

Discussion of criteria to assess the alternating current corrosion risk of cathodically protected pipelines

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Abstract

Buried and cathodically protected pipelines, that are parallel routed with high voltage lines or electrified railways are galvanically or inductively interfered by their operating and fault currents. As a result the pipe/ground a.c.-potential is increased with consequences regarding the safety of the pipeline against hazardous shocks and a.c.-corrosion where the coating is damaged.

This paper addresses the assessment of the corrosion risk of a pipeline due to ac. The state of the art technique is the use of coupons, which simulate a coating fault and which allow to measure the ac-current density and also to evaluate corrosion products and pits. Recently different criteria to assess the ac-corrosion risk have been proposed /1/ that are based on the ratio between ac- and dc-current density or the instantaneous off-potential (high speed off-potential measurement) measured on a coupon. These criteria are discussed on the basis of field experience from coupons and from (ac)-corrosion pits on high voltage interfered pipelines and in the light of the results of laboratory investigations which have recently been carried out.

1 Introduction

The operation of pipelines that are interfered by high voltage lines or electrified railways involves to consider a risk from alternating current (ac-) corrosion /1/. In order to do so criteria are required that allow to extract those pipeline sections suffering from an enhanced corrosion risk. Furthermore these criteria should indicate parameters that are linked to the operation of the corrosion protection system of the pipeline and that have to be adjusted in order to achieve corrosion protection. The criteria currently discussed in the field of ac-corrosion - according to /1/ and to be used if pipe/ground potential $U_{ac} > 10V$ - are:

- criterion a): $J_{ac} > 30A/m^2 \rightarrow$ corrosion risk high
 $J_{ac} < 30A/m^2 \rightarrow$ corrosion risk low

where J_{ac} is the ac-current density at the steel/medium interface.

- criterion b): $J_{ac}/J_{dc} > 10 \rightarrow$ corrosion risk high
 $3 < J_{ac}/J_{dc} < 10 \rightarrow$ corrosion risk medium
 $J_{ac}/J_{dc} < 3 \rightarrow$ corrosion risk low

where J_{ac}/J_{dc} is the ratio between ac- and dc-current density at the steel/medium interface.

- criterion c): $U_{IR-free} < -0.85V$ or $U_{IR-free} < -0,950$ mV in anaerobic soil containing sulphate-reducing bacteria at any moment
 \rightarrow corrosion risk low

where $U_{IR-free}$ is the potential at the steel/medium interface which has to be measured in realtime, i.e. during anodic and cathodic cycles of U_{ac} .

In the following these criteria will be separately discussed by considering their usefulness for assessing the ac-corrosion risk of a high voltage interfered pipelines and for the design of mitigation measures.

2 Ac-corrosion criteria

2.1 Criterion a): $J_{ac} < 30A/m^2$

Ac-current density at the steel/medium interface perhaps is the first parameter that was proposed to be used as a criterion to assess the ac-corrosion risk of a pipeline. It had been incorporated into German standards in 1992 /2/. As it is not possible to measure J_{ac} at the steel/medium interface coupons (e.g. $1cm^2$ bare steel surface area) have to be used that are electrically connected to the pipeline and thus simulate a coating fault. After more than 10 years experience with coupon measurements – while considering criterion a) - the following may be stated:

Accuracy of the criterion

J_{ac} should be interpreted in terms of a corrosion likelihood rather than a threshold, i.e. $J_{ac} < 30A/m^2$ will provide corrosion rates $v_{corr} < 0.1mm/year$ but negligible corrosion, i.e. $v_{corr} < 0.01mm/year$, may not be achieved /3/. On the contrary $J_{ac} > 30A/m^2$ may result in $v_{corr} < 0.01mm/year$ but an enhanced probability should be taken into account that $v_{corr} > 0.1mm/year$ /3/. This “grey area” makes it advisable to excavate coupons in order to excavate coupons and to assess depth of corrosion pits on the steel surface.

Practical aspects

Due to the fact that J_{ac} -measurements are bound to coupons the transferability of results from coupon measurements to the pipeline is of importance. From examples described elsewhere it may be concluded that coupon measurements correctly indicate an ac-corrosion risk of the pipeline /4/. On the contrary it has been found that coupons, simultaneously installed at the same site may show different functions of spread resistance R_{spread} with time /3,5/ and consequently different functions of J_{ac} with time. This result puts a question mark on the transferability of a single coupon measurement to a multitude of coating faults on the pipeline. Beyond this the following aspects have to be noted:

- The number of coupons that is installed at a high voltage interfered pipeline is generally limited. This raises the question where to install coupons in order to cover “worst case locations” where ac-corrosion risk is highest. Some advice may be found in /1/ where it is recommended to calculate or measure the pipe/ground potential U_{ac} that results from inductive or galvanic interference. These techniques are well established (see e.g. /6/) It is also known that physical and chemical parameters of the soil strongly influence the ac-corrosion risk. According to /7/ soil resistivity, overall- and carbonate hardness shall be taken into account. Up to now, however, no technical recommendation exists from which it is possible to reproducibly evaluate an “ac-corrosion risk profile” along an interfered pipeline from which worst case locations for the installation of coupons may be obtained.
- Coupon measurements on cathodically protected pipelines shall last over several month (minimum) which is due to the chemical alteration of the soil in the vicinity of the coupon by the cathodic protection current (e.g.

formation of NaOH followed by NaHCO₃/NaCO₃ after reaction with CO₂ and/or Ca(OH)₂ followed by CaCO₃/Ca(HCO₃)₂ /1,8/). This may dramatically influence the ac-current density in pores that exist within a surface layer and also the overall ac-current density /3/. This also means that J_{ac}-short term measurements, e.g. by using hand held probes, that are finished before the chemical composition of the soil in the vicinity of the coupon has reached a steady state, may result in an over- or – which appears to be more critical – underestimation of the existing ac-corrosion risk.

- The pipe/ground potential U_{ac} of an interfered pipeline generally varies with time due to variations of operating currents in high voltage lines or electrified railways and also does J_{ac}. A quantitative relation between ac-corrosion rate v_{corr} and peak load or short-time peak load currents (in case of electrified railways) has not been described yet. An interesting approach to this question is the use of the electric resistance (ER-) probe technique /9/.
- If used to control the success of any mitigation measures that aim to reduce U_{ac} the above mentioned topics have to be considered again

Conclusion

Criterion a) provides guidance to an operator on how to assess its corrosion protection status. It is restricted to the use of coupons and results obtained have to be transferred to the pipeline. The criterion should not be used as a threshold. Assessment of corrosion risk requires interpretation of data.

