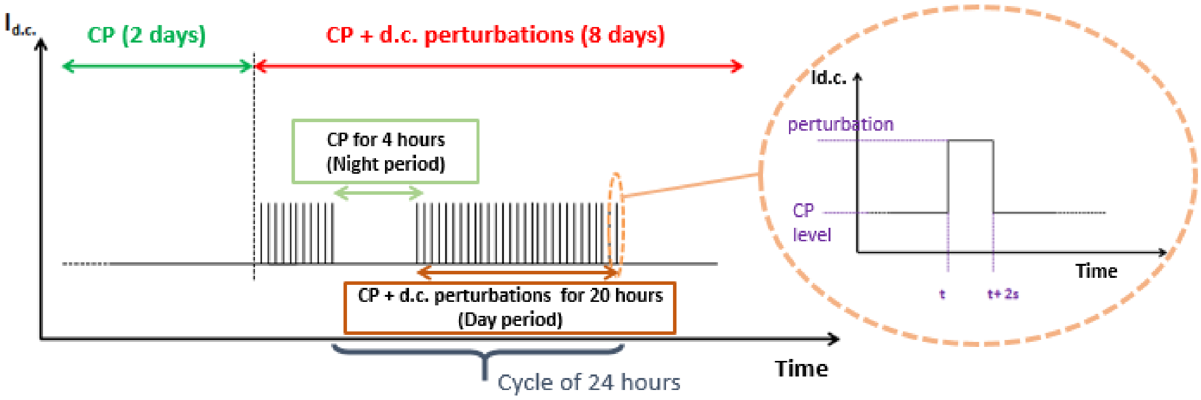


Figure 3. Schema of d.c. stray current perturbations applied during the laboratory tests

Moreover, depending on the nature of the WE, different test procedures were applied concerning the duration and d.c. current density of perturbations and global time of test:

a. For ER-Probes test:

Each 8 days (= a period), the intensity of the stray current was increased if the instantaneous corrosion rate observed on the steel sample of the probe is inferior to 10 µm/y. Before applying a new current intensity, the sample is maintained under CP during a minima 2 days to obtain a stabilized metal/soil interface. Six periods were performed. For each period, anodic d.c. currents were applied during 2 seconds:

- Period 1: $J_{d.c.}$ = +50 µA/m²;
- Period 2: $J_{d.c.}$ = +100 µA/m²;
- Period 3: $J_{d.c.}$ = +200 µA/cm²;
- Period 4: $J_{d.c.}$ = +500 µA/cm²;
- Period 5: $J_{d.c.}$ = +750 µA/cm²;
- Period 6: $J_{d.c.}$ = +1000 µA/cm².

A seventh period was added, with the same d.c. stray current intensity than the sixth period but with longer d.c. stray currents cycles of 5 seconds each 12 minutes (i.e. 25 seconds per hour) **during a minima 8 days**:

- Period 7: $J_{d.c.}$ = +1000 µA/cm².

Note that regarding the standard EN 50162, all these test conditions on ER-probes correspond to a risk of d.c. stray current corrosion.

b. For weight loss measurement test:

The electrical conditions of these tests are equal to the seventh period of the ER-Probes test, i.e. application of a d.c. perturbation of 5 seconds each 12 minutes with a current density of +1000 µA/cm² **during 21 days**.

In the same way, regarding to the standard EN 50162, these test conditions on weight loss coupons correspond to a risk assessment of d.c. stray current corrosion.

The estimation of the corrosion rate by weight loss measurement included the total time of exposure (including the step 1 on time duration) and referred to a one year time exposure, assuming a long term and a uniform attack on the total exposed area (1 cm²), leading to a constant corrosion rate.

For all the tests performed, basic parameters were automatically registered such as:
- d.c. current,
- ON-potential,
- redox potential at the soil/metal interface and in the bulk,
- temperature in the cell.

