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Title: Effects of non-stationary stray current on carbon steel buried pipelines under cathodic protection

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Abstract: DC stray currents may cause severe corrosion on buried carbon steel pipelines even if in cathodic protection. According to international standard anodic interference is unacceptable if the IR-free potential is more positive than the protection potential (-0.85 V CSE). But, duration and magnitude of the anodic peak is not defined. The criterion appears to be too restrictive if short periods of anodic interference are established. This paper deals with the study of the effects of anodic interference on carbon steel in cathodic protection in soil-simulating environment in the presence of DC interference at varying peak current density and duration.

Dear Editor,

I am enclosing herewith a manuscript entitled:

“Effects of non-stationary stray current on carbon steel buried pipelines under cathodic protection”

The manuscript has been prepared according to the “Construction and Building Materials” guidelines.

The article evaluates the effect of stray current originating from DC electrical systems on the corrosion of buried metal structures, as carbon steel pipes, tanks or vessels, under cathodic protection (CP). DC interference sources include high voltage transmission lines, electrical traction and power networks, and cathodic protection systems too. Depending on stray current source, stationary or fluctuating interference may occur on steel structures even under cathodic protection condition. Nowadays, international standards establish the general principles for the identification and control of DC interference, mainly based on potential and voltage gradients measurements over a 24 h period. Generally, in order to assess the corrosion to which any metal structure is exposed as a result of stray current, the positive (anodic) potential shift of the affected structure shall be considered. As regards carbon steel under cathodic protection condition, anodic DC interference is considered unacceptable if the IR-free potential is more positive than the protection potential provided by standard (-0.850 V CSE in aerobic condition). But, duration and magnitude of the anodic peak should be taken into account to evaluate the actual corrosion effects of the interference on protected steel. In fact, the -0.850 V CSE criterion appears to be too restrictive if short periods of anodic interference are alternated with the re-establishment of the protection condition with the beneficial increase of the pipe-to-soil alkalinity due to the cathodic current. This paper deals with the study of the effects of anodic interference on buried carbon steel structures in cathodic protection condition. Weight loss tests were carried out on cathodically protected steel specimens in soil-simulating environment in the presence of DC interference varying anodic current density (from 0.1 to 10 A/m²) and duration of the interference peaks, applied for 3600 s daily overall. IR-free potential was also monitored.

All authors of this research paper have directly participated in the design, execution, or analysis of this study; all authors have read and approved the final version submitted. The authors declare no competing financial interest. No specific funding source has supported this research. The paper is original and not considered for publication elsewhere. Please consider it for publishing in your Journal.

Thank you for kind attention.

Best regards,

Marco Ormellese

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Declaration

On behalf of all the authors of the submitted paper “Effects of non-stationary stray current on carbon steel buried pipelines under cathodic protection”, I declare there are no conflict of interest in publishing the work.

Best regards

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COMMENTS TO REVIEWERS

First, we would like to thank the reviewers for their precious comments, very helpful to improve the quality of the paper. Hereafter the answers to the comments.

Changes in the manuscript are highlighted in yellow.

REVIEWER #1

Introduction: Is there any relevant work reported previously on non-stationary DC interference on buried pipelines or other structures? If yes, please include to provide an insight into this interesting phenomenon.

Literature and introduction section has been improved according to the reviewer suggestion.

The authors should provide a diagram detailing the setup of the steel specimen under CP, while under interrupted DC interference. It would be mandatory to have the diagram as the electrical circuit to enable both CP and DC is critical to the reliability of the measured data.

A scheme of the electrical circuit has been added and described in the manuscript as requested.

p. 5: The cell contained "silica sand and a soil simulating solution". Please give details of the sands, i.e., size, shape, rounded or unrounded, content, etc.

Rounded sand (4 mm max diameter) has been used. Details have been reported in the manuscript

p. 7, Eq. (2): During two months of testing, it is expected that corrosion products would generate and deposit on the steel surface. The corrosion products can affect the actual current density flowing through the specimen when the authors use applied anodic current divide the specimen area. How were the authors quantify the actual current density applied on the specimen with corrosion products?

