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AC-corrosion in pipelines:
Field experiences from a highly corrosive test site using ER corrosivity probes*

L.V. Nielsen[1], and P. Cohn[2]

[1] MetriCorr, Glerupvej 20, DK 2610 Rødovre, Denmark
[2] DONG, Agern Allé 24-26, DK 2970 Hørsholm, Denmark

Abstract

Based on spot wise measurements on ER corrosivity probes mounted along the Danish gas grid system, a particularly aggressive site was identified. The site was subsequently used for a detailed test program in order to establish rate controlling parameters and further mechanistic evidence by use of high-sensitivity ER equipment.

The test program which is still in progress has so far included the following conditions:

- Corrosion rate and -conditions for probe at open circuit buried in the soil below groundwater.

- Corrosion rate and -conditions for probes electrically connected to the pipe in conditions:
  o Exposed in free water (drainage well) – connected to the pipe
  o Exposed above ground water level in soil - connected to pipe
  o Exposed below ground water level in soil – connected to pipe
  o Exposed below ground water level - connected to pipe via 5 mF capacitor.

The following observations were made:

- At OCP in wet soil, the corrosion rate was found to be in the range 45-60µm/y.

- Under AC load alone, the probe exposed in wet soil was effectively free from corrosion, probably due to a mild cathodic polarisation caused by the AC.

- In dry soil, the corrosion rate for a connected probe was in the range 0-15 µm/y (AC 3-25V)

- In free water, the corrosion rate for a connected probe was in the range 0-25µm/y (AC 3-25V)

- For the probe exposed in the wet soil, the tendency seems to be that initially, the corrosion rate can be described as one exponential function, whereas at later stages, a second steady state condition exponential function can be experimentally verified, showing corrosion rates excess of 2000-3000 µm/y at 25V AC.

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1. Introduction

Natural gas transmission pipelines are usually supplied with cathodic protection (CP) to protect coating defects against corrosion. In the specific case of CP of coating defects in buried pipelines influenced by induced AC current, the CP evaluation becomes complicated, and the usual potential criteria are no longer necessarily valid. Parameters like AC current density or anodic peak values of the true (IR-free) potential can be applied[1,2] but they provide no measure of the corrosion conditions.

The electrical equivalent diagram of a pipeline with superimposed AC may be sketched as in figure 1[3]. The electrochemical conditions as well as the CP rectifier produce electromotive forces. $E_0 1$ and $E_0 2$ denote equilibrium potentials relating to those electrochemical processes that are active at a coating defect (these e.g. may constitute ferrous corrosion and hydrogen production). VB1 and VB2 are components analogous to diodes and represent (Volmer-Butler) activation kinetics of involved processes. Warburg impedance component (W) is coupled to indicate influence of diffusion limitation. R_S denotes the ohmic resistance from pipe to remote earth (also known as spread resistance), and C denotes interfacial capacitance. The AC generator refers to AC on pipe due to induction from a paralleled high-voltage power line.
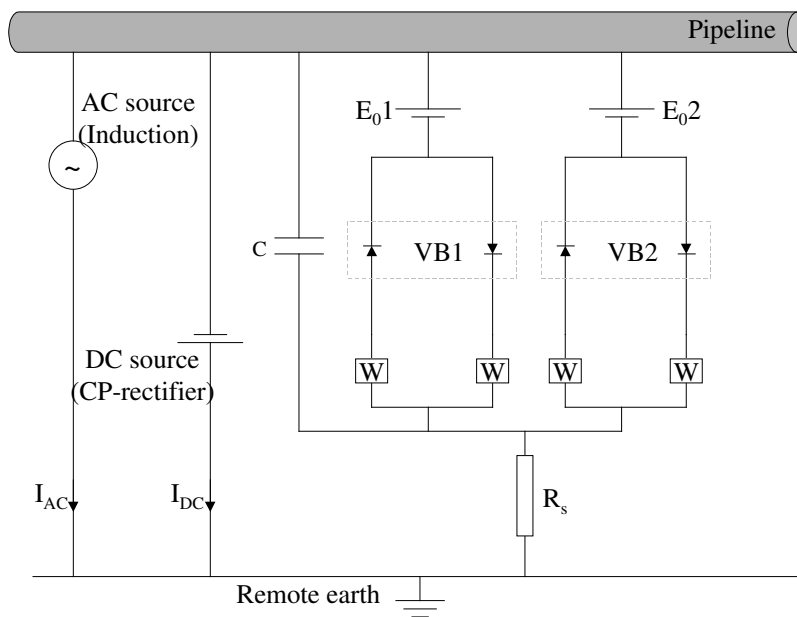

Fig. 1. Equivalent circuit diagram for pipeline CP-system with superimposed AC.

