Electrical resistance sensors for the determination of the protection potential of buried structure under cathodic protection

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1. Introduction

The introduction of measurement coupons in the vicinity of buried cathodic protection (CP) pipes theoretically makes it possible to measure the potential and the current density through a potentially existing coating defect. However, this type of monitored coupon does not measure the actual effectiveness of the cathodic protection (corrosion rate) or the corrosion caused by a CP defect over time. To do this it is necessary to introduce sensors of the same nature as the pipes (steel), connected to the pipes and in addition to the potential and current density, measure the corrosion rate in real time.

The main method used by this type of sensor relies on the measurement of the corrosion by a variation of the electrical resistance (ER) of a material of determined geometry. This method is recommended by the ISO 15589-1:2015 standard for the CP efficiency monitoring on site. A sensor of this type, developed specifically for the monitoring of cathodic protection in soils, in the field, is currently commercially available. In addition to corrosion rate measurements, this sensor allows measurements of current density and electrochemical potential. The French Corrosion Institute has developed a corrosion sensor, named "Aircorr", based on the same principle and initially developed for atmospheric applications. The preliminary tests in soils and in immersed medium appeared very promising. The Aircorr sensor allows almost instantaneous measurement of corrosion rate. The advantage of the device Aircorr is that it can be equipped with very thin probes (25 microns), well adapted for the laboratory scale and theoretically allowing a better precision on the measurement. This precision becomes particularly interesting when the (polarization) exposure conditions are close to the CP criteria. In the standard, the protection potential corresponds to the potential in where the corrosion rate is lower than 10µm per year [1]. Under these conditions, the corrosion rates are very low and require long-time exposures to be measured with traditional gravimetric method.

The objective of this study was to propose a short terms method to determine *in situ* the protection potential Ep for a given soil and hydrometric condition. Such a method would be particularly relevant to

better understand the pipe to soil interactions as function of the soil nature, the hydrometric and local conditions.

2. Experimental

2.1 Electrical Resistance Sensor

The sensor used to measure the corrosion rate are based on the principle of ER probe (Electrical Resistance). The principle of corrosion monitoring by measuring the electrical resistance used by ER probes is presented in Figure 1. The terminal resistance of a material depends on its geometry: width (w), thickness (t) and length (l), and its resistivity (ρ), as described in the equation of Figure 1.

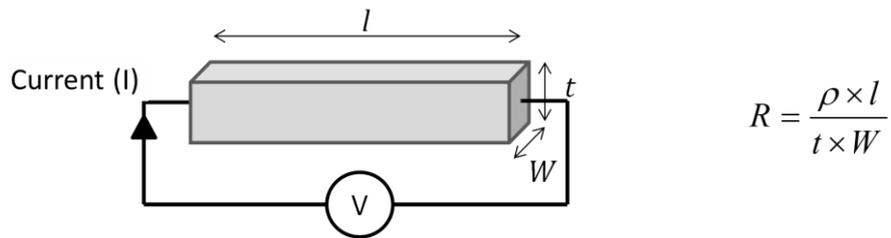$$R = \frac{\rho \times l}{t \times W}$$

Figure 1: Principle of measurement of Electrical Resistance (ER) probe

Under the action of corrosion, the metal is converted into a relatively insulating corrosion product, *i.e.*, of several orders of magnitude more resistive than the non-corroded metal. The resistance across the material may be in the form of two resistors in parallel, one corresponding to the metal and the other to the corrosion product. In general, when the metal section (W * t) is of the same order of magnitude as that of the corrosion products, according to the low resistivity of the metal, the total resistance is similar to that of the metal alone. On the other hand, when the metal section is very weak (nanometric), the resistance of the metal becomes of the same order of magnitude as that of the corrosion products and / or the electrolyte for submerged materials, and their influence cannot be neglected. With this method, particular care must be taken to ensure that the remaining metal portion is relatively important to ensure the validity of the calculation to determine the corrosion rate. For this purpose, it is usually considered that the ER sensor lifespan correspond to the half of its initial thickness.

The resistivity of the materials depends on the temperature. For metals, at room temperature, it increases linearly with temperature. This effect is also used for temperature measurement (Pt100 probe). In order to overcome this constraint, which directly influences the determination of corrosion, most ER probes use a differential measurement, between a part of the probe exposed to the environment and a second part protected from corrosion but not of the temperature. The schematic diagram of differential measurement is presented in Figure 2.
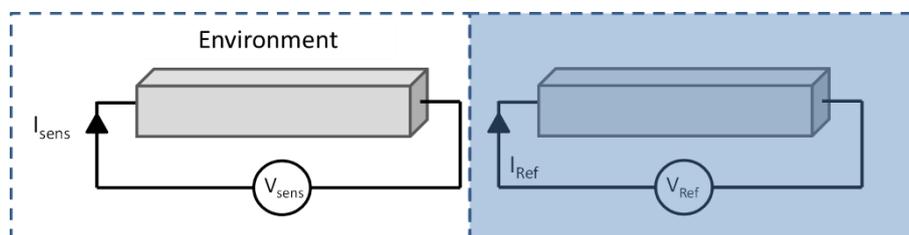

Figure 2: Principle of differential measurement

ER probes mainly use thin-film geometries. This geometry makes it possible to obtain a very small thickness t in front of the width W (t << W). Thus, when the corrosion is homogeneous, the thickness of corrosion appearing on the thin edge of the sensitive track, has little influence on the total resistance, compared to that appearing on the wide edges. It can therefore be neglected. The only parameter that significantly influences the resistance of the sensitive track is its thickness t.