At the end of the test, when samples were removed from the cell, corrosion products were present, mostly on tests performed at 10 A/m². In any case, they do not create any sort of electrical insulation. Corrosion product were conductive and do not form in two months sufficient insulation in order to reduce the net surface. Therefore, we assumed constant in time the surface exchanging current with soil. Accordingly, the current density was assumed to be constant in such a period.

Fig. 5: What is the reason that the potential cannot maintain constant as a function of time?

Tests have been performed in galvanostatic control. Therefore, potential may show some oscillations. The main reasons are diffusion of oxygen and temperature. In any case, the fluctuation associated to any tests, represented by different symbol, are acceptable. In fact, the main point was to guarantee a good cathodic protection level, according to standard.

Figs. 6-9: Why the two curves in each figure have different start potentials? Cannot start at the same level?

The difference in start potentials is due to the local difference of each cell. Since we perform test in galvanostatic control mode, it is not possible to assume a constant potential in all the cells. What is important is that in all the tested condition the steady stable potential is in the range -0.85 / -1.2 V CSE

Fig. 12: The explanation is nice in terms of the passivity-activity transition under DC application. It would be better if the authors provide direct evidence to support the proposed time % for passivity/corrosion in Table 2. If not, the explanation is speculative only.

We thank the reviewer to appreciate our interpretation.

The percentage values presented in Table 2 have been estimated by dividing the period in passivation, as defined in Figure 12, by the total duration of a peak. For example, if we consider test at CP 1 A/m², peak total duration 1 minute, we have a time in passivation of 37 s, which corresponds to the 62% of one minute.

The explanation of the % calculation been added in the manuscript.

REVIEWER #2

On page 3, line 63, it is not accurate to say "the anodic site is located under the substation", which is determined by the location of coating defects, soil resistivity and other factors.

A better explanation is given in the manuscript.

Besides, in the sentence of "In spite of the limited duration, the effects may be severe due to the high circulating current." What is the limited duration? Please give more explanation.

More information are given in the manuscript.

Because the work of this paper focused on the effects of non-stationary stray current, the introduction on stationary interference (from line 48~line 57) should be simplified.

Text has been simplified.

More introduction on the dynamic characteristics of stray current from DC traction systems and existing research work on the corrosion behavior under non-stationary stray current should be added in the paper. A more completed literature review is needed.

Literature and introduction section has been improved according to the reviewer suggestion.

On page 6, line 120, please give more detailed introduction on how to get IR-free potential, by instant-off method or only placing reference electrode close to the specimens?

IR-free potential was measured by means of a Luggin capillary, so placing the reference electrode as close as possible to the specimens. Text has been modified.

From Figure 6 to Figure 8, "in the presence of 10 A/m² DC interference, a strong increase of potential was recorded: maximum recorded value was close to +1.2V CSE" (Page 10, line 175), please give more detailed introduction on the measurement of IR-free potential when the interference is applied and analyze the ohmic drop error existed in the case of 10 A/m² DC interference. Although a luggin capillary filled with the test solution was placed as close as possible to the exposed carbon steel surface, when the DC interference current density is as large as 10A/m², the ohmic drop produced near the specimen could not be neglected unless other method such as instant off method was used to eliminate the IR drop.

Thank you to the reviewer; this is a good point to be clarified.

We do not use instant off readings. In any case, the ohmic drop could be roughly estimated by the following equation: $IR = \text{resistivity} \times \text{distance} \times \text{current density}$. Considering resistivity less than 20 ohm m, distance 1 mm, the ohmic drop is 2 mV if 0,1 A/m² are applied (negligible), 20 mV in the case of 1 A/m² (negligible) and 200 mV in the case of current density 10 A/m². In the last case, some ohmic drop is present in the reading; in any case, the potential trend recorded is not strongly affected by this ohmic drop contribution and the comments are still valid.