It is believed that one mechanism of AC induced corrosion involves alkalisation of the local environment around a coating defect due to enhanced cathode kinetics etc, which in combination with induced AC creates corrosive conditions. It has been shown that both AC induced passivity breakdown at moderately high pH values can occur, as well as high pH general corrosion (figure 2)[4,5]
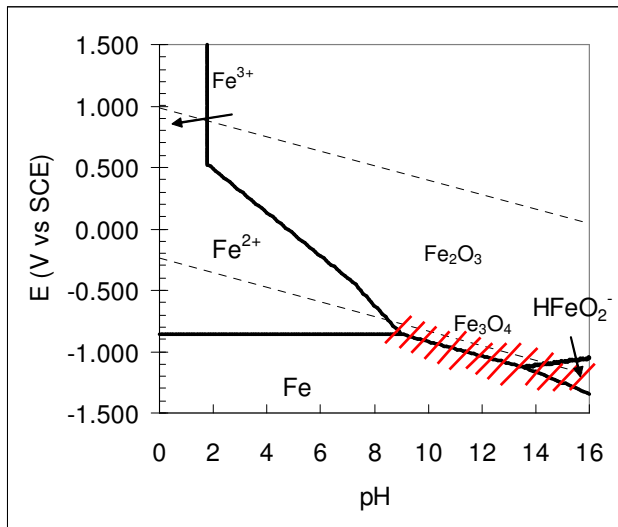
Fig. 2. Pourbaix-diagram showing area of AC induced passivity breakdown and area of high-pH general corrosion.

As part of the routine checks on AC-corrosion risk along the DONG natural gas transmission pipeline in Denmark, a number of ER corrosivity probes are buried along the pipeline and electrically connected hereto. Based on spot wise measurements on these probes, a particularly aggressive site was identified.

This site was subsequently used for a detailed test program in order to establish rate controlling parameters and further mechanistic evidence by use of high-sensitivity ER equipment.

At present, research is still progressing and this communiqué describes results achieved so far.

2. Experimental

The site chosen for the field studies was located at the Danish gas grit system in southern Jutland (fig. 3).
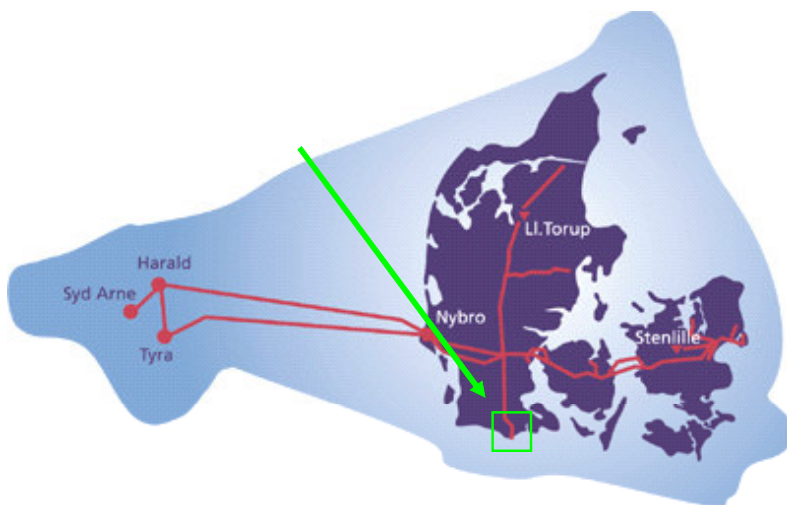

Fig. 3 Location of the test site at the Danish gas grit system in southern Jutland.

