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STATISTICAL EVALUATION OF RESULTS FROM A.C. CORROSION FIELD TESTS

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ABSTRACT

During some years alternating current (a.c.) corrosion has been studied in soil on steel test coupons, which were provided with cathodic protection, and exposed to constant a.c. voltage. The test site is located in the southern part of Sweden. Three test series with different a.c. voltage exposure have been performed: 30 V during 1½ year, 10 V during 2 years and 5 V during 1½ year. Sixteen test coupons of various area have been used in each series, half of them in clay and half of them in sand. Uniform corrosion and maximum local corrosion have been measured on each coupon.

Consequently, the large number of test coupons exposed for a.c. corrosion during very well controlled conditions gives a good possibility to statistically evaluate how the corrosion rate is correlated with measurable parameters such as a.c. voltage level, a.c. current density, coupon area, type of soil (sand or clay), and ratio between a.c current density and d.c. current density. This article presents the results of such a statistical evaluation. There is a clear tendency that the corrosion rate increases with increased a.c. voltage and increased a.c. current density. However, the variations are large, and there seems to be important parameters, which are not controlled. Even in cases, where the preconditions seem to be almost identical, the corrosion rates differ very significantly.

Hopefully this analysis can trigger similar statistical evaluations regarding a.c. corrosion correlation based on other test and investigations in Europe. Of special interest is to compare with results from significantly longer exposure.

1. Introduction and background

Since 1996 alternating current (a.c.) corrosion has been studied in soil on steel test coupons in southern Sweden. The test coupons were provided with cathodic protection and exposed to constant a.c. voltages but to different a.c. densities. Three series of tests were performed, one with 5 Vac during 1½ year, one with 10 Vac during almost two years, and a third one with 30 Vac during approx. 1½ year. 16 test coupons were used in each test series. In addition 12 reference coupons were used in the 5V-series. The test installation and the result has been described in [1] and [2]. These coupons realistically simulated a steel surface in a coating damage on a cathodically protected steel pipeline, which is exposed to an electrical influence for long time from a high voltage source with a 50 Hz alternating voltage.

The large number of results from the a.c. corrosion field tests, which were carried out under well-controlled conditions, is a reasonable good base for statistical evaluation of any possible correlation of a.c. corrosion with measurable parameters. However, the variations are large, and there seem to be important parameters, which are not controlled. The large variations also make that a single measured value can have a significant impact on the statistical result. Therefore, the result from the statistical evaluation must be interpreted with care.

2. Types of corrosion and corrosion rates

Two types of corrosion have been evaluated on the test coupons, which were exposed to a.c. current in soil. Uniform (or average) corrosion was evaluated by measurement of the weight loss after the exposure period. The weight loss (expressed as g per year and per m^2 steel area) was then recalculated to an anticipated uniform corrosion rate all over the exposed steel area, expressed as µm/year. Maximum local corrosion attack was evaluated by identification of the deepest local attack and measurement of the depth in a microscope. The depth was then recalculated to max. local corrosion rate.

3. Correlation

The first attempt to evaluate the correlation was to calculate the different correlation factors between corrosion and other parameters, starting from the one suggested as criteria. However, due to the large variation, all correlation factors were quite low, as seen in Table 1.

The next step was to test the hypothesises by using the T-distribution for changes in the mean value (average) and the F-distribution for changes in variation. The P-values in Table 1 indicate the probability that the mean value and the variation respectively of the corrosion depend on the parameters. As a general rule, the P-value should be higher than 95 % for being considered as statistically significant. Anyhow, the P-value gives a reasonable good indication. It can be noted that the changes of the variation is more significant than the changes of the mean value.

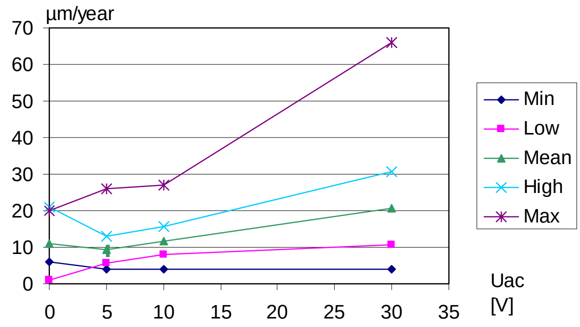
Table 1: Correlation factors for the corrosion of all coupons.

Uniform Corrosion Correlation		
Parameter	**Correlation factor**	**P-value [%] (mean/var)**
Jac	0.62	96.7 / 99.9
Jac/Uac	0.53	>99.9 / >99.9
Max Loc Corr	0.52	99.8 / >99.9
Uac	0.40	95.9 / >99.9
Iac	0.36	89 / 95.8
Area	-0.28	79 / 99.8
Jac/Jdc	0.15	46 / 95.7
Soil type	0.04	21 / 87
E_{Off}	0.03	88 /99.9
Resistance	0.02	90.3 / 99.9

Maximum Local Corrosion Correlation		
Parameter	**Correlation factor**	**P-value [%] (mean/var)**
Jac	0.74	>99.9 / >99.9
Iac	0.68	>99.9 />99.9
Uac	0.67	>99.9 / >99.9
Jac/Uac	0.58	99.5 / >99.9
Unif. Corr	0.52	94.9 / 99.9
Jac/Jdc	0.48	98.2 / >99.9
Resistance	-0.28	99.0 / >99.9
Area	0.23	71.5 / 98.2
E_{Off}	0.08	92.3 / >99.9
Soil type	0.05	25.1 / 97.5

In addition to the values in Table 1, the Figure 1 to Figure 6 show the variations graphically for some important parameters, a.c. voltage U_{ac}, a.c. current density J_{ac}, and the ratio between a.c. and d.c. current density J_{ac}/J_{dc}. The scale for the corrosion rate is µm/year.