An explanation has been introduced in the manuscript at the end of potential profile description.

On page 11, line 212, "Indeed, supposing a carbon steel anodic Tafel slope of about 60 mV/decade, the maximum potential shift should be in the range of 0.3 V at the highest anodic DC current density." Please provide the anodic polarization curve of the specimen in the experimental environment.

A Tafel curve has been performed and the graph has been reported in this section.

Please give more evidence to verify there exist passive film on the specimen in the presence of severe anodic current density (10 A/m²), such as the product analyses of the film or reaction phenomenon during the interference.

We described this point in the discussion section, describing the reaction phenomenon during both CP (effect of alkalinity) and DC interference at any level. We will take into consideration the reviewer suggestion regarding the chemical analysis. We will consider this part in a further paper.

*Highlights

- The alkalinity produced during CP reduces the DC interference effect
- Anodic reaction initially causes the neutralization of electrolyte alkalinity
- The anodic potential shift is higher than what expected by Tafel law
- Potential peak cannot be used as parameter to evaluate the risk of DC interference
- DC peak intensity and duration are the key parameters.

Effects of non-stationary stray current on carbon steel buried pipelines under cathodic protection

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Abstract

DC stray currents may cause severe corrosion on buried carbon steel pipelines even if in cathodic protection. According to international standard anodic interference is unacceptable if the IR-free potential is more positive than the protection potential (-0.85 V CSE). But, duration and magnitude of the anodic peak is not defined. The criterion appears to be too restrictive if short periods of anodic interference are established. This paper deals with the study of the effects of anodic interference on carbon steel in cathodic protection in soil-simulating environment in the presence of DC interference at varying peak current density and duration.

Keywords: carbon steel, cathodic protection, electrochemistry, pipeline, polarization, stray current.

28 1. Introduction

29 Buried carbon steel pipelines are typically protected against corrosion by combining an external
30 polymeric coating and cathodic protection (CP). The latter is an electrochemical technique used to
31 prevent and control corrosion, acting by lowering the potential of the protected structure (called the
32 cathode) by supplying an external DC current. The cathodic polarization favors oxygen reduction
33 reaction at the metal surface with a consequent positive alkalization at the pipe-to-soil interface.

34 ISO 15589-1 [2] defines CP criteria: if on-potential, i.e. potential measured during CP, is lower than
35 free corrosion potential, the general criterion is applied; if IR-free potential, i.e. potential measured
36 during CP without any ohmic drop contribution, is lower than the protection potential level reported
37 in the same standard, also CP effectiveness is assured. In this case, carbon steel corrosion rate is
38 negligible, lower than 10 $\mu\text{m/y}$.

39 The presence of stray current may cause severe damages on buried structures, even under CP
40 condition [3-10]. Generally, electric interference is defined as any alteration of the electric field
41 caused by a foreign structure. If the foreign body is a conductor, as a buried steel pipe, the current
42 is intercepted and can provoke corrosion where the current is released from the metal to soil (anodic
43 interference) [1].

44 Both DC and AC interference may cause corrosion on pipeline buried in soil. As regards the
45 presence of AC interference, there is lack of agreement about the CP criteria to control interference
46 and about the correct procedure to monitor buried pipeline potential [11-14].

47 DC interference can be stationary or non-stationary, depending on interference source. Stationary
48 interference can take place when the structure is immersed in a stationary electric field generated
49 for instance by a CP system with the ground bed close to the structure. An example is reported in
50 Figure 1: the non-protected pipeline suffers anodic interference, then corrosion, at the crossing
51 point. Corrosion can be very severe since the anodic current is typically released at coating defects
52 or holidays. A local current density as high as 10 A/m^2 is possible, then producing a corrosion rate
53 of about 10 mm/y .