10 probes were buried along the pipe (fig. 4). Two probes (denoted 5 and 8) were installed in the free ground water present in an adjacent drainage well, the rest buried in soil. One probe (denoted 1) was placed above the ground water level, and 7 probes were buried below the ground water level – in a very wet atmosphere.
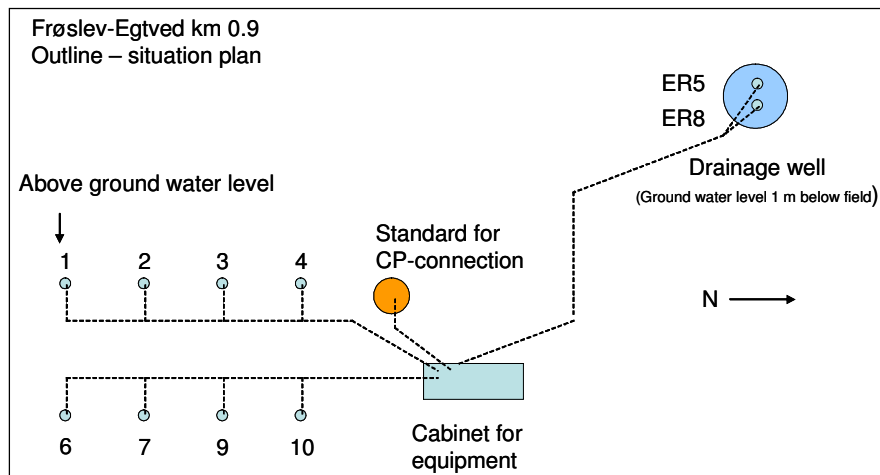

Fig. 4. In all 10 probes located at the test site.

Samples of soil were collected for analysis of texture and chemical parameters as described in table 1.

Table 1 – characteristics of the soil.

Chemical Parameter	pH (H2O)	pH (CaCl2)	BNE* cmol/kg	CaCO3 %	C %	Na+ cmol/kg	K+ cmol/kg	Mg2+ cmol/kg	Ca2+ cmol/kg
Sample 1	7.2	6.3	1.5	0	0.22	0.51	0.04	0.05	1.42
Sample 2	7.4	6.5	1.9	0	0.19	0.52	0.04	0.05	2.79
Texture	<2µm	2-20µm	20-63µm	63-125µm	125-250µm	250-500µm	500µm-1mm	1-2 mm	>2mm
Spl 1	2	1	1	2	17	33	34	10	5
Spl 2	2	1	1	2	16	35	32	11	6

*Base neutralising effect stating the quantity of hydroxyl needed to rise pH to 10. 5 different samples of the soil is shaken in different concentrations of NaOH solution for 22h to establish titration curve.

Apparently the soil had a coarse grained texture, a neutral pH and a low content of earth alkaline cations. The BNE value states the capability of the soil to buffer additions (e.g. by the CP) of hydroxyl ions. This factor has been observed to be within 1 and 20 depending on type of soil.

A modified high-resolution ER technology was used as on-line and real time corrosivity monitor. The electronic circuitry is shown schematically in figure 5 in comparison with traditional circuitry. Figure 5A shows the traditional circuitry. An excitation current is passed through a coupon-element (C) exposed in the corrosive environment and a reference-element (R) shielded from that environment. Amplifiers measure the voltages generated across the elements and

convert signals into coupon resistance (R_C) and reference resistance (R_R). The thickness of the coupon element at time t ($\sigma_C(t)$) can then (for plate geometry) be assessed by equations like

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

The resistance of a reference element is included in the algorithm in order to minimise artefacts caused by temperature changes. The limitation of the technique includes the amount of time needed to produce a measurable increase in resistance of the element. Typically, the traditional ER technique can be used solely to assess the degree of accumulated corrosion and was used in this study for the preliminary spot wise measurements.
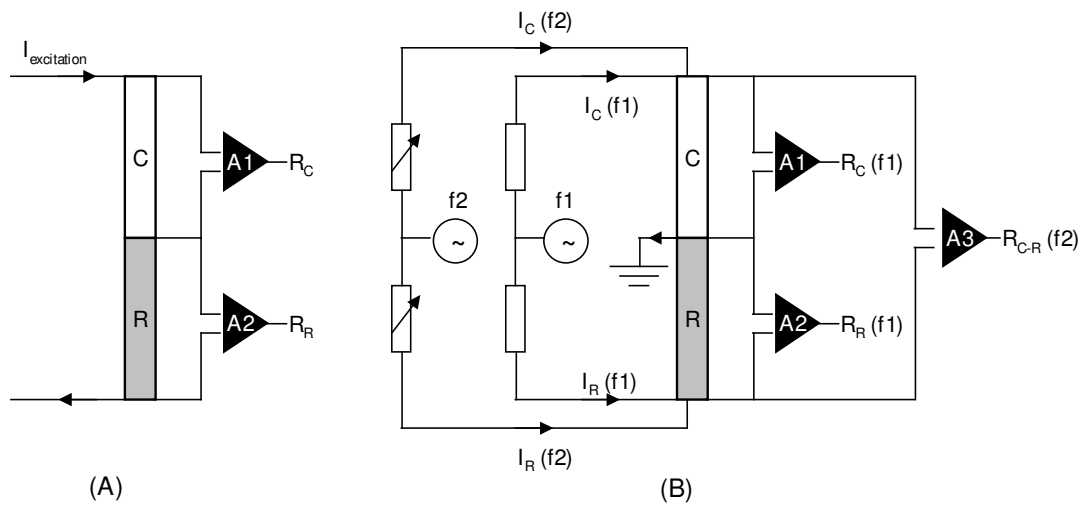