In the presence of a generalized corrosion, the corrosion thickness can be calculated as a function of the initial resistance values and over time, as well as the initial thickness of the thin film, such as:

$$\Delta h = h_{ref,init}\left(\frac{R_{ref,init}}{R_{sens,init}} - \frac{R_{ref}}{R_{sens}}\right) \quad Corrosion\ depth$$

$h_{ref,init}$ Initial reference track thickness
R_{sens} Resistance of the sensor track
R_{ref} Resistance of the reference track
$R_{sens,init}$ Initial resistance of the sensor track
$R_{ref,init}$ Initial resistance of the reference track

In the presence of localized corrosion, the results are more difficult to interpret and the ER method has to be only considered as binary answer, i.e. traducing the occurrence or not of corrosion [2].

The ER monitoring system AirCorr™, initially designed for atmospheric environments, has been used in aggressive environments, such as on operating vehicles [3], ships [4], weathering sites [5] and accelerated test [6,2]. For all these applications, the corrosion depth measured by the sensors appeared in good correlation with mass loss measured on metallic coupons, exposed in parallel. The ER Aircorr sensor is shown in Figure 3. In this study, 25 µm thick AISI 1010 carbon steel sensors were used. In order to polarize and / or measure the corrosion potential over time, an additional connection was added (working electrode). More details about the AirCorr™ logger dedicated to aggressive environments can be found elsewhere [6].
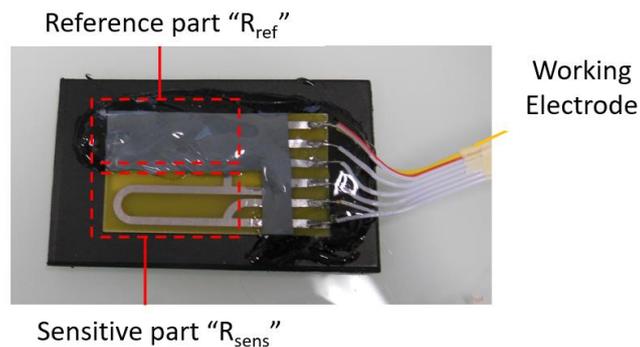
Reference part "R_{ref}"

Working Electrode

Sensitive part "R_{sens}"

Figure 3: ER Aircorr Sensor

2.2 Potential and current

In this study, off and on potential, i.e. respectively "E*off*" and "E*on*" were carried out by the use of a *Cou-Cou* from ADCA. This device allows a measurement of potential few milliseconds after punctual cut of the current and before its recovery. This method prevents the ohmic drop (IR) induced by the cathodic protection current (I) and the soil resistivity (R). Potential measurements were carried out punctually with a CuCuSO4 reference electrode CELCO 5 from Corexco. After each potential measurement, the reference electrode was recover to avoid any copper sulfate contamination of the media. Before and after each measurement series, these electrodes are verified using a saturated calomel reference electrode (SCE) certified by Radiometer (ref.421). The current applied to the coupon is measured across a shunt resistor placed between the laboratory supply and the counter electrode.

2.3 Polarization curves in soil

Previous studies have shown that the intentiostatic method is the most suitable for obtaining representative (stabilized) polarization curves in soils [7].

According to this method, the current is imposed in stages until the "E*off*" is stabilized for each of the steps. The stability criterion was arbitrarily defined as such: minimum 48h at the fixed current stage and stability of the E*off* at ± 10 mV on two separate measurements of 24 hours minimum. The experimental setup is shown schematically in Figure 4.
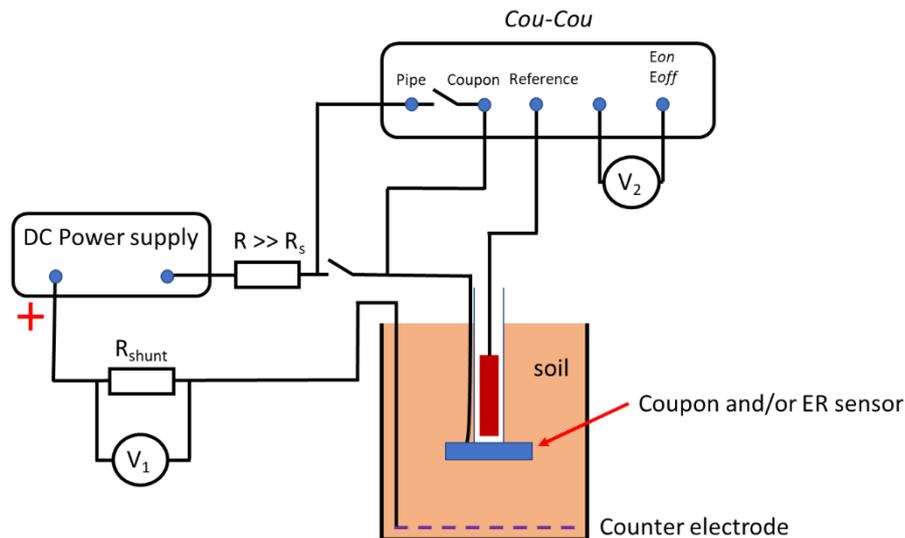
Figure 4: Schematic diagram of the intentiostatic experimental setup for polarization curves in soils.