Figure 1 - Scheme of stationary interference between two crossing pipelines

Non-stationary interference takes place when the electric field is variable, as in the typical case of stray currents dispersed by DC traction systems (Figure 2). Interference occurs only during the transit of the train. The current supplied by the positive pole of the substation flows in the aerial cable and then on the train through the pantograph. In the return path, part of the current flows into the ground, interfering pipelines parallel to the rail. Some pipeline areas absorb current, showing a cathodic behavior, some other release current, assuming an anodic behavior and then corroding. Anodic site is typically located in proximity of the substation, as all the current has to return to the negative pole of the substation. The exact location is determined by the presence of defects in the pipeline coating, by the local soil resistivity and by all the factors that affect it, i.e. soil composition, pipeline backfill, water retention. The duration of the interfering period is limited, and it is equal to the time the train circulates between two subsequent substations, typically some minutes, according to the train velocity. Despite the limited time, the corrosion effect may be severe as the circulating current is high, promoting typically a local anodic current density about $1\text{-}10\text{ A/m}^2$.

Figure 2 - Scheme of non-stationary interference caused by stray current dispersed by a DC transit system

73 Allahkaram [7] investigated the effects of stray currents generated by DC traction system on
74 cathodically protected gas pipelines in the city of Tehran. Results showed that when the distance
75 between rails and pipeline exceed 1.5 km the interference effect is negligible. At a lower distance,
76 parallel pipes are more affected than crossed aligned pipes. Besides pipe position, soil resistivity
77 plays a significant role. Birbilis [8] demonstrated the importance of soil resistivity. Even under very
78 severe anodic exposure (anodic polarization up to 0 V CSE), carbon steel corrosion is limited to
79 relatively modest values in high-resistivity soil (more than 200 Ω m). In low-resistivity soil (lower than
80 40 Ω m), corrosion rapidly accelerated. Birbilis pointed out that corrosion from anodic transients is
81 not cumulative and do not follow the values predicted from Faraday's law; he hypothesized the
82 beneficial effects of CP persist for some time even after the removal of protection. Hou [9] obtained
83 the same conclusion. Moreover, he defined a critical anodic transient duration, about 15 minutes
84 long, which is a sort of 'safe' period in any single anodic transients during which corrosion in
85 negligible on cathodically protected buried steel. He also concluded that the passive condition
86 promoted by CP are not completely destroyed by DC interference, provided the amplitude and
87 duration are below critical values. Same consideration are reported in [10].

88 CP criteria and mitigation measurements in the presence of DC interference are available for
89 several years [2, 15-16]. The European Standard EN 50162 "Protection against corrosion by stray
90 current from direct current systems" describes appropriate measures, which can be applied to
91 interfered DC systems and to structures exposed to stray current corrosion [15]. As regard
92 protection criteria, anodic interference on freely corroding metallic structures is considered
93 acceptable if the positive potential shift (excluding IR-drop) is lower than 20 mV for steel. For
94 structures under CP, anodic interference is considered unacceptable if the IR-free potential is
95 outside the potential range provided by ISO 15589-1, i.e. if the IR-free potential does not match the
96 -0.850 V CSE criterion [2, 17-19].

97 Nevertheless, this protection criterion in the presence of non-stationary interference seems to be too
98 restrictive considering that short periods of interference (in the order of a few seconds up to
99 maximum of a few minutes during the transit of the train) are alternated with the re-establishment of

100 CP condition. It follows that in a continuous digital potential recorder over a 24 h period, the
101 protection criterion will be not matched corresponding to the anodic potential peaks more positive
102 than -0.850 V CSE, regardless the duration and intensity of interference.

103 This paper deals with the study of the effect of DC anodic non-stationary interference on buried
104 carbon steel structures under CP condition. In particular, tests aim to verify the acceptability of a
105 3600 s daily DC interference on corrosion of cathodically protected carbon steel. Weight loss tests
106 were carried out on steel specimens in soil-simulating environment varying the anodic current
107 density (from 0.1 to 10 A/m²) and the duration of the peak (from 1 minute up to 1 hour). Preliminary
108 results were presented elsewhere [20].