Fig. 5. (A) Traditional ER technology circuit. (B) Modified circuit including differential measurement.

Figure 5B illustrates the modified circuitry by which also high-resolution differential impedance dR_{C-R} of the ER probe elements is measured.

Since the time change dR_{C-R}/dt of the real part of the differential impedance is a measure of the time change in resistance of the coupon element, the corrosion rate V_{corr} can be calculated using the equation:

$$V_{corr} = \frac{dR_{C-R}}{dt} \cdot \frac{W}{L} \cdot \frac{\sigma^2}{\rho} = \frac{dR_{C-R}}{dt} \cdot \frac{\rho}{R^2} \cdot \frac{L}{W}$$

where L is length of element, W is width of element, σ is element thickness, and ρ is (temperature dependent) material resistivity. More details are given elsewhere.[6,7]

The probe element defined an active area ("coating defect") of 0.4 cm2 (2x20mm) as illustrated in figure 6.
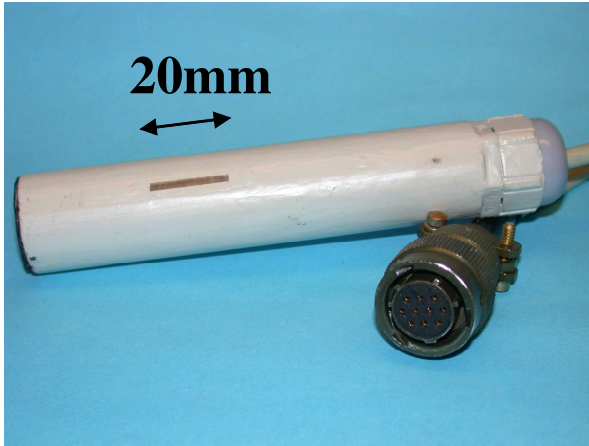
Fig.6. ER-probes used for the tests.

The measurements were compared with routine DONG measurements (real time) of the AC level present on the pipe. This level changes dramatically throughout a daily period, e.g. between 3V and 25V

At present, the following conditions have been measured by exposure and on-line real time monitoring for approximately 10 days each:

- Corrosion rate and -conditions for probe at open circuit buried in the soil below groundwater.

- Corrosion rate and -conditions for probes electrically connected to the pipe in conditions:
    o Exposed in free water (drainage well) – connected to the pipe
    o Exposed above ground water level in soil - connected to pipe
    o Exposed below ground water level in soil – connected to pipe
    o Exposed below ground water level - connected to pipe via 5 mF capacitor.

