Alternating current corrosion on cathodically protected steel in soil –

Field investigation with low constant AC voltage

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Abstract

Alternating current corrosion has been studied in soil on steel test coupons, which were provided with cathodic protection and exposed to constant AC voltages but to different AC-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. 16-28 test coupons were used in each test series. This report describes the results from the present 5V-series and they are compared with the results from the earlier 10V- and 30V-series. The 10V- and 30V-series have been reported in detail previously.

The corrosion rates (both average and local corrosion) varied widely between the test coupons in all three test series. The measured average corrosion rates in the 5V-test series were, surprisingly, of the same magnitude as those measured in the 10V-series.The average corrosion rates were clearly higher in the 30V-test series. This relationship was the same for the local corrosion in the three series. In the 30V-series some extremely high local corrosion rates appeared. Four coupons showed a local corrosion of 120-285 μm/year. There seemed to be a tendency of increasing local corrosion rate the higher the influencing AC-voltage is. The measured corrosion rates at different and constant AC-voltages can be used in the discussion whether a fixed AC-voltage can be used as a measurement criterion for AC-corrosion on cathodically protected pipelines.

In spite of a constant alternating voltage throughout the test series, the grounding resistance and thereby also the alternating current density of the coupons varied strongly on short-term up and down between different measurement occasions, due to i.a. weather and seasonal changes in soil resistivity. Long-term changes in the grounding resistances also occurred and it seemed to be a tendency of increasing grounding resistance, and decreasing AC-current density, with time. The increase in resistance and decrease in alternating current seemed to be larger for coupons with small exposed steel areas (0,5 and 1 cm^2). The observed short-term variations and long-term changes in alternating current densities complicate the use of this parameter as a criterion for AC-corrosion on cathodically protected pipelines.

Introduction and background

Since the end of the 1980s, corrosion damage caused by alternating current to underground steel pipelines has been discovered to an increasing extent in Europe. It concerns primarily natural gas pipelines with well electrically insulating external protective coatings. The corrosion has occurred even though the pipelines were provided with cathodic protection. (Ref. 1, 2, 3). In Sweden, two cases of severe corrosion damage were discovered in the early 1990s, which had been caused by high alternating current intensity (50 Hz). The damage was found on two separate natural gas pipelines, both of which were influenced by an alternating voltage because of their proximity to high voltage power lines. One damage was observed on the gas pipe and the other one on a steel coupon connected to the gas pipe. Both pipelines were provided with cathodic protection: OFF-potential ca - 1.0 V vs. saturated $Cu/CuSO_4$.

The discovery of these corrosion damages led to field trials focusing on alternating current corrosion. Investigations were started both with test coupons buried close to and connected to gas pipelines exposed to an alternating voltage and with test coupons in a field test installation, designed especially for the investigation of alternating current corrosion in soil. In the field test installation buried steel coupons were provided with cathodic protection and exposed to constant AC voltages but to different AC-densities. Three series of tests were performed, one with 5 Vac, one with 10 Vac and a third one with 30 Vac. This report describes the results from the 5V-series and they are compared with the results from the earlier 10V- and 30V-series. The 10V- and 30V-series have been reported previously in detail (4).

This report describes the investigations in the field test installation. Sydkraft Gas AB, Nova Naturgas AB and the Swedish Energy Agency have financed the investigation. The project has been administrated by the Swedish Gas Centre and supervised by the Swedish Corrosion Institute. Field work was carried out by Carl Bro Energy Consultant and ElektroSandberg Measurement technique.

Experimental procedure

The investigation was thus carried out in a field test installation, in which cathodically protected steel coupons buried in soil were exposed to constant AC-voltages but to different alternating current densities. 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 field-test installation and the test coupons

The field test installation includes a 150 meter long PE-coated steel pipe buried to a depth of 1.5 m. See **figure 1.** The native soil at the site consists of heavy clay. Close to each end of the pipe, a large and deep pit was dug in the clay soil, and this was then filled with sand. The groundwater level varies with the season but lies roughly at the pipe depth for most of the year. Approximately two years after the test pits had been filled with sand, soil samples were taken close to each test coupon both in the clay and in the sand. The sand was refilled before the start of the 5V-test series.