The applied current is calculated by the voltage measurement V_1 across a shunt resistor (R_{shunt}), allowing convenient reading of the measured currents. Potentials "E*on*" and "E*off*" are measured using *Cou-Cou* (voltage V_2). The switch between the negative terminal of the power supply and the coupon closes the circuit when the *Cou-Cou* is not installed.

2.4 Exposure cell

Specific cells have been designed to expose coupon measurement in well controlled soils. They consist of a cylindrical PVC tank whose bottom include of a permeable polymer hopper, allowing controlled humidification of the soil in the cylinder. A schematic diagram is given in Figure 5. The development and the principle of these exposure cells come from previous studies at the Institute of Corrosion and Swerea Kimab [8,9]. A platinum-plated titanium grid is placed inside the bottom of the cell to act as a counter electrode during the polarization tests. Two types of exposure conditions can be realized, *i.e.* static and rain. Under static conditions, the cell is immersed in a tray partially filled with electrolyte, usually deionized water. The position of the coupons in the soil relative to the surface of the water is determined according to the desired water content and also depends on the type of soil used (humidity gradient depending on the capillarity of the soil tested). The static exposure is particularly relevant to assess tri-phasic conditions (air, water and soil). Under rain conditions, the water from electrolyte is pumped and injected in the top of the cell. This condition leads to water saturated soil with hydrodynamic conditions depending of the soil permeability. In order to avoid digging the soil by the flow of water via preferential paths, a constant water level of 2 cm above the ground was maintained by watering.
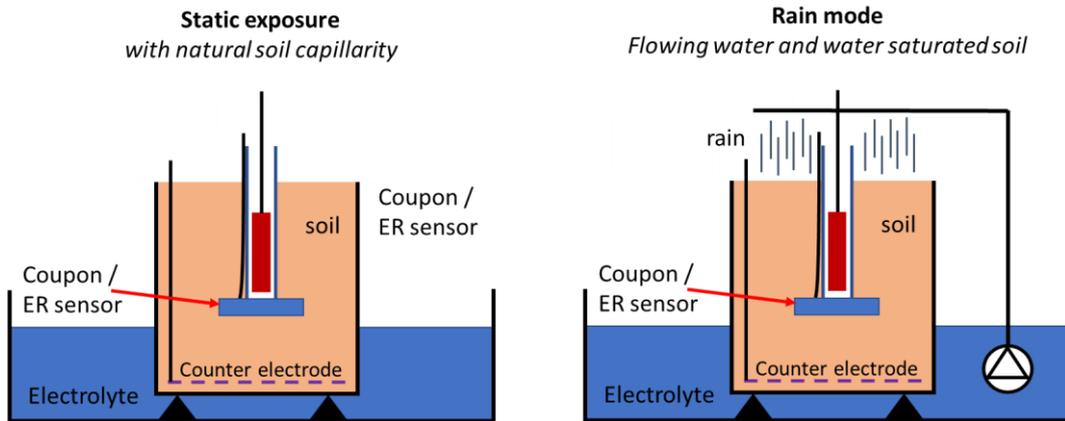
Figure 5: Diagram of the exposure cell – under static and rain exposure conditions

2.5 Water content in soil

The water content measurements in soil were determined gravimetrically. The soil removed, at different levels in a cell, was weighed directly after sampling (wet soil), then dried for 48h at 105 ° C and reweighed (dry soil). The water content is then calculated according to the following equation

$$\text{Water content (\%wt)} = \frac{\text{Wet mass} - \text{Dry mass}}{\text{Dry mass}}$$

It is important to note that in the equation selected, the ratio is relative to the mass of dry soil and not to the mass of wet soil. After 2, 3 and 4 weeks of stabilization at a constant water level in the tank, sand samples were taken in strata every 3 cm (to determine the water content gradient). For the whole of the water content gradient measurements, the tests were carried out on 3 distinct cells and repeated 3 times, for each of the soils tested.