3. Results and discussion

Figures 7 and 8 shows example of the data treatment for the probe exposed at open circuit in the wet soil. The open circuit corrosion rate was found in this manner to be within the range 45-60 µm/y, which is relatively high for the Danish type of soil – an average of 20 µm/y has been found in previous studies.
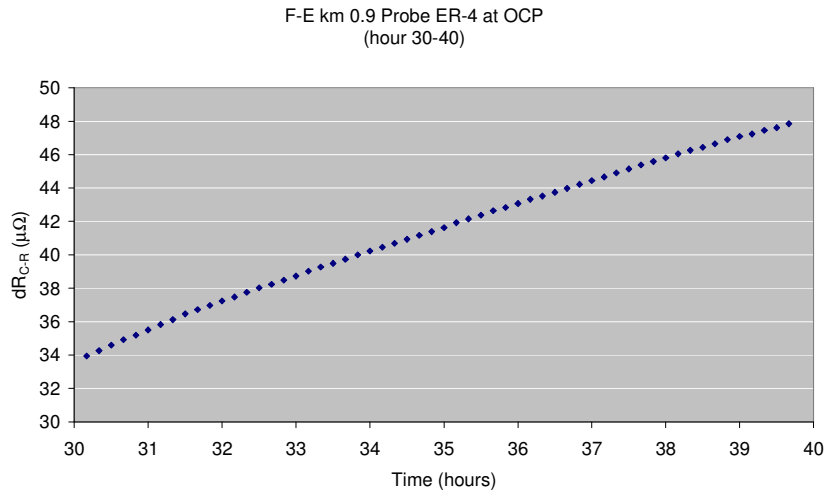
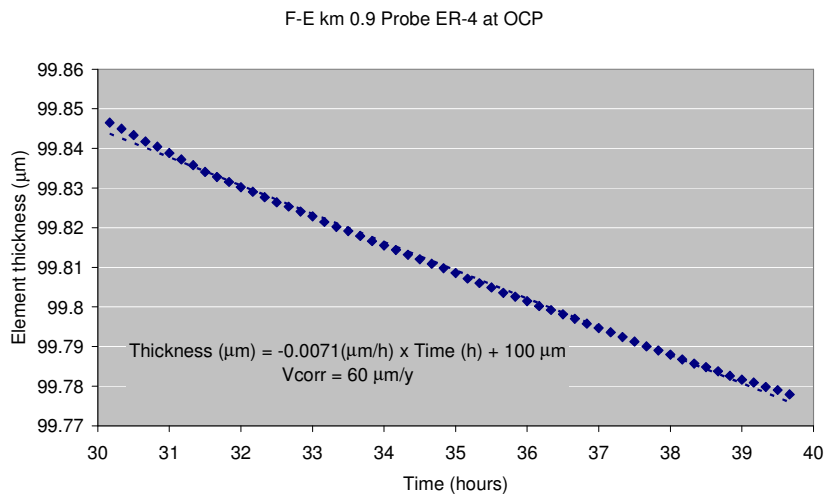Fig. 7. Differential ER data for probe exposed at open circuit in wet soil.

Fig. 8. Calculated reduction in thickness of the probe element ad corrosion rate derived from this.

Figure 9 shows assembly of the AC level on the pipe and the measured corrosion rate on probe exposed in wet soil. Figure 10 correlates corrosion rates with AC level for this probe. The correlation has been made throughout 24 h cycles in the initial part of the test, and for three periods towards the end (330h, 440h, and 490h). The tendency seems to be that initially, the corrosion rate can be described as a function of the AC voltage through:

$$V_{corr} \ (\mu m/y) = 0.45 \ x \ Exp\{0.39 \ x \ U_{AC}\} \qquad \text{Type 1 corrosion}$$

At later stages, the corrosion rate seems to be stabilised at the behaviour

$$V_{corr} \ (\mu m/y) = 85 \ x \ Exp\{0.15 \ x \ U_{AC}\} \qquad \text{Type 2 corrosion}$$