109 **2. Materials and methods**

110 Laboratory tests were carried out on carbon steel specimens type UNS G10180 (grade L360
111 according to EN 10208 [21]), equivalent to API 5L X52 (according to API 5L [22]). Chemical
112 composition (wt %) is 0.25 C, 1.4 Mn, 0.45 Si, 0.0025 P, 0.1 V and Fe balance. After preparation
113 and cleaning operations according to ASTM G1 [23], specimens were placed in a PVC cylindrical
114 watertight sample holder (Figure 3), exposing a circular net surface of 1 cm² to the electrolyte, in
115 order to simulate a coating defect of a steel pipe. A stainless steel screw on the top of the sample
116 holder provides the electrical contact with the sample. In order to prevent galvanic coupling effects,
117 a glass tube was placed to insulate the electrical contact.

118 Samples were placed in a cylindrical cell (diameter 150 mm; height 200 mm) containing silica sand
119 (grounded spherical sand, 4 mm maximum diameter, 1 kg for each cell) and a soil-simulating
120 solution: 1 g/L Na₂SO₄ and 0.2 g/L NaCl. Soil resistivity was less than 20 Ω m. A Luggin capillary,
121 filled with the same test solution, was placed as close as possible to the exposed carbon steel
122 surface (distance 1 mm) in order to eliminate the ohmic drop contribution during potential reading
123 (Figure 4).

Figure 3 - Carbon steel specimen

Figure 4 - Cell assembly

Figure 5 shows a schematic representation of the electrical circuit. Carbon steel specimens were cathodically polarized by means of a CP feeder through an activated mixed-metal-oxide titanium insoluble anode (Ti-MMO anode) placed in the same cell. A second DC feeder applied anodic interference. A programmable automatic switcher has been used to change the polarization mode from cathodic protection to interference according to the testing condition (see Table 1). A $10\ \Omega$ shunt was placed in series to the sample to measure the flowing current.

Figure 5 – Schematic representation of the electrical circuit used to supply cathodic protection and to apply DC interference

Firstly, CP was applied for two weeks, without any DC interference. Protection potential was monitored and adjusted in the range -0.85 V / -1.25 V CSE. Then anodic interference was applied. Three anodic current densities were considered: 0.1, 1.0, and 10 A/m². Duration of a single DC peak is reported in Table 1. The total duration of the interference was 1 h/day. In the presence of 0.1 A/m² anodic interference, a single peak 1 h long was applied.

Potential was daily measured by means of a high impedance voltmeter (200 MΩ) and an external Cu/CuSO_{4,sat} reference electrode (CSE, +0.32 V SHE, Standard Hydrogen Electrode) using the the Luggin capillary. Once a week potential was recorded by means of a data-logger (frequency 0.5 Hz).

Table 1 - Duration of DC anodic peak and total number of peak per day

Peak duration (minutes)	Total number of DC anodic peak per day	Total peak duration (minutes)	CP duration between two DC peaks (minutes)
1	60	60	23
2	15	60	46
5	12	60	115
60	1	60	1380 (23 h)

152 After two months testing, samples were extracted from the cell and corrosion products were
153 removed by means of a chemical cleaning at room temperature with hydrochloric acid 1:1 inhibited
154 with 3.5 g/L hexamethylenetetramine, according to ASTM G1 [23]. Corrosion rate, CR , was
155 calculated by means of weight loss measurement:

156

$$157 \quad CR = \Delta W / (S \cdot t \cdot \gamma) \quad (1)$$

158

159 where ΔW is weight loss, S is the exposed surface of the sample (1 cm^2), γ is carbon steel density
160 and t the duration of the tests.

161 Practical corrosion rate was compared with the theoretical steel dissolution rate, CR_{th} , calculated by
162 Faraday's law:

163

$$164 \quad CR_{th} = \frac{AW}{2 \cdot F \cdot \gamma} \cdot i \quad (2)$$

165 where AW is iron atomic weight (55.8 g/mol), F is Faraday constant (96485 C) and i is the applied
166 anodic current density.