2.2 Criterion b): J_{ac}/J_{dc} < 3

This criterion is interesting because by establishing the quotient J_{ac}/J_{dc} some generally unknown parameters, such as soil resistivity or – in case of real coating faults – the geometry of the bare steel surface are eliminated, provided both current densities follow Ohm's law by using the spread and pore resistance of a coupon/coating fault. (This assumption has to be checked, as specific polarisation resistance r_p (under dc-conditions) is app. 0,01Ωm² /6/ and spread resistance of corroding coupons has been found of the same order of magnitude /9/). Following this assumption J_{ac}/J_{dc} may also be written as:

$$\frac{J_{ac}}{J_{dc}} \approx \frac{U_{ac}}{U_{IR-free} - U_{on}} \quad (1)$$

where U_{IR-free} is the IR-free potential of the coupon/coating fault. In case of polyethylene coated pipelines with generally small coating faults U_{IR-free} ≈ U_{off} may be assumed thus neglecting a possible difference, e.g. 50 - 100mV, between both values. Equ. (1) means that J_{ac}/J_{dc} may be evaluated from data that can easily be measured on an operating pipeline.

Basically the following effects of the ratio J_{ac}/J_{dc} on ac-corrosion rate v_{corr} should be considered:

- The superposition of an increasing dc-voltage, i.e. U_{on}-U_{off}, with the pipe/ground potential U_{ac} will result in a decreasing maximum value of the

amplitude ($|U_{ac}| > |U_{on}-U_{off}|$ has been assumed). Consequently the anodic charge (which is generally assumed to contribute to the corrosion mechanism) passing the steel/medium interface will be decreased and thus V_{corr} .

- Simultaneously an increasing level of cathodic protection (i.e. U_{on} becoming more negative and $|U_{on}-U_{off}|$ becoming higher) results in enhanced cp-current density J_{dc} at the steel/medium interface and alkalinity increases. There is some evidence from literature that alkalinity plays an important role in the corrosion mechanism [1,9,10].
- The ratio does not consider the absolute level of J_{ac} , i.e. the ac-current density criterion described before is not taken into account.

In order to provide some data on how the ratio J_{ac}/J_{dc} influences ac-corrosion rate v_{corr} laboratory experiments had been carried out. The results are as follows.

Corrosion rate as a function of on-potential U_{on} at different ac-voltages U_{ac} .

Table 1 describes the conditions for the first series of laboratory investigations, i.e. series I. Coupons with a bare steel surface of 0.5cm^2 had been exposed to $U_{ac}=0, 2, 6, \text{ and } 10\text{V}$ while two different cp-potentials $U_{on}=-1.5\text{V}$ (series A, C, F) and $U_{on}=-3\text{V}$ (series B, D, E) had been applied thus using parameters that are frequently found at high voltage interfered and cathodically protected pipelines (a Cu/CuSO₄-electrode had been used for potential measurements). Three different soils (I, II, III) had been taken from three different sites along the right of way of a high voltage interfered pipeline and the test period was 150d.

The electric circuit is schematically drawn in fig. 1

Fig. 2 exemplary shows plots of J_{dc} and J_{ac} vs. time as measured for coupons from A and B series in soil I. The sharp increase of current densities after 35d (fig. 2a) and 21d (fig. 2b) results from adjusting the "groundwater level" (using demineralized water) in the container to where coupons were installed. For tests in soils II and III the "groundwater level" was adjusted to coupon level from the beginning.

The shapes of the curves in fig. 2a and 2b do not significantly differ from each other, except regarding J_{dc} , which is higher for coupons 9B and 10B (compared to coupons 11A and 12A) due to $U_{on}=-3\text{V}$. From the results of these measurements (in soils I, II and III) average values, i.e. $J_{dc,av}$ and $J_{ac,av}$ have been evaluated (for series A and B those data were neglected that had been obtained before adding "groundwater" to the container). Tab. 2a,b presents the results of all measurements of series A and B, table 2c,d data from series C and D and table 2e,f data from series E and F.

In tab. 2a,b,c,d,e,f l_{max} is the maximum depth of corrosion pits that had been measured after coupons were deinstalled from the container. $w_{l,max}$ is the penetration rate as calculated from the deepest corrosion pit. Average values for U_{on} and U_{off} had been calculated for series A and B as described before for J_{ac} . From results in tab. 2a, 2b equ. (1) may be verified with reasonable accuracy.

Fig. 3a, 3b, 3c compares the results from the measurements of corrosion pit depth for coupons of group A, C, E ($U_{on}=-1.5\text{V}$) with group B, D, F ($U_{on}=-3\text{V}$) respectively. For

soil I pit depth is higher for coupons operated at $U_{on}=-3V$. For soil II a similar statement holds but one exception should be noted, i.e. coupon C11, which shows heavy pitting corrosion distributed over the circular steel surface. This result should be compared coupons D9, D10, D11, D12, which are operated at $U_{ac}=10V$ and $U_{on}=-3V$: All of them show heavy corrosion but pit depth is less deep. For soil III the statement for soil II may be repeated; the exception is coupon E13 which shows a shallow corrosion pit.

Tab. 3 shows the test conditions for another test, i.e. series 2, carried out in laboratory using artificial soil solution. For these investigations coupons were initially (i.e. $t=0$) polarized (galvanostatically) with J_{dc} between 0.3 and $100A/m^2$ followed by superposing $J_{ac}=70A/m^2$. From now on U_{on} and U_{ac} were kept constant (cf. tab. 3). It should be noted that U_{ac} , needed to achieve $J_{ac}=70A/m^2$, increases with decreasing J_{dc} , indicating an increasing spread resistance of coupons.

Tab. 4 shows the results from series 2. It should be noted that equ. (1) is fulfilled within reasonable accuracy. Penetration rates are relatively low even in case of relatively high J_{ac} (see coupon 14 and 16); the maximum is achieved by coupon 12 with $w_{l,max}=0,1mm/year$.