For definition of the different curves in the figures, see Section 5 below.



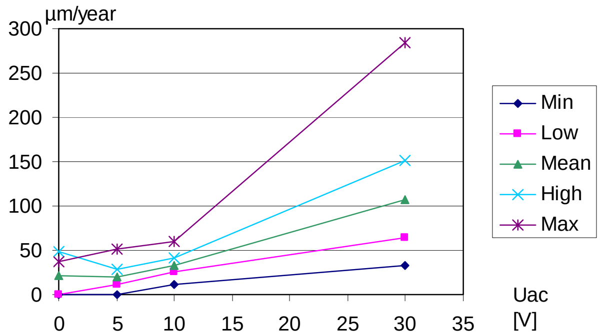
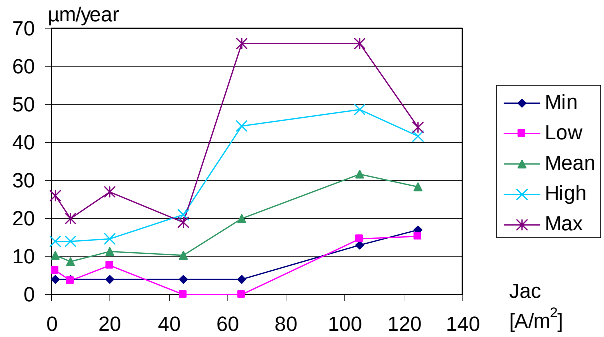


Figure 1: Uniform corros. as function of Uac. **Figure 2: Max local corros. as function of Uac.**



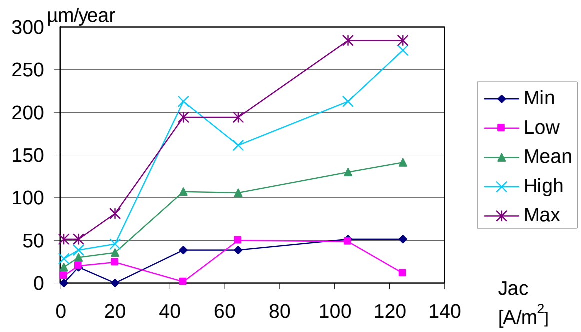
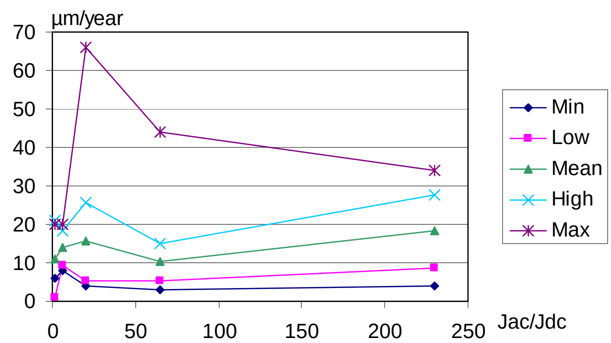


Figure 3: Uniform corrosion as function Jac. **Figure 4: Max local corrosion as function of Jac.**



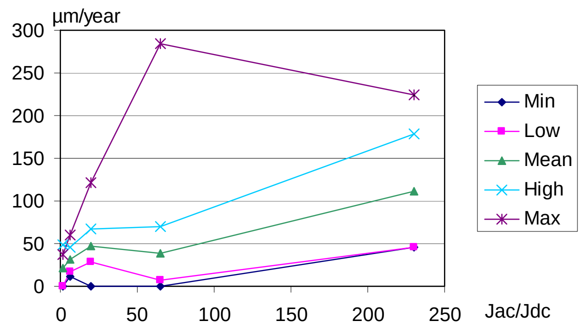


Figure 5: Uniform corr. as function of Jac/Jdc **Figure 6: Max local corr. as function of Jac/Jdc.**

4. The worst cases

As the worst cases of corrosion are of most importance, the 25 % of the coupons with the worst uniform corrosion and the worst local corrosion respectively, was selected and the correlation factors were calculated, see Table 2. The correlation factors are much more significant for the individuals with the highest corrosion than for the total set, compare Table 2 with Table 1. However, at looking at the detailed distribution in Figure 7 to Figure 14, it can be seen that single results impact the correlation factor a bit too much. There are too few values with high corrosion values for giving trustful results. Thus, the result is an indication, but must be interpreted with care.

Table 2: Correlation factors for the corrosion (only the 25 percent of the coupons with the worst corrosion from each test).

Uniform Corrosion Correlation	
Parameter	**Correlation factor**
Uac	0.74
Max Loc. Corr	0.69
Jac	0.65
Jac/Uac	0.54
Iac	0.43
Soil type	-0.37
Area	0.31
Resistance	-0.31
E_{Off}	0.24
Jac/Jdc	0.09

Max Local Corrosion Correlation	
Parameter	**Correlation factor**
Jac	0.94
Iac	0.91
Uac	0.90
Jac/Uac	0.88
Jac/Jdc	0.74
Unif. Corr	0.56
Soil type	0.45
Resistance	-0.29
E_{Off}	0.12
Area	0.09

As a complement to Table 2 the detailed distributions of the corrosion rate for the 25 % worst coupons as function of a.c. voltage U_{ac}, a.c. current density J_{ac}, the a.c. conductance J_{ac}/U_{ac} and the ration between a.c. and d.c current density J_{ac}/J_{dc} are shown in Figure 7 to Figure 14. The scale for the corrosion rate is µm/year.