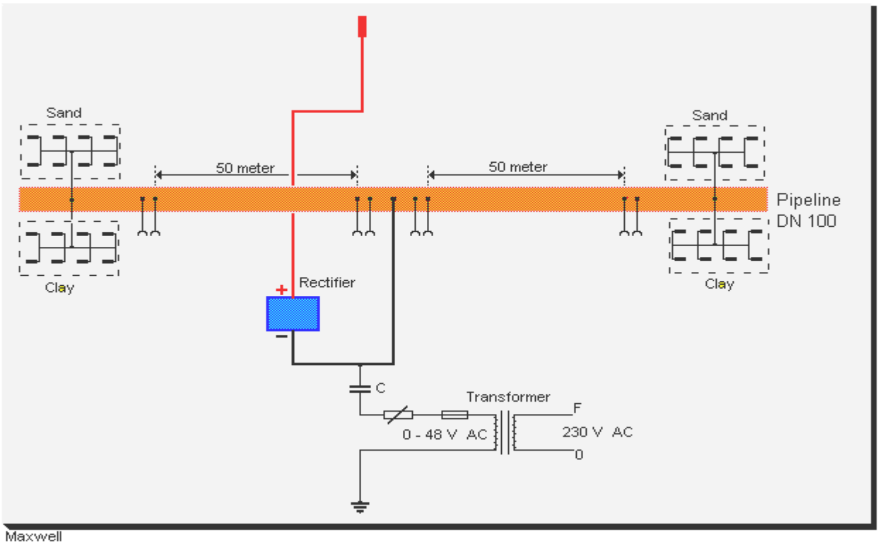

Figure 1. The field test plant with its electrical installations and buried test coupons. Nota bene: The position of reference coupons is not pointed out in the figure.

At each end of the pipe, 8 steel coupons were buried at a depth of ca.1m and were each connected electrically to the steel pipe via a cable. Half of the coupons were buried in clay and half in sand. In all, 16 coupons were thus exposed. Before the coupons were buried, they were carefully weighed and then covered with a thick and strongly adhesive PE- tape. On one side of each coupon, a circular hole was cut in the tape so that a circular steel surface with a given area was exposed. Four areas of different sizes were used: 5, 3, 1 and 0.5 cm^2. Thus, for each area two coupons were exposed in clay and two coupons in sand. The exposed steel surfaces simulated, as already mentioned, a steel surface in a coating damage on a buried steel pipeline.

The steel pipe and the connected test coupons were exposed to an alternating voltage in a resistive way with the help of an adjustable transformer (50 Hz) connected to the pipe and to a grounding rod. The alternating voltage was held constant during the whole exposure period. The pipe and the coupons were provided with cathodic protection with a dc- current from a constant-current rectifier, so that the protective current could be held constant throughout the exposure period.

Furthermore, 12 reference coupons with 1 cm^2 exposed steel area were buried near the steel pipe. Of these, 4 coupons were freely exposed in the soil without any DC or AC current, 4 coupons were exposed only to DC-current (cathodic protection) and 4 with were exposed only to AC-current. All coupons are listed together with their coupon number and electrical parameters in table 2. Reference coupons were unfortunately not used in the 10V- and 30V-test series.

Test series

Three test series (exposures) were, as already mentioned, carried out in sequence. The major difference between these was that the alternating voltage of the pipe and the coupons was 30 V with respect to distant earth in the first test series, 10 V in the second and 5 V in the third. Another difference, which is probably of less importance for the corrosion, was that the exposure times for practical reasons differed some months for the different test series. The exposure time for the 30V-series was 1,4 years, for the 10V-series 1,8 years and for the 5V-series 1,3 years.

Since the coupons had exposed steel areas of different sizes and since the soil resistively closest to the steel surface was somewhat different for the different coupons, the coupons in each test series had grounding resistances (“spread resistances”) of different magnitudes. As a consequence of the different grounding resistances, the coupons were exposed to current densities of different magnitudes, in spite of having the same constant alternating voltage.

Evaluation of the corrosion

After being withdrawn, the coupons were inspected visually with respect to corrosion products and adhering soil. Then, the coupons were cleaned through pickling in an acid bath (Clark's solution), after which they were weighed. The weight loss, which had occurred during the exposure, was recalculated to an average corrosion rate in µm/year for each coupon. The steel surfaces were then examined in a microscope and the depth of the deepest local corrosion attack was measured using the microscope focusing method. The corrosion depth was recalculated to a maximum local corrosion rate in µm/year for each coupon. The corrosion attacks were finally photographed.

Repeated measurements of electrical parameters on the coupons

During the exposure periods, a number of electrical parameters were measured on each coupon at intervals of about one month. The parameters measured were: the alternating current (I_{ac}) which was recalculated into alternating current density (J_{ac}) and the direct current, i.e. the cathodic protection current (I_{dc}), which was then recalculated into protection current density (J_{dc}). The protection potential of the coupons with and without ohmic voltage drop (E_{on} and E_{off}), alternating voltage (U_{ac}) and grounding resistance (R_{gr}) of all coupons were also measured. In this report the grounding resistance is given in kohm in the tables.