2.6 Soil resistivity

The soil resistivity measurements were carried out using a homemade apparatus described in Figure 6. This device consists in a cell with a defined geometry in where the soil is wet prior to filling of the cell. At the two terminals of the cell, two parallel stainless-steel plates are used to inject the current, which ensure a homogeneous distribution of the current inside the soil. The potential drop in the soil is measured using titanium wires and high impedance voltmeter. With the aim to asses the soil homogeneity in terms of resistivity, measurements can be performed at different soil locations using 6 equipotential points (titanium wires). The current injected is measured at the terminal of a shunt resistance (R_{shunt}). AC current is used at 50 Hz since it allows a stable current and potential measurement inside the cell. The cell is calibrated using a 0.1 mol/l of KCl solution at a knowing temperature. An example of soil resistivity obtained for a sandy soil is presented in Figure 7.
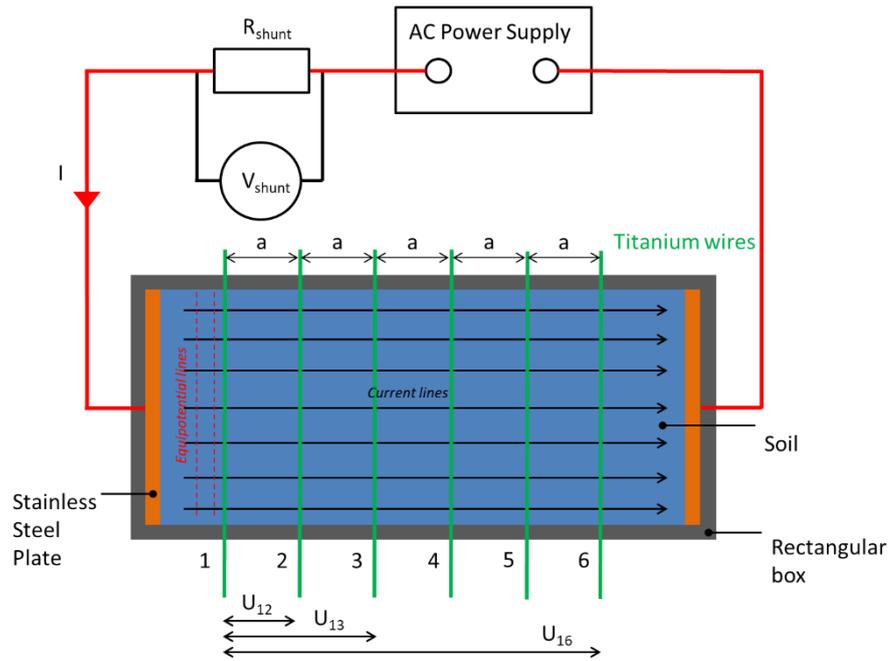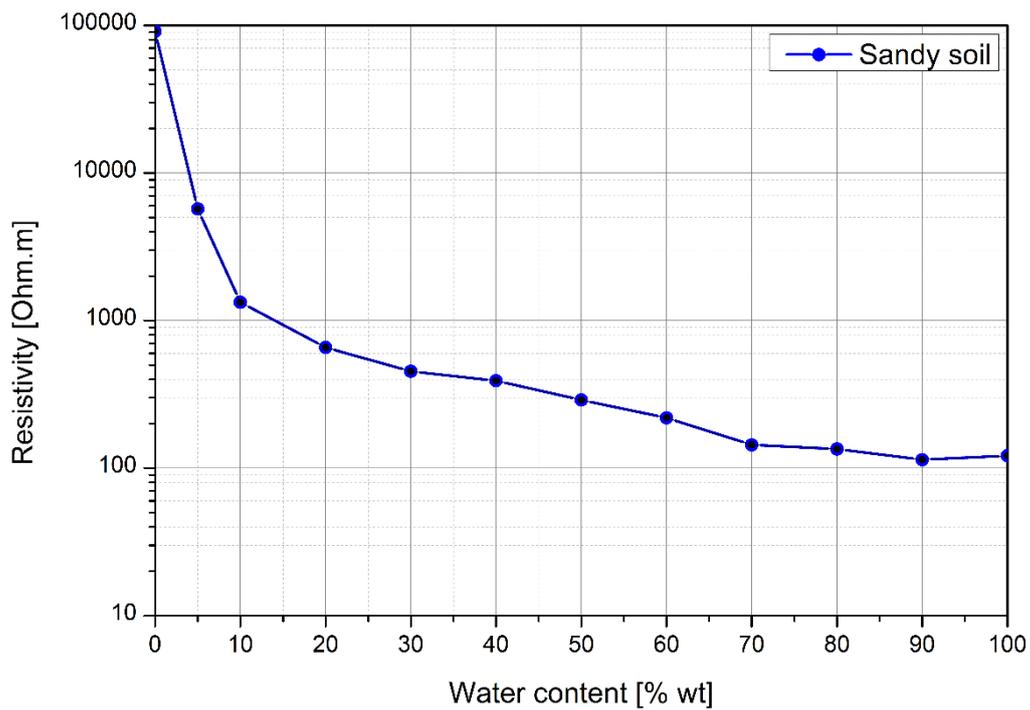
Figure 6 : Soil resistivity measurement method

Figure 7 : Example of sandy soil resistivity vs water content obtained

2.7 Type of soil and exposure conditions

In this study, two types of soil were considered, as detailed in Table 1 : i) a sandy soil from Landes (France) and ii) a sphagnum peat soil. These soils were relatively acid with a respective pH of 4.9 and 2.8. For the sandy soil, cathodic polarization was performed under rain condition, while for peat, static exposure was considered at 70-90% of the water saturation.

Table 1: Type, exposure conditions and main characteristics of the soils tested

Type of soil	Origin	pH	Resistivity [Ohm.m]	Chloride [mg/kg]	Exposure
Sand	France, sand from Landes	4.9	508 ± 25	< 42	Rain mode 100 % water saturation
Sphagnum Peat	Commercial product	2.8	138 ± 5	< 10	Static 70-90% of water saturation

3. Results

3.1 Sand from Landes – Rain mode

Figure 8 shows an example of E*off* potential measurement, current density and corrosion rate using ER sensor during 6 days in the sand from Landes under rain condition. The potential and the current density are measured punctually. The corrosion thickness was measured each hour during the exposure using the autonomous Aircorr logger. The corrosion kinetic was determined from the thickness measurement during a given period and linearly extrapolated to one year. This linear extrapolation can be considered as conservative because the corrosion products formed with time acts as barrier and lead to a decrease of the kinetic of corrosion.