167 3. Results

168 3.1 Potential monitoring

169 IR-free protection potential was measured every day before applying DC interference. Figure 6
170 shows protection potential reading during all the tests. Different symbols refer to different cells. The
171 potential in CP condition was in the fixed range -0.85 V to -1.25 V CSE. Accordingly, for all
172 specimens, the -0.85 V CSE criterion is always matched.

Figure 6 - Protection potential before DC interference

During the DC interference period, once a week the IR-free potential was recorded. Figures 7-10 show some examples of potential acquisition of steel specimens subjected to different levels of interference. In the presence of DC interference 0.1 A/m^2 a very small potential shift was recorded. Recorded potential is not reported in the following graphs. Only the peak 1 h long showed 0.2 V anodic polarization (Figure 10). During one-minute-long DC peaks were applied, IR-free potential increased up to -0.6 V CSE and 0.8 V CSE in the presence of 1 A/m^2 and 10 A/m^2 , respectively (Figure 7). At longer peak duration, the anodic polarization reached highest values (Figures 8-9). It should be noted that in the presence of 10 A/m^2 , after the considerable initial potential increase, a slow potential decrease over time was observed, mainly in tests at longer peak duration (Figure 10). This trend confirmed what reported in [10].

Figure 7 - IR-free potential profile during DC anodic peaks 1-minute long

Figure 8 - IR-free potential profile during DC anodic peaks 2-minute long

Figure 9 - IR-free potential profile during DC anodic peaks 10-minute long

Figure 10 - IR-free potential profile during DC anodic peaks 1-hour long

Summarizing, once the interference is applied, a sudden potential shift towards more noble values is recorded. Higher the applied DC interference, higher the potential shift:

- in the presence of 0.1 A/m^2 DC interference the potential increase up to -1.0 V CSE
- in the presence of 1 A/m^2 DC interference potential as high as -0.6 V CSE was recorded; potential increased up to 0 V CSE only during 1 h long peak

- in the presence of 10 A/m² DC interference, a strong increase of potential was recorded:
maximum recorded value was close to +1.2 V CSE.

At DC current density 1 and 10 A/m², the potential assumes values higher than the threshold value, -0.850 V CSE (as provided by ISO 15589-1 [2]).

At the end of the peak, cathodic protection was re-applied; potential instantaneously decreases, then a subsequent downward trend until protection level was reached.

It is important to state that potential readings under DC interference are not affected by the ohmic drop due to the position of the tip of the Luggin capillary. In fact, ohmic drop, IR (in V), could be roughly estimated as follow [1]:

$$IR = \rho \cdot d \cdot i \quad (3)$$

where ρ is resistivity (less than 20 Ω m in tested condition), d is the distance between capillary tube tip and carbon steel specimen (= 1 mm), i is the applied anodic current density. Accordingly, the ohmic drop is 0.002 V, 0.02 V and 0.2 V in the presence of an anodic current density of 0,1 A/m², 1 A/m² and 10 A/m², respectively. Only in the last case, ohmic drop has a minimum effect on potential reading, even if the trend in potential variation is not strongly influenced.

3.2 Corrosion rate

Figure 11 show experimental corrosion rate calculated by means of weight loss measurement (Eq. 1) for specimens cathodically polarized exposed to anodic DC interference 0.1, 1 and 10 A/m² at different peak duration. Corrosion rate of carbon steel specimens exposed to a daily 0.1 A/m² DC anodic interference 1 h long is negligible, lower than 10 μ m/y. Corrosion may be considered negligible also in the presence of an anodic DC interference 1 A/m², 1-minute long. In the presence of a DC interference 10 A/m² corrosion rate is never negligible, in the range of 250 to 440 μ m/y.

Figure 11 - Corrosion rate of cathodically protected carbon steel specimens

In Figure 11 theoretical corrosion rate, calculated by Faraday's law (Eq. 2), is also reported.

Measured corrosion rate is always lower than the theoretical value, confirming results reported in [9].