OFF-potential measurements were also performed during the tests. *Note that in this paper, we considered that the "OFF-potential (E_{OFF})" is similar to the "IR-Free potential" and the term "OFF-potential" is preferentially used*.

For the determination of the OFF-potential, we use an oscilloscope and consider that the E_{OFF} corresponds to the average potential measured between 5 ms and 25 ms after the CP has been switched off, which is the method adopted by French pipeline operators. All the OFF-potential values presented here are measured outside the anodic d.c. perturbations signal.

3 Results & discussion

3.1 Results of ER-probes

3.1.1 Electrical parameters measurements

The Open-circuit potential (OCP) of each sample was initially measured, the stabilized value of the OCP is given in Table 3 below.

Then, the ON-potentials and the cathodic d.c. currents corresponding to cathodic protection were monitored all test long. Their average values are also presented in the Table 3 below.

Tests reference	Initial OCP	Average ON-Potential	Average fixed d.c. protection current density
T1 *ER-probe* *Low CP (E_{OFF}= -910 mV$_{CSE}$)*	-658 mV$_{CSE}$	-1.1V$_{CSE}$	-360 µA/cm^2
T2 *ER-probe* *High CP (E_{OFF}= -1150 mV$_{CSE}$)*	-693 mV$_{CSE}$	-1.8V$_{CSE}$	-2700 µA/cm^2
T3 *Weight Loss Coupon* *Low CP (E_{OFF} = -910 mV$_{CSE}$)*	-657 mV$_{CSE}$	-1.1V$_{CSE}$	-380 µA/cm^2
T4 *Weight Loss Coupon* *High CP (E_{OFF} = -1150 mV$_{CSE}$)*	-611 mV$_{CSE}$	-2.4V$_{CSE}$	-6100 µA/cm^2

Table 3. Comparison of main electrical parameters measured

The value of the different parameters measured for tests at low CP level (T1 and T3) are consistent. On the contrary, these values are quite different for tests at high CP level (T2 and T4). In fact, even if the soil conditions and the bedding method are similar for each test performed, OCP is lower for test T4 on WL coupon than for test T2 on ER-probe (respectively -611 mV$_{CSE}$ and -693 mV$_{CSE}$) which resulting in a lower ON-potential and a lower d.c. protection current to reach the same fixed-OFF potential of -1150 mV$_{CSE}$. This observation could be due to a different contact area at the soil/metal interface.

3.1.2 Comparison of induced ON-potential during an anodic d.c. perturbation depending on the CP level applied

During the tests T1 and T2 on the ER-probes (respectively low and high CP level), the ON-potentials with high acquisition frequency were monitored during different anodic d.c. current perturbations (2 s with $I_{d.c.}$ equal to +200, +500, +750 and +1000 µA/cm^2). The results are illustrated in Figure 4 below.

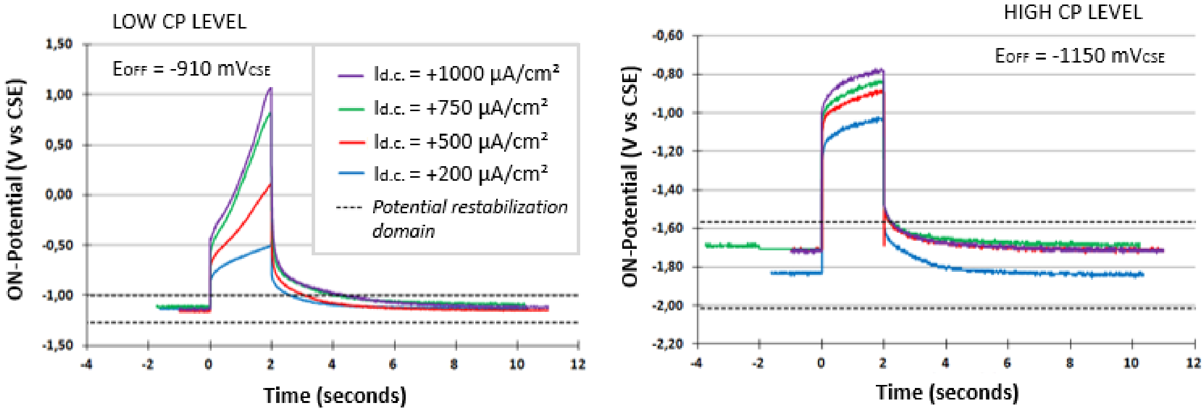


Figure 4. Monitoring of the ON-potential during anodic d.c. perturbation depending on CP level applied