One of the average measurement points obtained is detailed in Table 2. Once stabilization is achieved, over a period of about one week, a bias is applied to move the operating point in terms of potential, current density and thus corrosion rate.
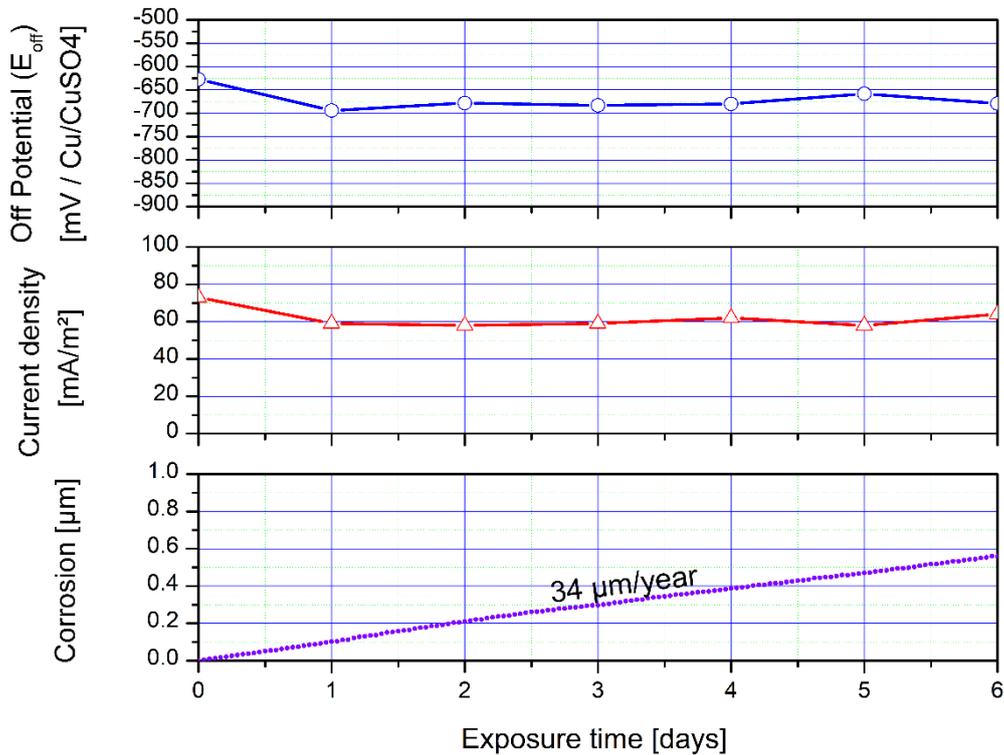

Figure 8: Method for determining stabilized corrosion rate, potential and current density.

Table 2: Example of stabilized E_{off} potential, current density and corrosion rate.

Type of soil / Conditions	E_{off} Potential [mV/CuCuSO$_4$]	Cathodic Current density [mA/m²]	Corrosion kinetic [µm/year]
Sand from Landes Rain	-671 ± 22	39 ± 3	34

Figure 9 shows the cathodic polarization curve of the 25 µm steel Aircorr sensor (1.6 cm²) and a 10 cm² coupon in the sand from Landes, under rain condition. This result show that the current density measured with the Aircorr sensor at a given potential is similar to those obtained with a 10 cm² coupon used in field applications.
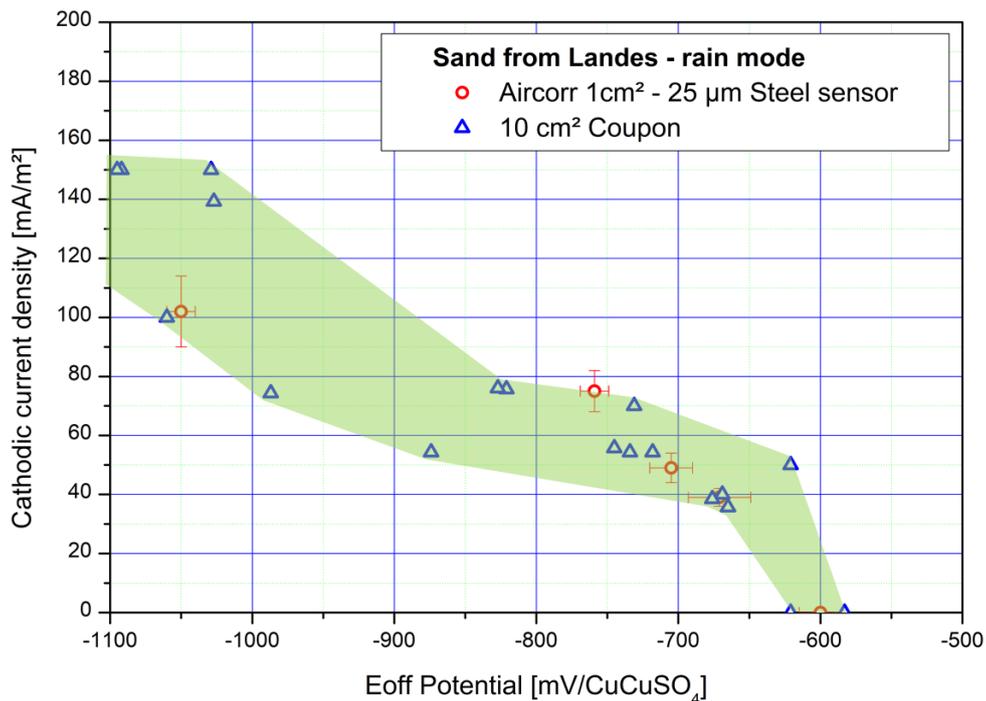

Figure 9: Stabilized cathodic polarization curves of the 25 µm steel Aircorr sensor (1.6 cm²) and a Coupon (10 cm²) in the sand from Landes, in rain mode.