It is possible to assume that during the anodic peak, the anodic current has initially to “neutralize” the benefic effect of CP, namely has to consume the alkalinity produced at the metal-to-soil interface due to the cathodic reactions occurring at the metal surface. Then corrosion of metal may occur. This point will be discussed later on.

As expected, at a constant anodic DC interference, measured corrosion rate increases with peak duration, even if the increase is not directly proportional, as expected by Faraday's law, endorsing the previous hypothesis regarding the presence of two different phases during the anodic peak: an initial phase in which passivation is destroyed and a second phase of metallic corrosion. This point will be discussed later on.

At a constant peak duration, higher is the anodic DC interference, more severe is the measured corrosion rate.

4. Discussion

4.1 Peak potential profile interpretation

During DC anodic interference a potential positive shift was measured on the cathodically polarized carbon steel specimens. The potential increased about 0.2 V in the presence of 0.1 A/m^2 , more than 0.5 V in the presence of 1 A/m^2 , even 1 V in the presence of 10 A/m^2 . This anodic shift cannot be explained considering the Tafel behaviour ($E\text{-log}i$) of active steel in soil. Figure 12 reports the Tafel curve of carbon steel in soil simulating solution, obtained scanning the potential from -0.2 V to +0.2 V with respect the free corrosion potential at a scan rate of 10 mV/minute. The Tafel slope of the anodic part is about 60 mV/decade. Accordingly, at the highest anodic DC current density (10 A/m^2) the maximum potential shift should be in the range of 0.3 V from the protection condition; instead, the measure potential shift was about 1 V.

256

257 Figure 12 – Potentiodynamic polarization curve of carbon steel in soil-simulating solution

258

259 To interpret this high potential shift, it should be considered the different electrochemical behaviour
260 of carbon steel in CP condition. In fact, the presence of a cathodic process occurring on steel
261 surface before any DC interference deeply affects carbon steel corrosion behaviour. More precisely,

262 cathodic reactions on steel in CP condition are oxygen reduction and hydrogen evolution,
263 depending on protection potential and current density:

264

267

268 The evolution of both reactions produces a significant pH increase at the steel-to-soil interface, also
269 promoted by soil stagnant condition. The alkaline environment in contact with the metal (pH can
270 increase up to 11 or higher, depending on cathodic current density [24]) has a beneficial effect on
271 the metal as it promotes the formation of a passivity condition, as expected by iron Pourbaix
272 diagram [25]. Then, carbon steel electrochemical behaviour under CP is typical of a passive
273 material.

274 The interruption of CP during the anodic DC interference does not remove instantly the alkalinity
275 previously generated by the cathodic reactions on the steel: in other words, the residual alkalinity
276 allows keeping steel in passive conditions even after the interruption of the cathodic current. Due to
277 the presence of a passive film, carbon steel provides high resistance to current exchange, then
278 justifying the initial high potential shifts recorded immediately after the anodic DC interference.
279 Conversely, potential variations would be more contained on a carbon steel specimen in freely
280 corroding condition, due to the absence of the passive film. Once the alkalinity is neutralized,
281 potential decreases to values typical of active metal and anodic corrosion may occur. The period of
282 passivation and corrosion will be discussed in the next paragraph.

283 In the presence of severe anodic current density (10 A/m^2), potential reaches values that exceed the
284 equilibrium potential of water dissociation reaction, which leads to oxygen evolution and local
285 increase of acidity, according to the following reaction:

286

288

289 The acidity produced by oxygen evolution reaction (Eq. 5) contributes to quickly neutralize the
 290 residual alkalinity produced by CP, weakening the passivity of steel; a decrease of potential
 291 (confirmed by potential readings, Figures 9 and 10) is measured in a shorten period. Once the
 292 passivation is destroyed, steel corrosion starts at a corrosion rate expected by Faraday's law.