Fig. 4 shows penetration rates for all coupons ($J_{ac,av}>30A/m^2$) of series 1 and 2 as function of J_{ac}/J_{dc} . In principle this diagram reflects the data from fig. 3a,b,c: Data from series A,C,E with $U_{on}=-1,5V$ are found between $10<J_{ac}/J_{dc}<100$ and data from series B,D,F with $U_{on}=-3,0V$ are found between $1<J_{ac}/J_{dc}<10$. Generally corrosion rates are lower for $U_{on}=-1,5V$. Extrem values for J_{ac}/J_{dc} had been realized with experiment in artificial soil solution, i.e. $J_{ac}/J_{dc}<1$ and $J_{ac}/J_{dc}>100$. Although "ac-corrosivity" of this medium seems to be low ($w_{l,max}$ reaches a flat maximum at $J_{ac}/J_{dc}\approx 2$) data for $J_{ac}/J_{dc}<1$ suggest – in combination with data from series B and F that ac-corrosion may be successfully mitigated if $J_{ac}/J_{dc}<3$. Fig. 4 also suggests that corrosion rate is low if $J_{ac}\gg J_{dc}$ (e.g. see data from series 2). It should be noted, however, that one coupon from series C, i.e. C11, shows a high corrosion rate. Furthermore it should not be considered to enhance J_{ac} to achieve protection against ac-corrosion (because this would also result in an enhanced ratio J_{ac}/J_{dc} but this would not pay attention to criterion a), i.e. $J_{ac}<30A/m^2$. In order to support this conclusion fig. 5 shows corrosion rates $w_{l,max}$ as a function of ac-current density J_{ac} , which clearly shows that likelihood for increasing ac-corrosion rate increases with increasing J_{ac} . From fig. 4 it may be concluded, however, that ac-corrosion likelihood is reduced by careful adjustment of U_{on} , i.e. avoiding cp-overprotection, while carefully observing cp-protection criteria, e.g. given by EN 12954 /11/.

Experimental results that are in accordance with this conclusion have recently been reported /9, 12/.

Conclusion

From the results of this work it should be concluded in accordance with criterion b that $J_{ac}/J_{dc}<3$ indicates protection against ac-corrosion /see also 13/ and $J_{ac}/J_{dc}>3$ enhances corrosion risk. This should be taken into account if corrosion protection measures based on cp-adjustment is intended to be designed for a high voltage interfered pipeline: Enhancing the cp-level shall yield $J_{ac}/J_{dc}<3$ (and accompanied questions regarding coating disbondment, interference on third party structures and hydrogen embrittlement should be considered). For $J_{ac}/J_{dc}>10$ however the results

suggest a decreasing ac-corrosion likelihood meaning that adjustment of U_{on} , e.g. to a slightly more positive level, reduces corrosion risk possibly due to reduced alkalinity at the steel/medium interface.

For practical purposes the ratio J_{ac}/J_{dc} of current densities within a coating fault may be estimated from $U_{ac}/(U_{off}-U_{on})$, see equ. (1).

Note: It has non successfully been tried to evaluate data from /14,15/ according to the relation between w_{int} and J_{ac}/J_{dc} . Equ. (1) does not hold for provided data. Results for J_{ac}/J_{dc} are distributed with large deviations around the value for $U_{ac}/(U_{off}-U_{on})$ which is relatively constant due to constant conditions for U_{ac} and U_{on} . This result implies that further research is needed in order to fully understand the interplay between U_{ac} and the level of applied cathodic protection potential, i.e. U_{on} , which represent those parameters that are to be modified by the operator of a pipeline to achieve protection against ac-corrosion.

2.3 Criterion c): $U_{IR-free}(realtime) < -0,85V$ or $-0,95V$ in case of SRB present

As a matter of principle this criterion may be applied to a coating fault of a high voltage interfered pipeline if techniques to measure the IR-free potential as described in /16/ are used. The background of this criterion has been investigated extensively /10, 17, 18, 19/. The following considerations have been reported:

- Even fast data acquisition rate in the instantaneous off-potential measurement up to 1 MHz had turned out to be insufficient to detect the anodic polarization of the metal surface due to the ac-current load. No exceeding of the threshold could be observed in electrolyte solutions not containing calcium ions although ac-corrosion was taking place. In presence of calcium ions the depolarization of the metal surface is altered due to the formation of a chalk layer, resulting in an exceeding of the threshold even at ac-current densities that do not cause ac-corrosion. The strong dependence of the obtained data on the soil composition and the very fast depolarization of the metal surface make the instantaneous off-potential measurement a non suitable technique for the characterization of the ac-corrosion risk of cathodically protected structures /19/.
- Recently modifications of criterion c had been proposed /10, 18/:
 - whenever the maximum true peak potential is higher (i.e. less negative) than $-1200mV_{Cu/CuSO_4}$ there is a risk of corrosion. The risk is significant where peak potential exceeds $1200mV_{Cu/CuSO_4}$.
 - where maximum peak potential is always more negative than $-1200mV_{Cu/CuSO_4}$ there is no corrosion regardless of the environment and the value of the ac-currents.

Regarding the modified potential criterion it is interesting to note that cp-current density, i.e. J_{dc} needs to be high in to achieve that level of cathodic polarization. An example for non corrosive conditions in a soil according to this criterion is provided in /10, 18/ and the following data are given: $J_{ac}=197A/m^2$, $J_{dc}=84A/m^2$ yielding $J_{ac}/J_{dc}=2.3$, which also indicates corrosion protection if assessed according to criterion b).

Considering practical aspects it should be noted that at present techniques to measure $U_{IR-free}$ (realtime) on a high voltage interfered pipeline are restricted to coupons that are electrically connected to it. Therefore the comments given to criterion a) (see 2.1) apply.

2.4 Note on the use of pipe/ground potential U_{ac} as ac-corrosion criterion

According to /1/ criteria a) b) c) should be applied in case that $U_{ac} > 10V$ which may be interpreted in a way that $U_{ac} < 10V$ would indicate protection against ac-corrosion.

The results presented in chapter 2.2 suggest that in case of $U_{ac} = 6V$ corrosion rate is significantly lower compared to $U_{ac} = 10V$. From fig. 3a, however, it may be concluded that even at this low voltage an influence exists from the adjustment of cathodic protection.

An extensive field study on the impact of U_{ac} on corrosion rate may be found in /14,15/ where pipe/ground potentials between $5V < U_{ac} < 30V$ had been applied. Unfortunately field conditions were such that $J_{ac} < 30A/m^2$ for all coupons operated with $U_{ac} = 10V$ and $5V$, which may not reflect conditions that occur on high voltage interfered pipelines, where pitting had been found at U_{ac} around $4V-8V$ /4/.

Contributions to imply U_{ac} – probably in combination with additional parameters - as an aid to assess the ac-corrosion risk of a high voltage interfered pipeline are currently under discussion in working group CEN TC 219 WG 1 adhoc 4.