The corrosion rate and the cathodic protection criterion (Vcorr <10 µm/year), as a function of the potential and the cathodic protection current density, are shown in Figure 10. These results confirm that the lower the potential and/or the higher the cathodic current density, the lower the corrosion rate. Under these conditions, the cathodic protection criterion, detailed in Table 3, corresponds to an E_{off} potential of -729 mV/CuCuSO$_4$ and a cathodic current density of 61 mA/m².
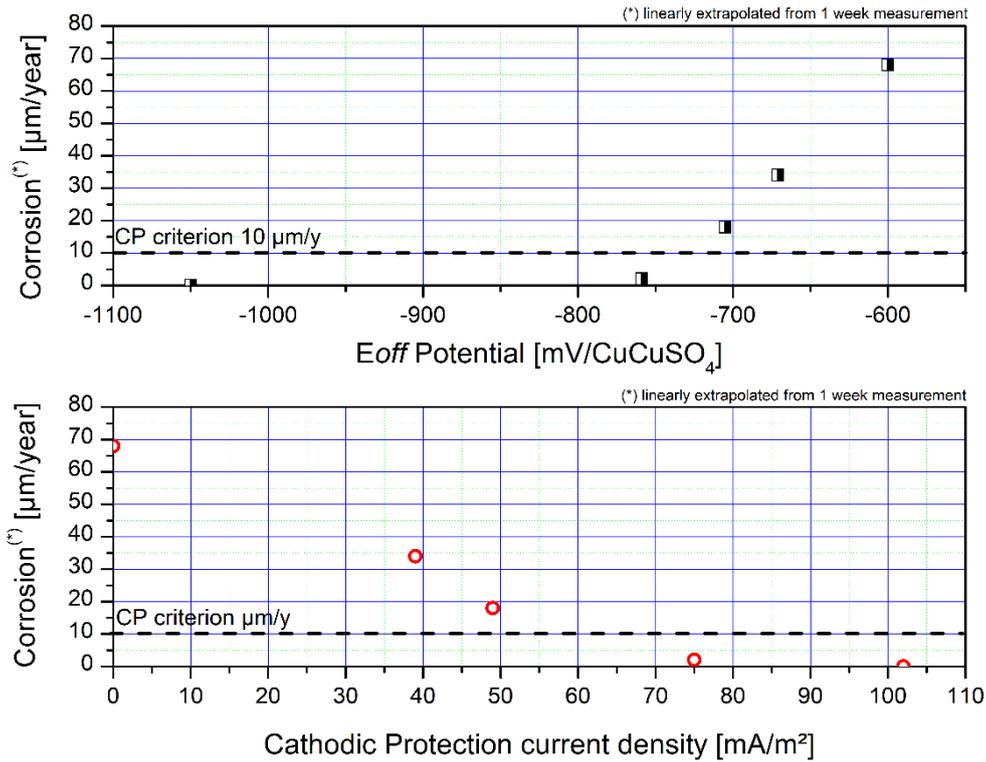
Figure 10: Corrosion rate and cathodic protection criterion, as a function of potential and cathodic current density, sand from Landes under rain condition.

Table 3: Conditions, potential and current density at the cathodic protection criterion of 10 µm/y, Sand from Landes under rain condition.

CP criterion	Soil / Condition	E_{off} Potential [mV/CuCuSO$_4$]	Cathodic current density [mA/m²]
Corrosion < 10µm/an	Sand from Landes Rain	-729	61