293 4.2 Passivation and anodic corrosion during an anodic peak

294 It has been demonstrated that measured corrosion rate of cathodically polarized carbon steel
 295 specimens exposed to anodic DC interference are always lower than the theoretical value estimated
 296 through the Faraday's law.

297 Due to the electrochemical behavior of carbon steel in CP condition, it is possible to assume that
 298 during each anodic peak, two phases may be identified (Figure 13):

- 299 • *phase 1 – time in passivity* ($t_0 - t_{passivity}$): the anodic current initially “neutralizes” the benefic
 300 effect of CP, namely consumes the alkalinity produced at the metal-to-soil interface due to
 301 the cathodic reactions occurring at the metal surface
- 302 • *phase 2 – time in corrosion* ($t_{passivity} - t_{peak}$): once the alkalinity is neutralized, then anodic
 303 current may corrode the metal according to the Faraday's law.

304
305 Figure 13 - Phases during a DC anodic peak

306
307 Before t_0 and after t_{peak} , carbon steel is cathodically protected, then corrosion is nil. During the peak,
 308 in phase 1 corrosion rate is still zero, while after $t_{passivity}$ (phase 2) corrosion rate equals the
 309 maximum expected corrosion rate according to Faraday's law, CR_{th} .

310

311 Taking $t_0 = 0$, the following applies:

312

313
$$CR_{th} \cdot (t_{peak} - t_{passivity}) = CR_{exp} \cdot (t_{peak}) \quad (6)$$

314 where CR_{exp} is the measured corrosion rate. The time in $t_{passivity}$ may be calculated as follow:

315

316
$$t_{passivity} = t_{peak} \cdot \left(1 - \frac{CR_{exp}}{CR_{th}} \right) \quad (7)$$

317

318 Duration of phases 1 and 2 are reported in Figure 14. Table 2 summarizes the percentage of
319 maintenance in each phase. For each tested condition, the percentage has been calculated as the
320 ratio between the time in passivation (or in corrosion) as reported in Figure 13 over the total duration
321 of the peak.

322 The following can be drawn:

- 323 • at a constant DC current density, both the time in passivation and time in corrosion increase
324 with increasing peak duration, the latter in a more predominant way
- 325 • at a constant peak duration peak, the higher the anodic DC interference, the lower the time
326 in passivation, the higher the time in corrosion
- 327 • the time in which the passive film is stable is proportional to the duration of cathodic
328 protection, which is greater for the specimens subjected to 1 h and 5 minutes of interference.

329

Figure 14 - Time in passivity and time in corrosion during each DC anodic peak

Table 2 - Percentage of time in passivity and time in corrosion

DC anodic current density (A/m ²)	Peak duration (minutes)	Time in passivation	Time in corrosion
1	1	62%	38%
	2	42%	58%
	5	32%	68%
	60	11%	89%
10	1	43%	57%
	2	28%	72%
	5	16%	84%
	60	10%	90%

5. Conclusions

Weight loss tests were carried out in soil-simulating environment on cathodically protected carbon steel specimens varying the DC interference (0.1, 1 and 10 A/m²) and the peak duration.

Laboratory experimental results allow to state:

- potential readings confirm the formation of passive condition on steel under CP condition, due to the alkalinity produced by oxygen reduction and hydrogen evolution reactions;
- during a DC anodic peak, initially the anodic reaction occurring on the metal causes the progressive neutralization of electrolyte alkalinity in contact with steel with loss of passive condition; then anodic corrosion occurs;
- a potential increase was measured during each anodic peak: the potential shift was higher than what expected by Tafel Law;
- consequently, potential peak cannot be considered a parameter to evaluate the risk of DC interference on a cathodically protected specimens;
- peak duration and DC peak intensity are the key parameters:
 - a daily peak 1 h long is acceptable provided the anodic DC is lower than 1 A/m²;
 - peak few-minute-long are acceptable, provided the total anodic duration is 1 h per day and the maximum DC intensity is in the range of 1 A/m²;
 - if anodic current density is close to 10 A/m², any interference duration is not acceptable.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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