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Tables

Tab. 1: Test conditions for laboratory investigations in three different soils; series 1

	U_{on} (V)*	U_{ac} (V)	coupons
group A	-1,5	0	3A/C/F, 4 A/C/F
	-1,5	2	1 A/C/F, 2A/C/F, 5A/C/F, 6A/C/F
	-1,5	6	7A/C/F, 8A/C/F, 13A/C/F, 14A/C/F
	-1,5	10	9A/C/F, 10A/C/F, 11A/C/F, 12A/C/F
group B	-3,0	0	3B/D/E, 4B/D/E
	-3,0	2	1B/D/E, 2B/D/E, 5B/D/E, 6B/D/E
	-3,0	6	7B/D/E, 8B/D/E, 13B/D/E, 14B/D/E
	-3,0	10	9B/D/E, 10B/D/E, 11B/D/E, 12B/D/E
medium: soil from the righth of way of a high voltage interferred pipeline A and B –samples in soil I with $\rho \approx 70 \Omega m$ C and D –samples in soil II with $\rho \approx 150 \Omega m$ E and F –samples in soil III with $\rho \approx 90 \Omega m$			
test period: 150d;		bare steel surface of coupons: $0,5 cm^2$	

Tab. 2a: Results from laboratory measurements series A in soil I

U_{ac} (V)	probe no	$U_{on,av}$ (V)	$U_{off,av}$ (V)	$U_{ac} / (U_{off,av} - U_{on,av})$	$J_{ac,av}$ (A/m^2)	$J_{dc,av}$ (A/m^2)	$J_{ac,av} / J_{dc,av}$	l_{max} (mm)	$w_{l,max}$ (mm)
0	3A	-1,50	-1,07	0	2,90	3,90			
0	4A	-1,50	-1,04	0	0,50	2,20			
2	1A	-1,50	-1,08	4,76	23,30	4,20	5,55		
2	2A	-1,50	-1,08	4,76	18,60	3,10	6,00		
2	5A	-1,47	-0,99	4,17	21,10	3,40	6,21		
2	6A	-1,48	-1,07	4,88	17,90	2,90	6,17		
6	7A	-1,44	-1,08	16,67	75,20	3,60	20,89		
6	8A	-1,45	-1,09	16,67	74,30	3,60	20,64	0,05	0,16
6	13A	-1,47	-1,10	16,22	103,30	6,10	16,93	0,04	0,13
6	14A	-1,47	-1,06	14,63	97,80	6,30	15,52	0,04	0,13
10	9A	-1,44	-0,95	20,41	172,50	6,80	25,37	0,04	0,13
10	10A	-1,45	-1,09	27,78	79,00	3,20	24,69		
10	11A	-1,46	-1,07	25,64	156,00	6,00	26,00		
10	12A	-1,45	-1,05	25,00	154,30	6,40	24,11	0,04	0,13

Tab. 2b: Results from laboratory measurements series B in soil I

U_{ac} (V)	probe no	$U_{on,av}$ (V)	$U_{off,av}$ (V)	$U_{ac} / (U_{off,av} - U_{on,av})$	$J_{ac,av}$ (A/m^2)	$J_{dc,av}$ (A/m^2)	$J_{ac,av} / J_{dc,av}$	l_{max} (mm)	$w_{l,max}$ (mm)
0	3B	-2,94	-1,12	0	0,30	9,40			
0	4B	-2,95	-1,14	0	2,20	16,90			
2	1B	-3,00	-1,13	1,07	16,60	14,70	1,13		
2	2B	-3,00	-1,16	1,09	22,60	19,80	1,14		
2	5B	-2,83	-1,21	1,23	15,60	12,80	1,22		
2	6B	-2,80	-1,20	1,25	78,80	69,60	1,13		
6	7B	-2,87	-1,17	3,53	73,10	18,60	3,93		
6	8B	-2,89	-1,18	3,51	49,80	10,30	4,83	0,08	0,23
6	13B	-2,92	-1,21	3,51	43,10	13,40	3,22	0,04	0,11
6	14B	-2,91	-1,15	3,41	62,00	18,70	3,32	0,16	0,45
10	9B	-2,85	-1,14	5,85	122,70	33,30	3,68	0,27	0,76
10	10B	-2,85	-1,15	5,88	306,20	48,80	6,27	0,16	0,45
10	11B	-2,84	-1,19	6,06	156,60	23,40	6,69	0,24	0,68
10	12B	-2,82	-1,14	5,95	122,60	18,20	6,74	0,17	0,48

Tab. 2c,2d: Results from laboratory measurements series C,D in soil II

U_{ac} (V)	probe no	U_{on} adjusted to (V)	$J_{ac,av}$ (A/m ²)	$J_{dc,av}$ (A/m ²)	$J_{ac,av}/$ $J_{dc,av}$	I_{max} (mm)	$W_{i,max}$ (mm)
0	3C	-1,5	0,98	1,10	0,89		
0	4C	-1,5	3,17	1,90	1,67		
2	1C	-1,5	15,05	2,08	7,24		
2	2C	-1,5	10,95	1,41	7,77		
2	5C	-1,5	4,27	1,19	3,60		
2	6C	-1,5	3,25	1,10	2,95		
6	7C	-1,5	30,00	1,82	16,50		
6	8C	-1,5	47,50	3,64	13,06		
6	13C	-1,5	18,32	0,89	20,67	0,03	0,07
6	14C	-1,5	14,50	0,79	18,44	0,03	0,07
10	9C	-1,5	68,00	1,90	35,70		
10	10C	-1,5	64,00	2,00	32,07	0,03	0,07
10	11C	-1,5	85,86	2,41	35,64	0,14	0,33
10	12C	-1,5	45,23	1,58	28,67	0,03	0,07

U_{ac} (V)	probe no	U_{on} adjusted to (V)	$J_{ac,av}$ (A/m ²)	$J_{dc,av}$ (A/m ²)	$J_{ac,av}/$ $J_{dc,av}$	I_{max} (mm)	$W_{i,max}$ (mm)
0	3D	-3,0	1,30	8,27	0,16		
0	4D	-3,0	1,8	7,9	0,23		
2	1D	-3,0	4,8	6,2	0,77		
2	2D	-3,0	11,9	15,5	0,77		
2	5D	-3,0	12,2	13,4	0,91		
2	6D	-3,0	4,8	7,7	0,63		
6	7D	-3,0	14,8	5,1	2,92		
6	8D	-3,0	27,8	10,7	2,59	0,03	0,07
6	13D	-3,0	52,1	19,9	2,62		
6	14D	-3,0	13,6	4,4	3,13		
10	9D	-3,0	24,8	4,2	5,97	0,07	0,17
10	10D	-3,0	123,2	17,8	6,92	0,09	0,21
10	11D	-3,0	45,9	5,2	8,80	0,09	0,21
10	12D	-3,0	80,8	10,3	7,86	0,08	0,19