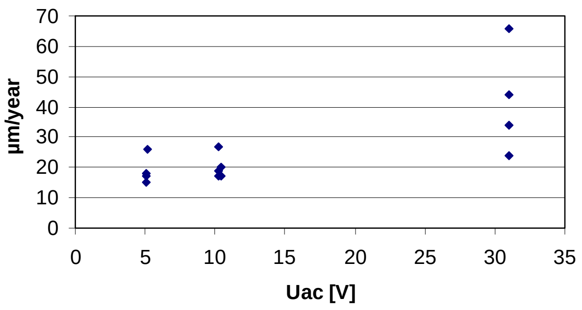


Figure 7: Worst uniform corros. related to U_{ac}.

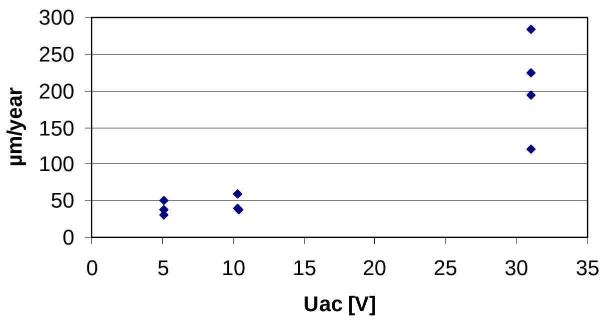


Figure 8: Worst max local corros. related to U_{ac}.

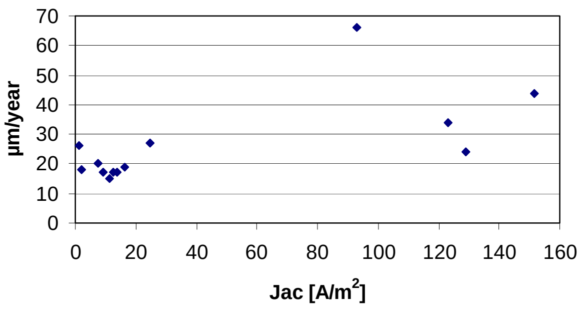


Figure 9: Worst uniform corr. related to J_{ac}.

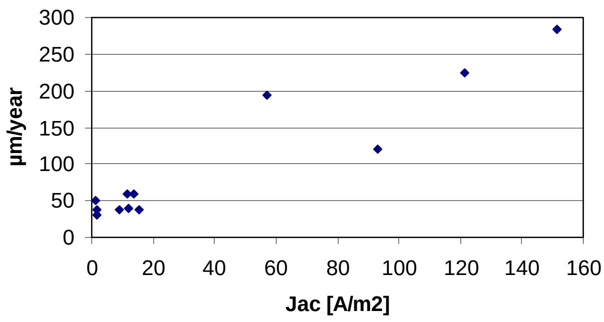


Figure 10: Worst max local corr. related to J_{ac}.

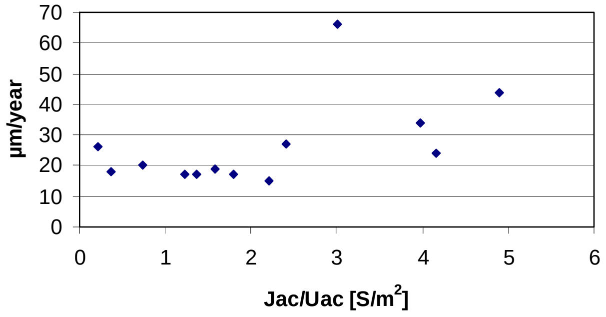


Figure 11: Worst unif. corr. related to J_{ac}/U_{ac}.

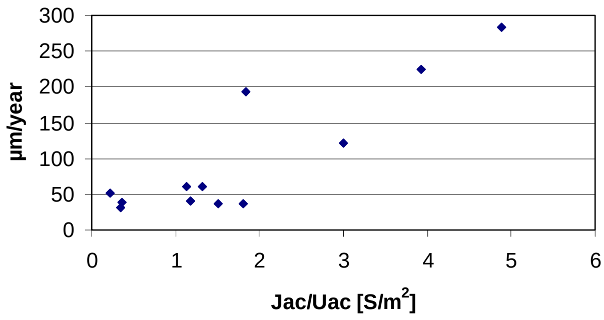


Figure 12: Worst max local corr. related to J_{ac}/U_{ac}

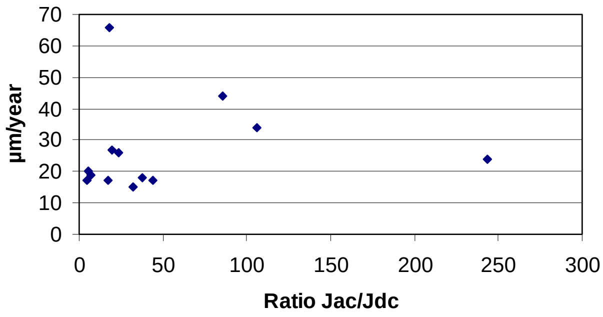


Figure 13: Worst unif. corr. related to J_{ac}/J_{dc}.