Results and discussion

In the following, results from the test series with 5 Vac are presented and discussed. A comparison with the results from the 10 Vac and 30 Vac test series is also made. All electrode potentials are given with respect to the saturated $Cu/CuSO_4$ reference electrode.

Soil analysis

Results from the analysis of the soil samples are shown in **table 1.** The chemical composition of the clay is typical for clay soils in the region in southern Sweden where the investigation was performed. Both the pH-value and the cation content in the sand are, however, higher than expected. The sand resistivity is also lower than expected. This is probably due to the fact that the groundwater in the clay, which is the native soil on the site, has penetrated into the test pit with sand, with the result that the chemical composition of the groundwater is reflected in the sand. Also the quite low sand resistivity points in this direction.

Table 1. Chemical composition of the clay and sand soil at the field test installation.

Soil	pH	K mg/kg	Ca mg/kg	Mg mg/kg	Na mg/kg	Cl mg/kg	Resistivity (Wenner 4-pin) Ω·cm
Clay	7,8 - 8,1	28 - 68	2 400 - 2 500	120 - 230	25 - 37	< 10	1 800
Sand	8,0 - 8,3	10 - 34	660 - 1 300	28 - 65	8 - 21	< 10	19 000

The grounding resistance and alternating current density of the test coupons

Results from the repeated measurements of electrical parameters in the 5V-test series are shown in **table 2.** Each parameter is given as a mean value of all the single values obtained during the exposure period.

Table 2. Mean values of electrical parameters measured on the test coupons at 16 occasions in the 5V-test series.

Coupon no.	Exposed steel area cm^2	Coupon exposed to	Coupon exposed in	Uac V	Jdc A/m^2	Jac A/m^2	Rgr. kohm
333	0,5	DC&AC	sand	5,11	0,06	2,52	63,57
331	0,5	DC&AC	sand	5,13	0,05	1,14	90,42
332	0,5	DC&AC	clay	5,11	0,28	11,30	24,96
334	0,5	DC&AC	clay	5,13	0,05	2,02	40,75
342	1,1	DC&AC	sand	5,11	0,05	1,89	37,55
336	1,1	DC&AC	sand	5,13	0,14	2,93	19,32
348	1,1	DC&AC	clay	5,11	0,19	9,19	13,99
340	1,1	DC&AC	clay	5,13	0,56	23,01	2,21
328	3,1	DC&AC	sand	5,12	0,06	1,80	8,98
326	3,1	DC&AC	sand	5,13	0,09	2,21	8,33
330	3,1	DC&AC	clay	5,11	0,10	4,23	4,45
327	3,1	DC&AC	clay	5,13	0,03	1,18	10,48
324	4,9	DC&AC	sand	5,11	0,06	1,80	5,67
323	4,9	DC&AC	sand	5,13	0,09	1,85	6,15
325	4,9	DC&AC	clay	5,11	0,22	8,33	1,40
322	4,9	DC&AC	clay	5,13	0,21	8,76	1,25
345	1,1	free exp	sand	–	–	–	6,95
335	1,1	free exp	sand	–	–	–	7,51
346	1,1	free exp	clay	–	–	–	1,51
339	1,1	free exp	clay	–	–	–	1,15
349	1,1	only DC	sand	–	0,06	–	31,69
329	1,1	only DC	sand	–	0,06	–	32,11
344	1,1	only DC	clay	–	0,09	–	5,09
338	1,1	only DC	clay	–	0,08	–	6,60
347	1,1	only AC	sand	5,10	–	8,66	5,34
337	1,1	only AC	sand	5,13	–	7,53	6,79
343	1,1	only AC	clay	5,10	–	39,20	1,17
341	1,1	only AC	clay	5,13	–	39,69	1,19

Each single grounding resistance and each single AC current density measured at each measurement occasion is shown in diagrams (one diagram for each size of exposed steel area) in **figure 2** and **figure 3** respectively. These diagrams show that, in spite of a constant alternating voltage throughout the exposure, the grounding resistance and thereby also the alternating current density varied upwards and downwards on different measurement occasions. Long-term changes in the grounding resistances, and thereby also in alternating current density, also occur. It seems to be a tendency of increasing grounding resistance, and decreasing alternating current density, with time. This tendency, however, is not equally pronounced for all test coupons. The increase in resistance and decrease in alternating current seems to be larger for coupons with small exposed steel areas (0,5 and 1 cm^2).