These results point out interesting information:

- Logically, the higher the anodic d.c. current of the perturbation, the higher the ON-potential;
- Depending on the CP level applied to the coupon:
    - The shape of the ON-potential signals is different: quite stabilized for high CP but not for low CP;
    - The values of the ON-potential stay cathodic at the end of the 2 s d.c. perturbation applied for high CP level and vary between -800 mV_{CSE} and -1100 mV_{CSE} whereas for low CP level, ON-potentials reach very anodic values from -500 mV_{CSE} to +1000mV_{CSE}. This result show an influence of CP level on corrosion behaviour at the soil/metal interface.

3.1.3 Residual thickness of ER-probes

Residual thicknesses of each ER-probe were monitored during 90 days and are illustrated by the Figure 5 below. These results show that no corrosion behaviour was detected on both probes, independently on either the CP level conditions fixed during the tests (-910 $mV_{OFF,CSE}$ or -1150 $mV_{OFF,CSE}$), nor the d.c. current intensity of the electrical perturbation of any period (which goes from +50 µA/cm² to +1000 µA/cm²).

The residual thicknesses measured are in accordance with the observation of metallic exposed area of each probe, indicating only very superficial attack (see probe pictures on Figure 5). Moreover, the residual thicknesses of the probes correspond to a corrosion rate inferior to 10 µm/y, considering an initial residual thickness of 494,4µm for low CP level and 493,7µm for high CP level.

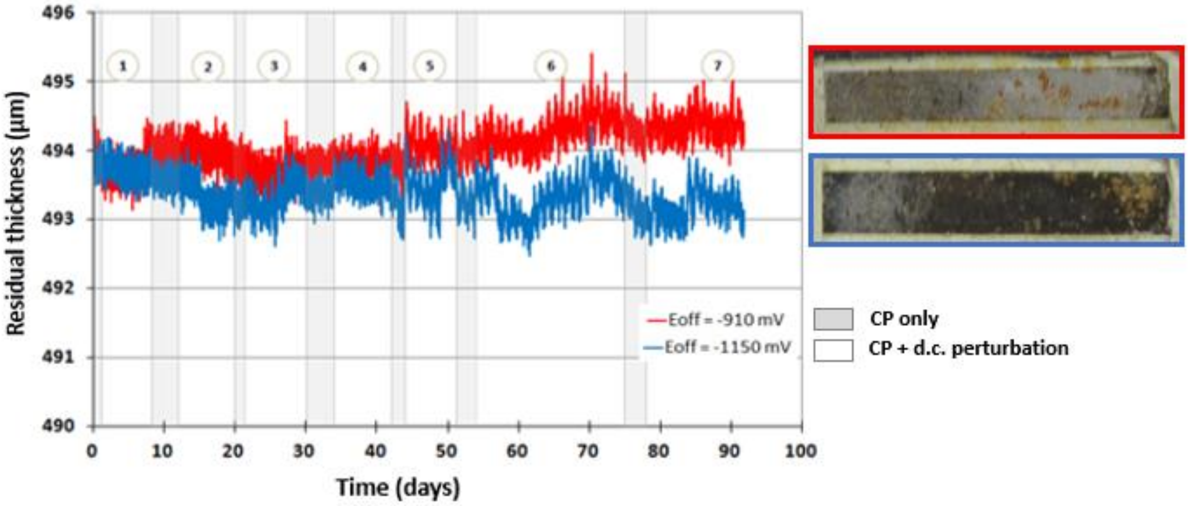


Figure 5. Residual thickness of ER-probes vary between 492 µm and 496 µm for both CP level conditions (E_{OFF} = -910 mV_{CSE} – red line - and -1150 mV_{CSE} – blue line).