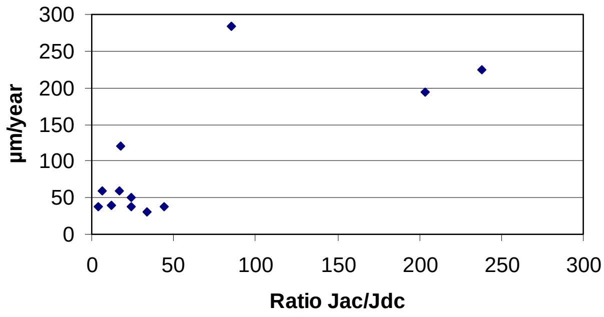


Figure 14: Worst max local corr. related to J_{ac}/J_{dc}.

Comments:
The four high values from the 30 V series are dominating the picture completely. As an overview, the correlation with the a.c. voltage Uac seems to be most reliable. Of the parameters in Figure 7 to Figure 14 the ratio between a.c and d.c current density J_{ac}/J_{dc} seem to be the least useful one.

5. Definitions of designations used in the figures

The following designation is used in the figures.

- 97.5 % Statistically 97.5 % of the values should be below this value. This curve is only given in some figures.
- Max Maximum recorded level within the group.
- High Upper 95 % confidence value for the mean value.
- Mean Average of the values within the group.
- Low Lower 95 % confidence value for the mean value.
- Min Minimum recorded level within the group.

The span between "High" and "Low" indicates the uncertainty of the mean value both considering the variation and the number of samples in the group.

The Y-values within the group corresponds to the coupons with X-values within the group as defined in Appendix A.

6. Correlation with some other parameters

Also the correlation between a.c. corrosion and some other parameters have been investigated graphically. This in addition to the correlation figures in Table 1 and Table 2.

6.1. Correlation with a.c. current, coupon area, and soil type

The correlation of the corrosion rate with a.c. current, coupon area, and soil type is graphically illustrated in Figure 15 to Figure 20. The corrosion rate is given in µm/year.

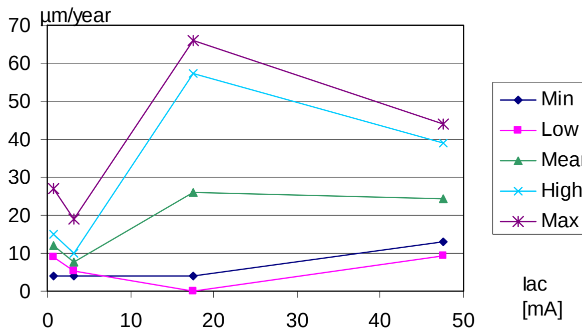


Figure 15: Uniform corrosion related to I_{ac}.

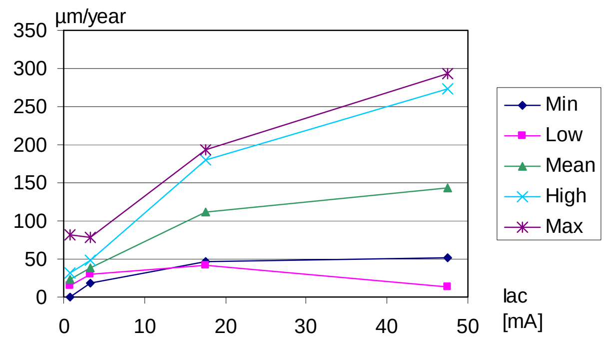


Figure 16: Max local corrosion related to I_{ac}.

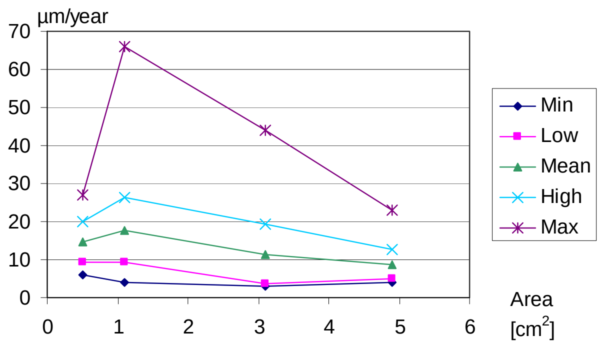


Figure 17: Uniform corrosion related to area.

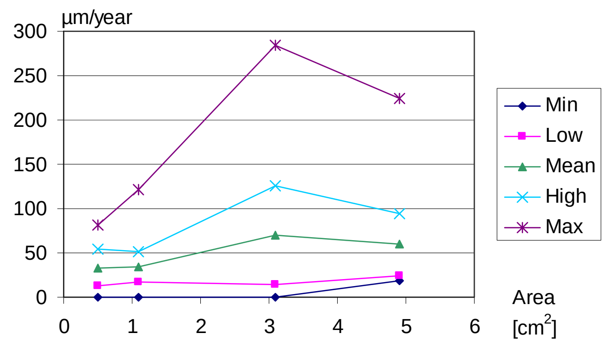


Figure 18: Max local corrosion related to area.