This shift in behaviour can well be due to a shift in pH from medium alkaline (creating type 1 corrosion due to destabilisation of the passive film) to very high pH (creating type 2 general corrosion. Note that for type 1 corrosion, zero AC load gives zero corrosion, whereas in type 2 corrosion, zero AC load still gives corrosion in the order of 85 µm/y.
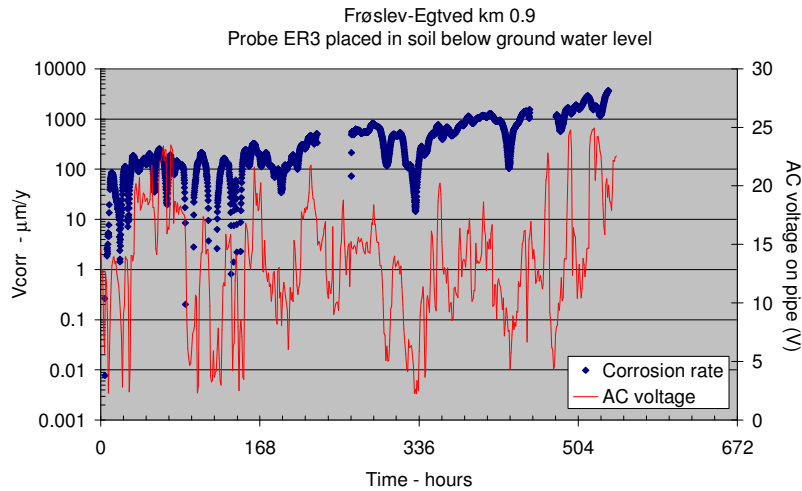
Fig. 9. Corrosion rate and AC voltage throughout time of measuring period. .
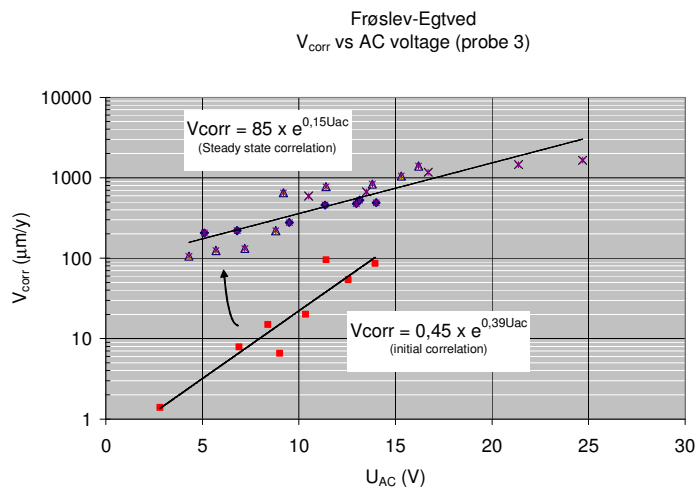

Fig. 10. Calculated Corrosion rate as a function of the AC voltage.

Note that corrosion rates can be as high as 2-3 mm/y at 25V AC.

Table 2 outlines the corrosion conditions experienced for the total of the program at its present state.

Note that apparently, the combination of water and soil is important, since no or modest corrosion takes place in water alone or in dry soil alone, although the AC conditions are alike.

Note also that if the probe is connected via capacitor, the corrosion does not develop. The potential (DC level) shift caused by the pure AC is slightly in the cathodic direction, hence, it may provide a mild cathodic protection without the heavy alkali production resulting from combined DC and AC load.

Table 2 – characteristic results from the AC test program.

Condition	Spread resistance Ω.m2	AC level V	DC level (ON) mV CSE	Corrosion rate µm/y
OCP in wet soil	0.12	0	-750	45-60
In free water connected to pipe	0.12	3-25	-1100 to -1200	0-25 in the AC range
In wet soil connected to pipe	0.04	3-25	-1100 to -1200	$V_{corr} (\mu m/y) = 85 \times Exp\{0.15 \times U_{AC}\}$ 130-3000 in the AC range
In dry soil connected to pipe	>12	3-25	-1100 to -1200	0-15 in the AC range
In wet soil connected via capacitor	0.10	3-25	$-750 \rightarrow -850$	0

4. Conclusions

Based on spot wise measurements on ER corrosivity probes mounted along the Danish gas grid system, a particularly aggressive site was identified. The site was subsequently used for a detailed test program in order to establish rate controlling parameters and further mechanistic evidence by use of high-sensitivity ER equipment.

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- For the probe exposed in the wet soil, the tendency seems to be that initially, the corrosion rate can be described as a function of the AC voltage through:

  Vcorr (μm/y) = 0.45 x Exp{0.39 x U_{AC})   Type 1 corrosion

  At later stages, the corrosion rate seems to be stabilised at the behaviour

  Vcorr (μm/y) = 85 x Exp{0.15 x U_{AC})   Type 2 corrosion

  This shift in behaviour can well be due to a shift in pH from medium alkaline (creating type 1 corrosion due to destabilisation of the passive film) to very high pH (creating type 2 general corrosion. Note that for type 1 corrosion, zero AC load gives zero corrosion, whereas in type 2 corrosion, zero AC load still gives corrosion in the order of 85 μm/y, whereas 25V AC load produces corrosion rates of 2000-3000 μm/y.

Acknowledgements

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References

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