Tab. 2e,2f: Results from laboratory measurements series E,F in soil III

U_{ac} (V)	probe no	U_{on} adjusted to (V)	$J_{ac,av}$ (A/m ²)	$J_{dc,av}$ (A/m ²)	$J_{ac,av}/$ $J_{dc,av}$	I_{max} (mm)	$W_{i,max}$ (mm)
0	3E	-1,5	0,36	0,27	1,33		
0	4E	-1,5	0,8	0,4	2,00		
2	1E	-1,5	8,7	1,0	8,70		
2	2E	-1,5	20,6	2,2	9,36		
2	5E	-1,5	1,7	0,2	8,50		
2	6E	-1,5	19,5	3,0	6,50		
6	7E	-1,5	36,0	1,6	22,50		
6	8E	-1,5	40,6	1,9	21,37		
6	13E	-1,5	53,5	2,8	19,11	0,06	0,14
6	14E	-1,5	4,2	0,2	21,00	0,03	0,07
10	9E	-1,5	111,8	3,2	34,94		
10	10E	-1,5	79,3	2,2	36,05		
10	11E	-1,5	93,6	2,7	34,67	0,04	0,10
10	12E	-1,5	107,3	2,8	38,32		

U_{ac} (V)	probe no	U_{on} adjusted to (V)	$J_{ac,av}$ (A/m ²)	$J_{dc,av}$ (A/m ²)	$J_{ac,av}/$ $J_{dc,av}$	I_{max} (mm)	$W_{i,max}$ (mm)
0	3F	-3,0	9,25	90,91	0,10		
0	4F	-3,0	1,0	3,2	0,31		
2	1F	-3,0	62,6	81,6	0,77		
2	2F	-3,0	14,5	15,0	0,97		
2	5F	-3,0	9,7	42,5	0,23	0,03	0,07
2	6F	-3,0	7,8	55,3	0,14		
6	7F	-3,0	108,4	49,9	2,17		
6	8F	-3,0	103,3	55,8	1,85		
6	13F	-3,0	83,5	33,2	2,52		
6	14F	-3,0	108,4	42,8	2,53	0,04	0,10
10	9F	-3,0	314,6	58,4	5,39		
10	10F	-3,0	388,2	59,2	6,56	0,04	0,10
10	11F	-3,0	629,5	94,7	6,65	0,24	0,57
10	12F	-3,0	21,8	4,1	5,32	0,06	0,14

Tab. 3: Test conditions for laboratory investigations; series 2

	$J_{dc,t=0 \text{ to } 24h}$ A/m ²	$J_{ac,t=24h}$ A/m ²	$U_{ac,t=1d \text{ to } 100d}$ (V)	$U_{on,t=0 \text{ to } 100d}$ (V)	coupon
group I	100	70	9,4	-18,4	1
			8,0	-15,6	15
			8,5	-16,6	7
group II	30	70	8,8	-5,5	13
			9,6	-6,0	11
			12,4	-7,5	12
group III	3	70	22,6	-2,1	6
			15,3	-1,8	5
			18,5	-1,9	9
group IV	0,3	70	57,6	-1,03	14
			34,1	-0,95	8
			51,7	-0,99	16
medium: artificial soil solution with washed sand (pH app. 8);					
Test period: 100d					
Bare steel surface of coupons: 1,0cm ²					
artificial soil solution	concentration [mol/l]	concentration [mg/l]			
MgSO ₄ x 7 H ₂ O	2,5 x 10 ⁻³	617			
CaSO ₄ x 2 H ₂ O	2,5 x 10 ⁻³	430			
NaHCO ₃	2,5 x 10 ⁻³	210			
CaCl ₂	5 x 10 ⁻³	554			

Tab: 4: Results of measurements of series 2.

coupon	1	15	7	13	11	12	6	5	9	14	8	16
U_{ac} (V)	9,4	8	8,5	8,8	9,6	12,4	22,6	15,3	18,5	57,6	34,1	51,7
U_{on} (V)	-18,4	-15,6	-16,6	-5,50	-6,00	-7,50	-2,10	-1,80	-1,90	-1,03	-0,95	-0,99
$U_{off,av}$ (V)	-1,45	-1,40	-1,36	-1,08	-1,07	-1,14	-0,95	-0,94	-1,10	-0,79	-0,78	-0,73
$J_{ac,av}$ (A/m ²)	135	119	84	68	65	57	78	82	103	170	127	198
$J_{dc,av}$ (A/m ²)	151	139	111	29	29	25	3,6	3,9	6,1	0,7	0,6	1,0
pH on steel surface	12,0	12,0	12,0	12,0	11,8	11,2	5,0	11,0	10,2	10,0	10,0	6,0
w_{max} (mm/a)	0,019	0,015	0,050	0,069	0,062	0,102	0,063	0,018	0,048	0,054	0,029	0,070