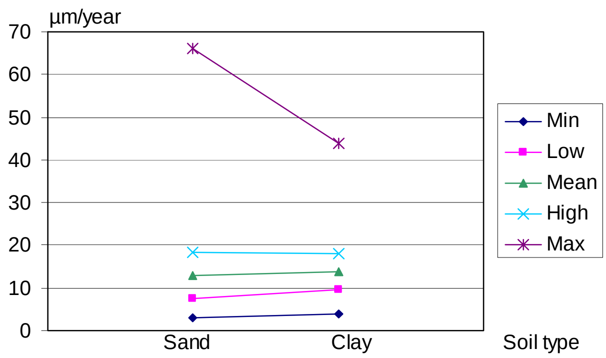


Figure 19: Uniform corrosion related to soil.

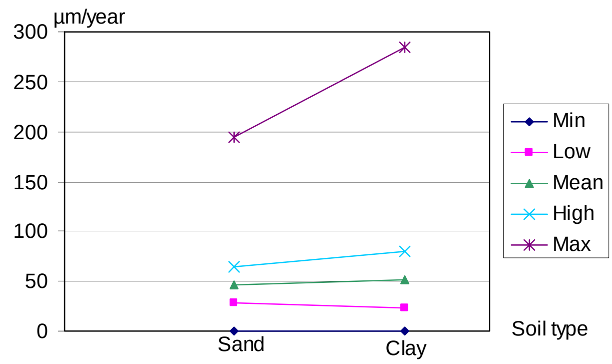
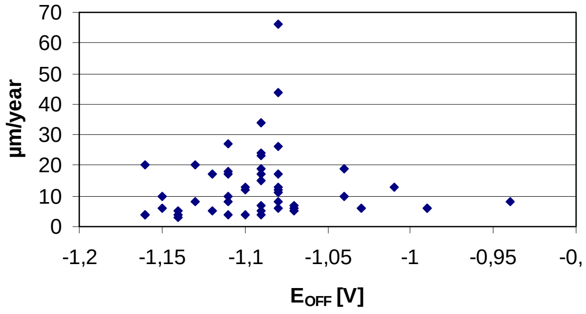


Figure 20: Max local corrosion related to soil.

6.2. Correlation of corrosion rate with EOFF

Figure 23 and Figure 24 demonstrates the correlation of uniform corrosion and max local corrosion respectively with the pipe-to-soil OFF-potential E_{OFF}.



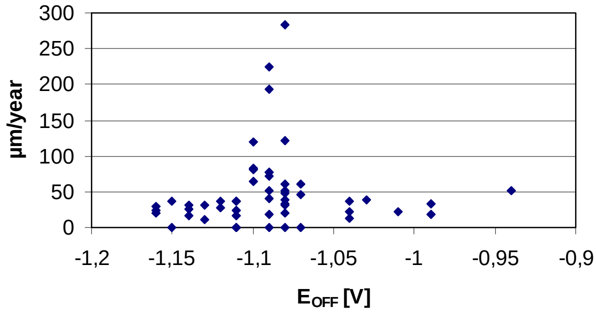


Figure 21: Uniform corrosion related to E_{OFF}. **Figure 22: Max local corrosion related to E_{OFF}.**

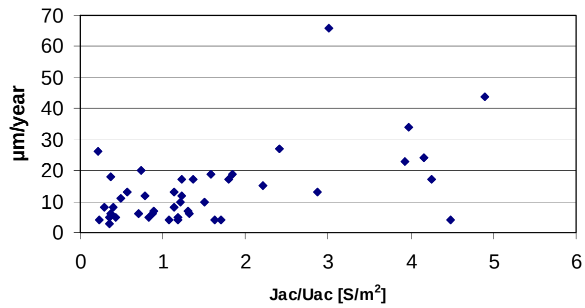
Comment:

The reason for the high corrosion around E_{OFF} = -1.1 V is that the measured E_{OFF} values from the 30 V series are in the range from –1.10 V to –1.07 V.

Statistically the corrosion depends on the measured values of E_{OFF}. However, the result is a bit confusing.

6.3. Correlation of corrosion rate with a.c. conductance

Table 2, Figure 9 and Figure 12 indicate that the corrosion rate for the 25 % worst cases from each test is correlated to the a.c. conductance J_{ac}/U_{ac}. Figure 25 and Figure 26 show the correlation for all coupons.



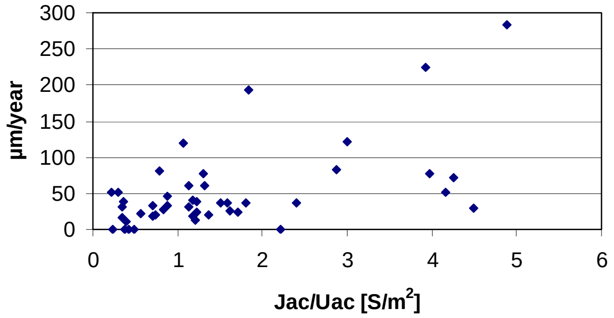


Figure 23: Unif. corrosion related to J_{ac}/U_{ac}. **Figure 24: Max local corrosion related to J_{ac}/U_{ac}.**

6.4. Correlation of a.c. conductance with soil type and area

A.C. voltage and a.c. current density are both important parameters for evaluation of the risk for a.c. corrosion. As the relation between these two important parameters a.c. conductance it is of interest to study also how the a.c conductance is correlated to some other parameters. Figure 25 and Figure 26 show how the current density in S/m^2 depends on the coupon area in sand and clay respectively.