3.2 Peat, 70-90% of the water saturation in static

Figure 11 shows the cathodic polarization curve of the 25 µm steel Aircorr sensor (1.6 cm²), in acid Peat at 70-90% of the water saturation (static). The corrosion rate and the cathodic protection criterion (Vcorr <10 µm / year), as a function of the potential and the current density are presented in Figure 12. Under these conditions, the cathodic protection criterion, detailed in Table 4, corresponds to an Eoff potential of -823 mV/CuCuSO$_4$ and a current density of 39 mA/m². It is recalled that the tested medium is very acidic (pH 2.8) and aerated (oxygen saturation), making it potentially very corrosive for carbon steel.
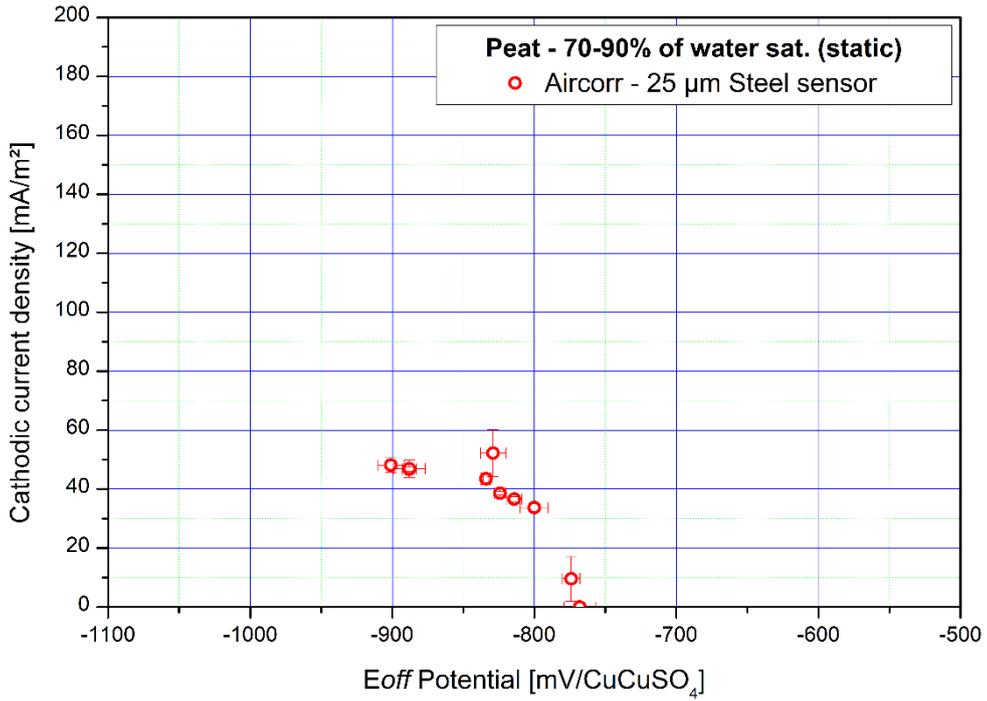
Figure 11: Stabilized cathodic polarization curves of the 25 µm steel Aircorr sensor (1.6 cm²), Peat 70-90% water saturation (static).
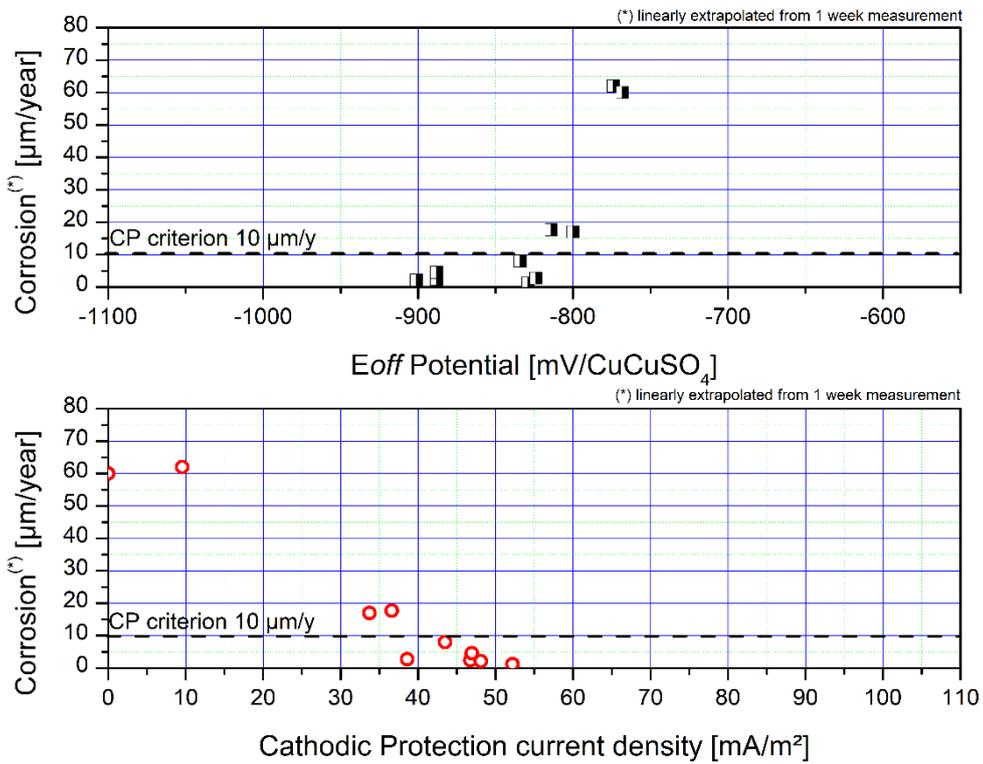

Figure 12: Corrosion rate and cathodic protection criterion, as a function of potential and cathodic current density, Peat 70-90% of water saturation (static).

Table 4: Conditions, potential and current density at the cathodic protection criterion, Peat 70-90% of water saturation (static)

CP criterion	Soil / Condition	E_{off} Potential [mV/CuCuSO$_4$]	Cathodic current density [mA/m²]
Corrosion < 10µm/an	Peat 70-90% of water saturation (static)	-823	39

4. Discussion

In this study, Aircorr 25 µm steel probes were used to determine the CP criterion. The results obtained indicate that the cathodic protection criterion can be accurately determined for a given environment using ER probes in short terms exposures. Table 5 presents the latest cathodic protection criteria for carbon steels, low alloyed steels and cast iron according to ISO 15589-1: 2015.

Table 5 presents the different criteria obtained for each soil type, the test conditions, the soil resistivity under these conditions and the CP criterion recommended by ISO 15589-1: 2015. For the sand from Landes, which corresponds to an aerobic soil with T <40 ° C and a resistivity of $100 < \rho < 1000$ Ω.m, the PC criterion according to the standard is -850 mV/CuCuSO$_4$, because its corrosion potential is of the order of -600 mV/CuCuSO$_4$. The PC criterion obtained in our test conditions (rain mode) of -729 mV/CuCuSO$_4$, is 120 mV above the protection potential recommended by ISO 15589-1: 2015. For this type of soil, the criterion define by the standard appears therefore very conservative. For Peat, the corrosion potential is -770 mV/CuCuSO$_4$, this parameter being the most critical, the CP criterion recommended by the standard is -950 mV/Cu CuSO$_4$. The PC criterion experimentally determined using the ER probes is -823 mV/CuCuSO$_4$. In this configuration, the protection criterion proposed by the standard is therefore also very conservative.