Figures

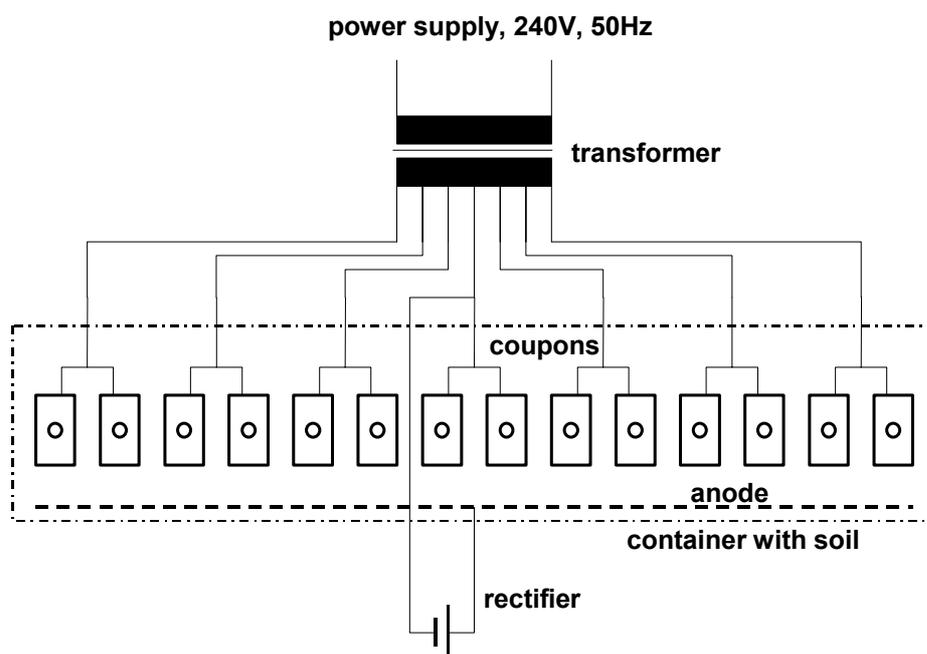


Fig. 1

Schematic drawing of the electric circuit for the tests of series 1. J_{dc} and J_{ac} are measured for each coupon as voltage drops (u_{ac} and u_{dc}) across 10Ω resistors (u_{ac} is measured as rms, u_{dc} is measured with high attenuation (80db)). To measure U_{off} each coupon could be temporarily disconnected from the electric circuit.

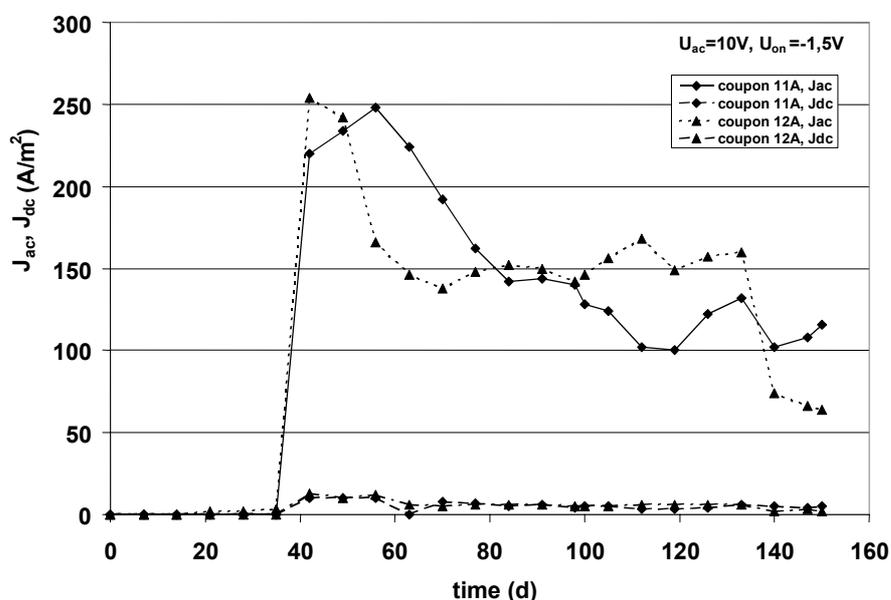


Fig. 2a:

J_{dc} and J_{ac} vs. time for coupons 11A and 12A in soil I

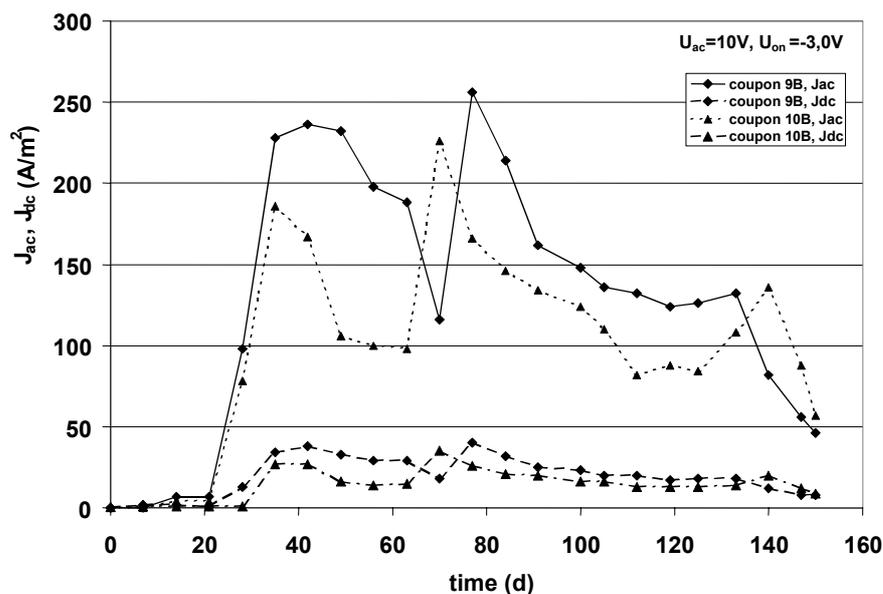


Fig. 2b:
 J_{dc} and J_{ac} vs. time for coupons 9B and 10B in soil II

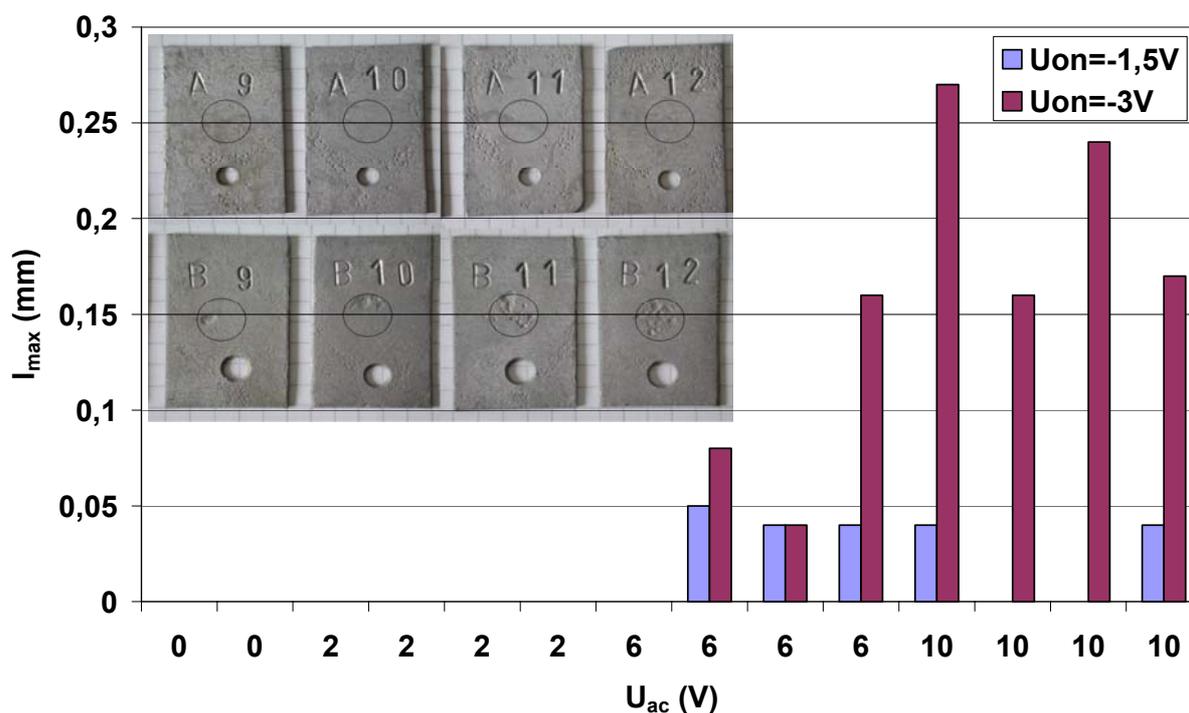


Fig. 3a: Maximum pit depth of coupons from series A (U_{on}=-1,5V), B (U_{on}=-3V) in soil I. The black circle on each coupon indicates the 0,5cm² bare steel area. Minor corrosion pits that are visible outside of the circle are due to disbondment of the coating material (silicon) and successive penetration of electrolyte solution.

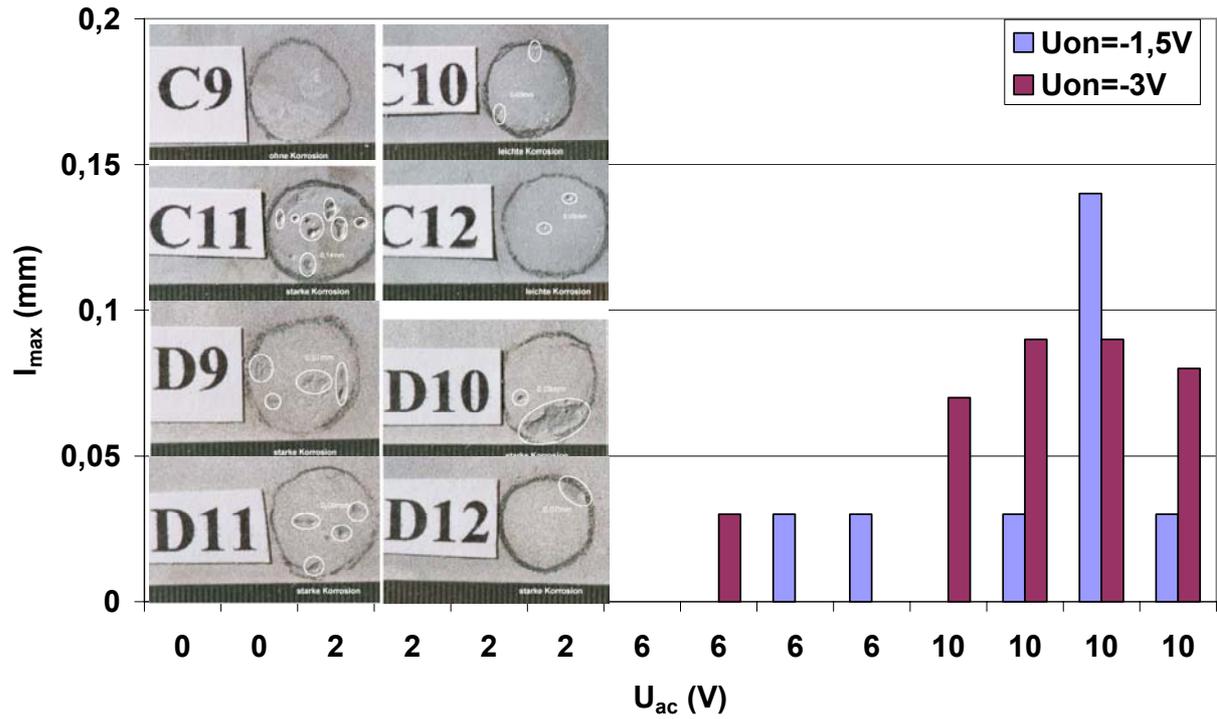


Fig. 3b: Maximum pit depth of coupons from series C ($U_{on}=-1,5V$), D ($U_{on}=-3V$), in soil II