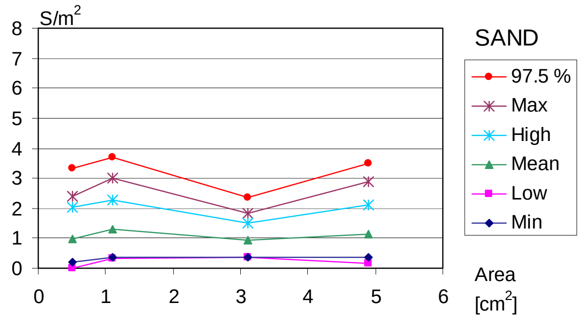


Figure 25: A.C conductance correlation with coupon area in sand.

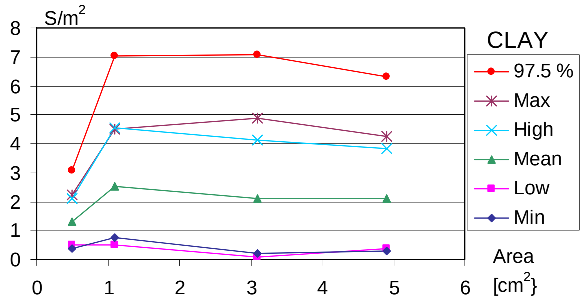


Figure 26: A.C conductance correlation with coupon area in clay.

Comments:
The a.c. conductance is about twice as high in clay than in sand, which could be expected. Thus, also the a.c. current density is in mean twice as high in clay than in sand.

Theoretically the a.c. current conductance/m^2 should decrease with increased area. No such tendency can be found in Figure 25 and Figure 26.

The variation of the current density is significant. Thus, the a.c. current is not easy to predict precisely by calculations based on external end geometrical conditions.

6.5. Variation of conductance with voltage – it is not linear

Figure 27 and Figure 28 indicate that the a.c. conductance varies with the a.c. voltage both in sand and in clay.

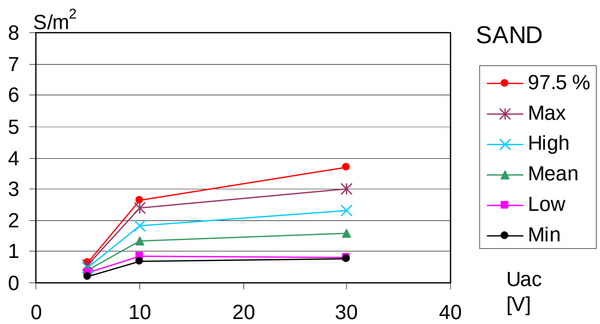


Figure 27: A.C conductance variation with. a.c. voltage in sand.

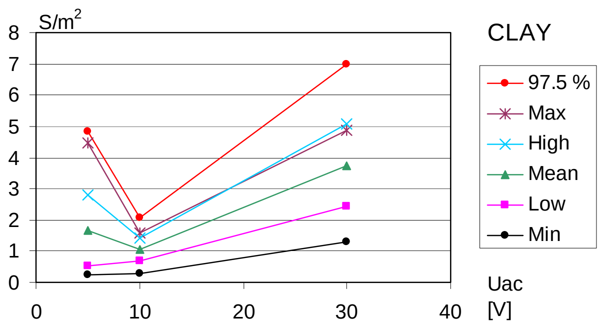


Figure 28: A.C conductance variation with a.c. voltage in clay.

The a.c. conductance increases with the voltage, most clearly for the sand coupons. This means that the a.c. current is not only determined by the nominal resistivity of the material. It is most likely that the very local electrochemical process is important for the conductance.

7. Some interesting findings

If current density should be a better criteria for a.c. corrosion than a.c. voltage one could expect the corrosion rate to be clearly correlated to the ratio Jac/Uac, which is the a.c. conductance per m^2. Figure 23 and Figure 24 do not necessarily support such a conclusion. Besides, Section 6.4 shows that the mean value of the current density is twice as high in clay than in sand, but Figure 19 and Figure 20 do not indicate any higher corrosion rate for the coupons in sand. Although the variation is significant, this weakens the importance of the a.c. current density J_{ac}. However, for the 25 % worst cases there is a better correlation between corrosion rate and a.c. conductivity, see Figure 11 and Figure 12, at least for maximum local corrosion.

One unexpected observation is that the maximum local corrosion seems to have a correlation with the total a.c. current Iac, which is as good as the correlation with the a.c. current density Jac, see Figure 16 and Figure 4. For the uniform corrosion the a.c. current density seems to be more important than the total current, see Figure 15 and Figure 3.

From Figure 17 and Figure 18 it can be concluded that the uniform corrosion tends to decrease with increased coupon area while the maximum local corrosion tends to increase. Furthermore, the corrosion rate seems to be independent on soil type, see Figure 19 and Figure 20. However, the variation may depend on the soil type.

It is hard to correlate the corrosion rate with the measured E_{OFF}-potential, see Figure 21 and Figure 22.

One very interesting finding is that the ratio Jac/Uac increases with increased voltage, see Figure 27 and Figure 28. Thus the behaviour is non-linear. Besides, the variation is large. This stresses the importance of the a.c. voltage.

An observation is that the uniform corrosion and the maximum local corrosion are related to each other, but they can have quite different pattern.