Table 5: cathodic protection criteria for carbon steels, low alloyed steels and cast iron according to ISO 15589-1: 2015.

Environmental conditions	Corrosion potential (indicative values) E_{cor} [mV/CuCuSO$_4$]	Protection potential (IR free) E_p [mV/CuCuSO$_4$]	Limit potential (IR free) E_l [mV/CuCuSO$_4$]
Soils and waters in all conditions other than those described below T < 40°C	-650 à -400	-850	a
Soils and waters under aerobic conditions at T < 40°C with $100 < \rho < 1000\ \Omega.m$	-500 à -300	-750	a
Soils and waters under aerobic conditions at T < 40°C with $\rho > 1000\ \Omega.m$	-400 à -200	-650	a
Soils and waters in anaerobic conditions with risks of corrosion due to the activity of sulphate-reducing bacteria	-800 à -650	-950	a

(a) In order to prevent hydrogen embrittlement on high strength, low alloy, low alloy steels with a defined yield strength exceeding 550 N.mm², the critical limit potential shall be detailed in documents or determined experimentally.

Table 6: Conditions, resistivity, potential and current density at the cathodic protection criterion, for all the types of soil of this study.

CP Criterion	Soil / Conditions	Soil Resistivity [Ohm.m]	This study			ISO 15589-1
			Corrosion potential E_{cor} [mV/CuCuSO$_4$]	Protection potential [1] E_p [mV/CuCuSO$_4$]	Cathodic current density [mA/m²]	Protection potential[1] E_p [mV/CuCuSO$_4$]
Corrosion < 10µm/an	Sand from Landes Rain mode	508 ± 25	-600	-729	61	-850
	Peat 70-90% water sat. Static	138 ± 5	-770	-823	39	-950

(1) IR free

5. Conclusions

The objective of this study was to determine in situ the protection potential Ep for a given soil and hydrometric condition. In the standard, the protection potential corresponds to the potential in where the corrosion rate is lower than 10µm per year [1].

The ER method, in particular with very thin metallic films, such as the Aircorr 25 µm steel probe, seems particularly suited to the determination of the cathodic protection criterion, in a given medium, in a relatively short time. The results obtained in a sandy and a peat soil showed that the cathodic protection criteria recommended by ISO 15589-1:2015 are conservative compared to those measured experimentally. This method therefore seems particularly relevant for:

i) The determination of the CP criterion in complex or polluted media, in the absence of data in the literature.

ii) The understanding of the evolution of the protection potential, for a given soil, as function of the environmental conditions, such under water saturation or triphasic conditions (air, water and soil).

It should be noted, however, that the reliability of the results is closely linked to the nature and quality of the soil / coupon interfaces. The small geometry of the ER tracks therefore implies particular care to be taken to satisfy a representative interface of wider geometries, as well as the multiplication of measurements to obtain statistical results.

6. References

[1]   ISO 15589-1:2015 - Industries du pétrole, de la pétrochimie et du gaz naturel -- Protection cathodique des systèmes de transport par conduites -- Partie 1: Conduites terrestres, (n.d.). http://www.iso.org/iso/fr/catalogue_detail.htm?csnumber=54503 (accessed January 4, 2017).

[2]   E. Diler, F. Lédan, N. LeBozec, D. Thierry, Real-time monitoring of the degradation of metallic and organic coatings using electrical resistance sensors, Mater. Corros. (2017). doi:10.1002/maco.201709655.

[3]   L. Vaissie, M. Ragazzini, G. Despert, N. Le Bozec, D. Thierry, Use of corrosion sensors for mapping corrosion on operating vehicle, in: EUROCORR, Stockholm, 2011: p. 4631.

[4]   N. LeBozec, D. Thierry, P. Le Calvé, J.P. Pautasso, Performance of marine paint systems on operating ships and outdoor marine sites, in: EUROCORR, Stocholm, 2011.

[5]   M. Omoda, H. Harada, T. Kawano, H. Kajiyama, M. Kimura, Real-time monitoring of corrosion rate in atmospheric environments using the electrical resistance technique, in: Jeju, KOREA, n.d.

[6]   T. Prosek, N. Le Bozec, D. Thierry, Application of automated corrosion sensors for monitoring the rate of corrosion during accelerated corrosion tests, Mater. Corros. 65 (2014) 448–456. doi:10.1002/maco.201206655.

[7]   N. Larche, E. Leroy, Etude de la Corrosion et de la Protection Cathodique de Coupons « on-shore » de type « puits de mesure », IC Rep. 201512. Joint Indu (2015).

[8]   N. Larché, D. Thierry, Development of Laboratory Soil Corrosion Testing, IC-Report 2011-1, Join Ind. Progr. Inst. La Corros. (2011).

[9]   Sederholm B., Svensson T., T. Vinka, Korrosion pa metaller i jordar med olika surhetsgrad och vattenhalt. Report R7:1992., (1992).

7. Acknowledgements