Therefore, in these experimental soil conditions, the application of anodic d.c. current (i.e. outward currents) on ER-probe samples during more than 3,6 seconds per hour (as recommended by EN 50162) involves no corrosion behaviour. These results will be compared to weight loss tests to confirm the corrosion rates obtained.

3.2 Results of weight loss coupon tests

Pictures of samples after corrosion tests T3 and T4 and corresponding corrosion rates are gathered in **Table 4**.
These results confirm those observed on the ER-probes and show superficial corrosion on the exposed area of the metallic coupons. The corresponding estimated corrosion rates are lower than 20 µm/y (which is the measurement uncertainty considered here), with respectively, 4 µm/y for low CP level and 10 µm/y for high CP level.

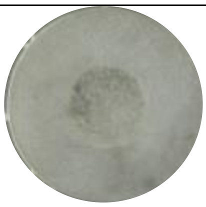
Tests reference	Picture after test	Picture after mechanic and chemical cleaning	Corrosion rate
T3 $E_{OFF} = -910\ mV_{CSE}$			< 20 µm/y (4 µm/y)
T4 $E_{OFF} = -1150\ mV_{CSE}$			< 20 µm/y (10 µm/y)

Table 4. Results of corrosion tests on weight loss coupons

The corrosion rates estimated on weight loss coupons show no significant corrosion behaviour while 25 s anodic d.c. perturbation at +1000 µA/cm² was applied on coupons, and confirm the results obtained on ER-probes. Even if, the WL tests were performed on a shorter time (21 days), the criterion of the European Standard EN 50162 appears to be too conservative and more investigations are needed to improve it.

4 Conclusions

The objectives of this study were to illustrate the impact of some parameters on anodic d.c. stray currents corrosion such as CP level applied, intensity of anodic d.c. perturbation and global duration of anodic perturbation per hour.

The tests performed in soil boxes with carbon steel samples lead to the following principal results:

- No significant corrosion behavior was highlighted either on ER-probes, nor on weight loss coupons (estimated corrosion rates are lower than 20 µm/y) while the criterion of the European standard EN 50162 assesses a corrosion risk;
- The duration of the anodic d.c. perturbation is a key parameter to initiate d.c. stray current corrosion and 3,6 seconds per hour (as recommended in EN 50162) seems to be too conservative;
- The intensity of the anodic d.c. perturbation has no significant corrosion impact for these low durations of anodic d.c. perturbation (fixed at 2s or 5s per anodic perturbation with, respectively, a global duration per hour of 10s or 25s). In fact, anodic d.c. current densities range from +50 µA/cm² to +1000 µA/cm² and involve no significant corrosion whereas it corresponds to high level of d.c. stray current densities in comparison to operational experience;
- The CP levels applied involve different behaviours at the soil/metal interface during the application of an anodic d.c. perturbation even if the durations are very short (2 s). We mainly observed very anodic ON-potential (superior to -500 mV) for low CP level (E_{OFF} = -910 mV_{CSE}) whereas for high CP level (E_{OFF} = -1150 mV_{CSE}), ON-potential stay cathodic (lower than -800 mV_{CSE});

The future investigation involves the use of a corrosion model in order (i) to have a better understanding of the d.c. stray current corrosion and (ii) to extract some key parameters in order to test them with some laboratory tests. The aim would be to be able to suggest other criteria in order to improve the European Standard EN 50162 which is too conservative at the moment.

6 References

[1] EN 50162:2005, « Protection against corrosion by stray current from direct current systems »

[2] EN 12954:2001, « Cathodic protection of buried or immersed metallic structures - General principles and application for pipelines »