There is no clear relation between the a.c. corrosion rate and any of the parameters investigated. Higher a.c. voltage, higher a.c. current density and even higher a.c. current are related to higher mean values and higher variation of a.c. corrosion rate, but the picture is fuzzy. No other criterion seems to be better than the a.c. voltage Uac as a risk criterion. However, the variation is very significant, regardless of applied criterion.

8. Discussions

Although the correlation between corrosion and a.c. voltage and the correlation between corrosion and a.c. current density are of the same magnitude, the practical use of these two parameters as a risk criterion differs essentially in the practicability. For reference see [2]. The observed large seasonal and weather dependent variations in earthing resistance of the exposed steel surfaces during the exposure periods, which was reflected in corresponding variations in a.c. current density, makes it difficult to use a.c. current density as a risk criterion in the practice. An instantaneous measurement value could thus be fully misleading. The time period for obtaining a reliable measurement value would be in the order of one year for covering seasonal variations. Using a.c. voltage as a risk criterion involves no such problems in the practice. The actual measured a.c. voltage of the pipeline can be recalculated to “the worst case” by comparing the actual loading with the maximum loading of the inducing a.c. power line.

It also should be noted, that due to the large variation, several coupons are needed for establishing the a.c. current and a.c. current density with any reasonable accuracy.

Due to the fact that some of the coupons were partly covered with limestone, only a fraction of the coupon area was exposed for the a.c. current. Thus the very local a.c. current density was much higher that the mean one, which was recorded as the actual one. This, much higher a.c. current density on a fraction of the coupon area may explain the high maximum local corrosion on some coupons. It was also noted at analysis of coupons after the tests, that for some coupons the corrosion was very uneven [1], [2]. The limestone deposition on the coupons can seriously disturb measurement of the a.c. current density, as the area may be smaller that thought to be. This is another obstacle in practical establishment of the a.c. current density, in addition to the time seasonal variation of the spread resistance.

Although the number of test coupons from the Swedish field test site is significant, the total number still is quite low for precise statistical evaluation, especially as the variations are so large. Besides, the test results are just from one physical installation. Even if some of the test coupons were put in sand, the water from the surrounding clay area also penetrated the sand. Thus, the coupons installed in sand may not be representative for sandy areas with significantly soil resistivity. Thus, it would be very interesting with a similar statistical evaluation on other and larger results from a.c. corrosion tests.

Besides it could be interesting with results from test with longer durations as it seems as the initial corrosion at installation of the test coupons might impact the result, at least at low a.c. voltage and low corrosion rate.

9. Conclusion

The a.c. corrosion test in the Swedish test site has been performed under quite controlled conditions. The results from a significant number of test coupons were available for three test series at 5V, 10 V and 30 V applied a.c. voltage. This could be a perfect material for a statistical analysis for finding the correlation between the corrosion rate and the different stress parameters. However, also at those controlled conditions there are large variations in the corrosion rates and the complete picture is fuzzy. Both uniform corrosion and maximum local corrosion has been investigated for coupons with different area.

The mean value and particularly the variations are found to increase with increased a.c. voltage, increased a.c. current density and even increased a.c. current. However, the corrosion rate was about the same in sand and in clay although the current density was twice as high in clay as in sand.

None of the investigated parameters was better correlated to the corrosion rates than the a.c. voltage.

10. References

[1] Camitz G & Johansson C & Marbe Å: Alternating current corrosion on cathodically protected steel in soil – A long-term field investigation. CEOCOR 5th International Corrosion Congress, Brussels May 2000. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.

[2] Camitz G & Persson C & Lundberg R: Alternating current corrosion of cathodically protected steel in soil - Field investigation with low constant AC voltage. CEOCOR 6th International Corrosion Congress, Giardini Naxos,Sicily, Italy, 13-16 May 2003. Available at: CEOCOR, c/o C.I.B.E, Rue aux Laines 70, B-1000 BRUSSELS, Belgium.

Appendix A

Detailed information about data used

Table A.1 show how the date was grouped before used in the statistical evaluation.

Table A.1: Definition of groups used in the statistical evaluation. The corrosion is given in [μm/year].

Groups Uac [V]		
Group	Mean	No.
0	0.0	4
5.11-5.13	5.0	16
10.2-10.5	10.0	15
30-31	30	14

Groups Area [cm^2]	
Group	No.
0.5	10
1.1	15
3.1	12
4.9	12

Groups Iac [mA]		
Group	Mean	No.
0.0-1.5	0.75	24
1.5-5	3.25	15
5-30	17.5	5
30-65	47.5	5

Groups Resistance [kΩ]	
Group	No.
0.57-3	10
3-10	15
10-30	12
30-91	12

Groups Jac [A/m^2]		
Group	Mean	No.
0-3	1.5	14
3-10	6.5	8
10-30	20	60
30-60	45	4
30-100	65	6
60-150	105	7
100-150	125	5
Note. Overlapping groups		

Groups E_{Off} [V]	
Group	No.
-1.16;-1.10	21
-1.11;-0.94	28

Groups Jac/Uac [S/m^2]	
Group	No.
0.2-1	17
1-2	16
2-4.9	9

Groups of Soils		
Soil type	Resistivity	No.
1. Sand	190 Ω*m	25
2. Clay	18 Ω*m	24

Group Uniform Corrosion	
Group	No.
3-5	11
6-9	12
10-15	10
16-66	16

Groups Max Local Corrosion	
Group	No.
0-19	12
20-50	22
51-285	15

The complete database for the statistical evaluation is shown in Appendix B, which is a summary of the result from the test site described in [1] and [2].