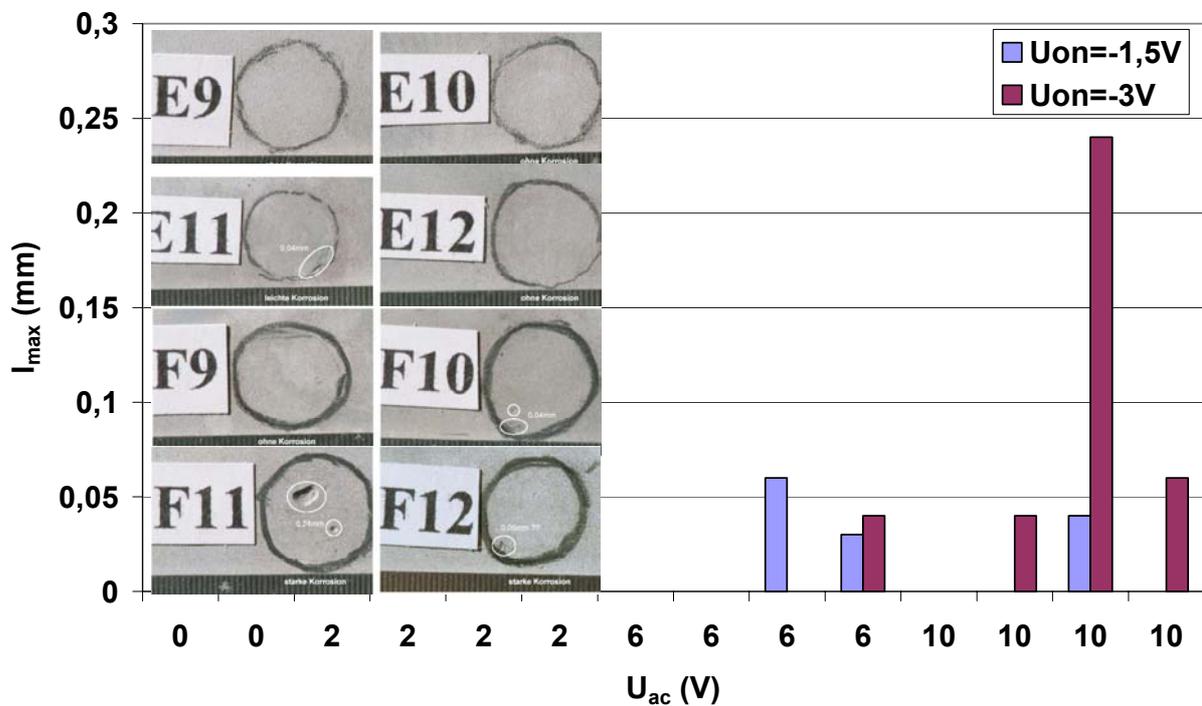


Fig. 3c: Maximum pit depth of coupons from series E ($U_{on}=-1,5V$), F ($U_{on}=-3V$), in soil III

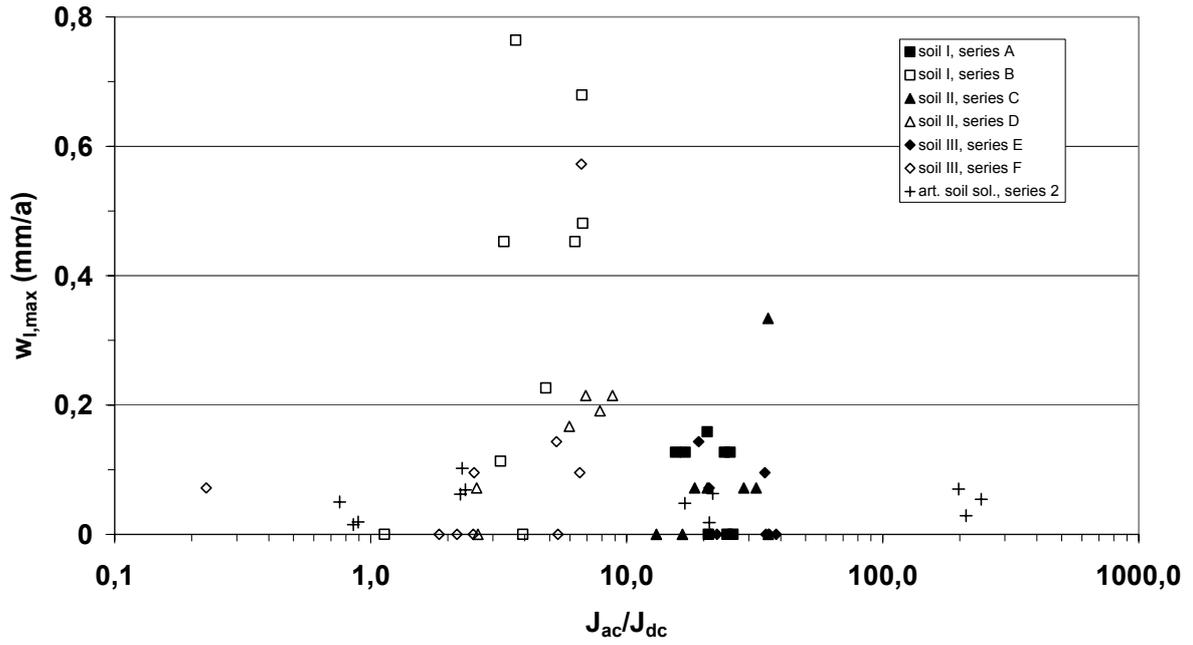


Fig. 4: Corrosion rate v_{corr} for all coupons of series 1 and 2 showing $J_{ac,av} > 30 A/m^2$ as a function of J_{ac}/J_{dc} .

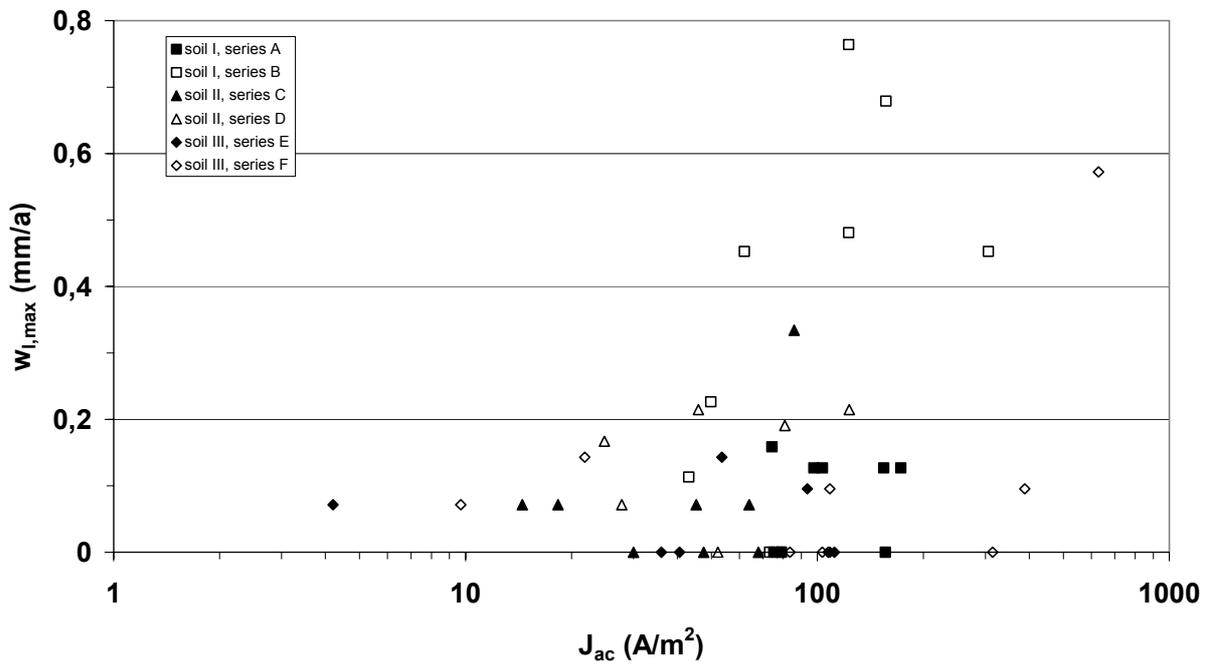


Fig. 5: Corrosion rate v_{corr} for all coupons of series 1 as a function of J_{ac} .