Appendix B

Table B.1: Source data for the statistical evaluation. Corrosion is given in [μm/year].

Coupon	Soil	Area	E_{OFF}	U_{ac}	I_{ac}	J_{ac}	J_{ac}/J_{dc}	R	Uniform Corros.	Max local Corr
333	1	0,5	-1,08	5,11	0,13	2,52	71,71	63570	11	0
331	1	0,5	-1,08	5,13	0,06	1,14	23,79	90420	26	51
332	2	0,5	-1,09	5,11	0,56	11,3	32,47	24960	15	0
334	2	0,5	-1,13	5,13	0,1	2,02	43,62	40750	8	11
342	1	1,1	-1,11	5,11	0,21	1,89	37,43	37550	18	0
336	1	1,1	-1,01	5,13	0,32	2,93	28,91	19320	13	23
348	2	1,1	-1,12	5,11	1,01	9,19	44,17	13990	17	37
340	2	1,1	-1,16	5,13	2,53	23,01	45,79	2210	4	30
328	1	3,1	-1,14	5,12	0,56	1,8	36,77	8980	3	17
326	1	3,1	-1,07	5,13	0,69	2,21	28,42	8330	5	0
330	2	3,1	-1,12	5,11	1,31	4,23	35,94	4450	5	27
327	2	3,1	-1,11	5,13	0,37	1,18	33,23	10480	4	0
324	1	4,9	-1,14	5,11	0,88	1,8	33,47	5670	5	31
323	1	4,9	-1,03	5,13	0,91	1,85	23,95	6150	6	38
325	2	4,9	-1,14	5,13	4,08	8,33	35,81	1400	4	25
322	2	4,9	-1,16	5,13	4,29	8,76	48,63	1250	4	24
290	2	4,9	-0,94	10,45	1,53	3,12	26,00	51324	8	51
291	1	4,9	-1,09	10,29	3,75	12,11	11,76	3835	4	40
292	2	4,9	-0,99	10,28	3,57	7,29	48,60	19849	6	19
293	1	4,9	-1,08	10,32	3,62	11,69	6,35	3181	8	60
294	2	3,1	-1,07	10,34	4,25	13,7	16,51	2907	6	60
295	1	3,1	-1,09	10,29	3,75	12,11	11,76	3835	5	19
296	2	3,1	-1,08	10,32	3,62	11,69	6,35	3181	13	31
297	1	3,1	-0,99	10,28	3,57	7,29	48,60	19849	6	34
298	2	1,1	-1,04	10,28	1,79	16,27	7,36	10668	19	36
299	1	1,1	-1,11	10,36	1,72	15,61	4,18	25460	10	37
300	2	1,1	-1,16	10,39	0,85	7,71	5,28	17250	20	20
301	1	1,1	-1,04	10,28	1,37	12,49	5,31	57725	10	12
302	2	0,5	-1,11	10,42	0,64	12,77	4,97	29955	17	24
303	1	0,5	-1,11	10,25	1,23	24,69	19,44	57205	27	36
304	2	0,5	-1,08	10,29	0,7	14,02	17,10	30857	17	21
272	2	4,9	-1,09	30	62,56	127,7	354,72	1570	17	72
273	1	4,9	-1,07	31	13,44	27,4	195,71	6904	7	46
274	2	4,9	-1,09	31	59,56	121,6	238,43	569	23	225
275	1	4,9	-1,1	31	43,56	88,9	78,67	1316	13	83
276	2	3,1	-1,09	31	40	129	243,40	998	24	52
277	1	3,1	-1,1	31	10,33	33,3	175,26	7138	4	119
278	2	3,1	-1,08	31	47	151,6	85,65	1438	44	284
279	1	3,1	-1,09	31	17,67	57	203,57	3305	19	194
280	2	1,1	-1,09	31	13,56	123,3	106,29	3384	34	77
281	1	1,1	-1,08	31	4,18	38	55,07	18191	12	39
283	1	1,1	-1,08	31	10,24	93,1	17,90	2249	66	121
284	2	0,5	-1,09	31	2,01	40,2	25,77	28809	7	78
285	1	0,5	-1,1	31	1,21	24,2	20,51	34865	12	81
287	1	0,5	-1,08	31	1,36	27,2	34,00	57643	6	33
349	1	1,1	-1,13	0	0	0	0,00	31690	20	32
329	1	1,1	-1,11	0	0	0	0,00	32110	8	17
344	2	1,1	-1,15	0	0	0	0,00	5090	6	37
338	2	1,1	-1,15	0	0	0	0,00	6600	10	0

As a complement Table B.2 list date for some coupons not included in the statistical evaluation as they were corroded outside the defined area.

Table B.2: Data not used in the statistical evaluation

Coupon	Soil	Area	EOFF	Uac	Iac	Jac	Jac/Jdc	R	Uniform Corr	Maximum local Corr
305	1	0,5	-1,04	10,25	0,42	8,5	4,67	33829	NA	22
282	2	1,1	-1,1	31	4,89	44,5	13,69	6094	NA	64
286	2	0,5	-1,08	31	47	940	85,77	33400	NA	48

Note: The coupons listed in Table B.2 were not used in the statistical evaluation as they were corroded outside the defined area, underneath the plastic insulation.