The electrical parameters were measured at an approximately 3-weeks interval. In order to follow the variations more closely the AC-current on some of the coupons were logged during the period between a number of measurement occasions. It appeared from the logging that the abrupt changes in grounding resistance and AC-current density, as they are shown in the diagrams, do not reflect the reality. The logged changes are much more slow and “smooth”.

The variations in the grounding resistance may be due to more than one factor. The soil resistivity closest to the steel surfaces may have varied because of weather and seasonal variations in the moisture content of the soil. The formation of, and changes in, corrosion products and calcareous/or salt layers on the steel surfaces may also have had an influence.

Corrosion rates

The corrosion rates, expressed as average corrosion and maximum local corrosion, on all coupons (also the reference coupons) in the 5V-test series are shown in **table 3.** The corrosion rates are also shown in histograms in **figure 4**, where they are ordered from left to right according to increasing average corrosion rate. For comparison the corrosion rates on coupons in the 10V- and 30V-test series are also shown in figure 4. The range of distribution of the corrosion rates in all three test series is shown in **table 4.**

As can be seen in figure 4 and table 3 the corrosion rates vary widely between the test coupons in all three test series. Somewhat surprisingly, the magnitude of average corrosion is about the same in the 5V- and 10V-test series. The average corrosion is, however, higher in the 30V-test series. This relationship is the same for the local corrosion rates in the three test series. In the 30V-test series some extremely high local corrosion rates were measured. Four coupons showed a local corrosion rate between 120 and 285 μm/year. In figure 4 it can be seen that there seems to be a tendency of increasing local corrosion the higher the AC-voltage is.

In the European standard EN 12954 (5) it is stated that a criterion for complete cathodic protection is a corrosion rate lower than 0,01 mm/year (10 μm/year). Among all 16 cathodically protected and AC-influenced test coupons in each of the three test series 10 coupons in the 5V-test series, 7 coupons in the 10V-test series and only 4 coupons in the 30V-test series met this criterion, when regarding average corrosion. The rest of the coupons had a higher average corrosion rate than the criterion for cathodic protection.

The reference coupons, which were AC-influenced <u>without</u> cathodic protection, showed an average corrosion of the same magnitude as AC-influenced coupons <u>with</u> cathodic protection. These two groups of coupons had the same size of exposed area (1 cm^2). It is remarkable that one of the coupons, which were cathodically protected without AC-influence, showed an average corrosion as high as 20 μm/year. The other three coupons in this group, however, met the criterion for complete cathodic protection, when regarding average corrosion.

Table 3. Corrosion rates (average and max. local corrosion) on all test coupons, also the reference coupons, in the 5V-test series.

Coupon no.	Exposed steel area cm^2	Coupon exposed to	Coupon exposed in	Corrosion rate	
				Average corrosion µm/year	Max. local corrosion µm/year
333	0,5	DC&AC	sand	11	–
331	0,5	DC&AC	sand	26	51
332	0,5	DC&AC	clay	15	–
334	0,5	DC&AC	clay	8	11
342	1,1	DC&AC	sand	18	–
336	1,1	DC&AC	sand	13	23
348	1,1	DC&AC	clay	17	37
340	1,1	DC&AC	clay	4	30
328	3,1	DC&AC	sand	3	17
326	3,1	DC&AC	sand	5	–
330	3,1	DC&AC	clay	5	27
327	3,1	DC&AC	clay	4	–
324	4,9	DC&AC	sand	5	30
323	4,9	DC&AC	sand	6	38
325	4,9	DC&AC	clay	4	25
322	4,9	DC&AC	clay	4	24
345	1,1	free exp	sand	6	46
335	1,1	free exp	sand	23	68
346	1,1	free exp	clay	13	–
339	1,1	free exp	clay	15	33
349	1,1	only DC	sand	20	32
329	1,1	only DC	sand	8	17
344	1,1	only DC	clay	6	37
338	1,1	only DC	clay	10	–
347	1,1	only AC	sand	14	48
337	1,1	only AC	sand	15	–
343	1,1	only AC	clay	15	–
341	1,1	only AC	clay	17	–

Table 4. Range of distribution of corrosion rates (average and local corrosion) in the 5V-, 10V- and 30V-test series.

Type of corrosion	Distribution range of corrosion rates in test series		
	5 Vac	10 Vac	30 Vac
Average corrosion, µm/year	3 – 26	4 – 27	4 – 66
Localized corrosion, µm/year	11 – 51	12 – 60	33 – 284

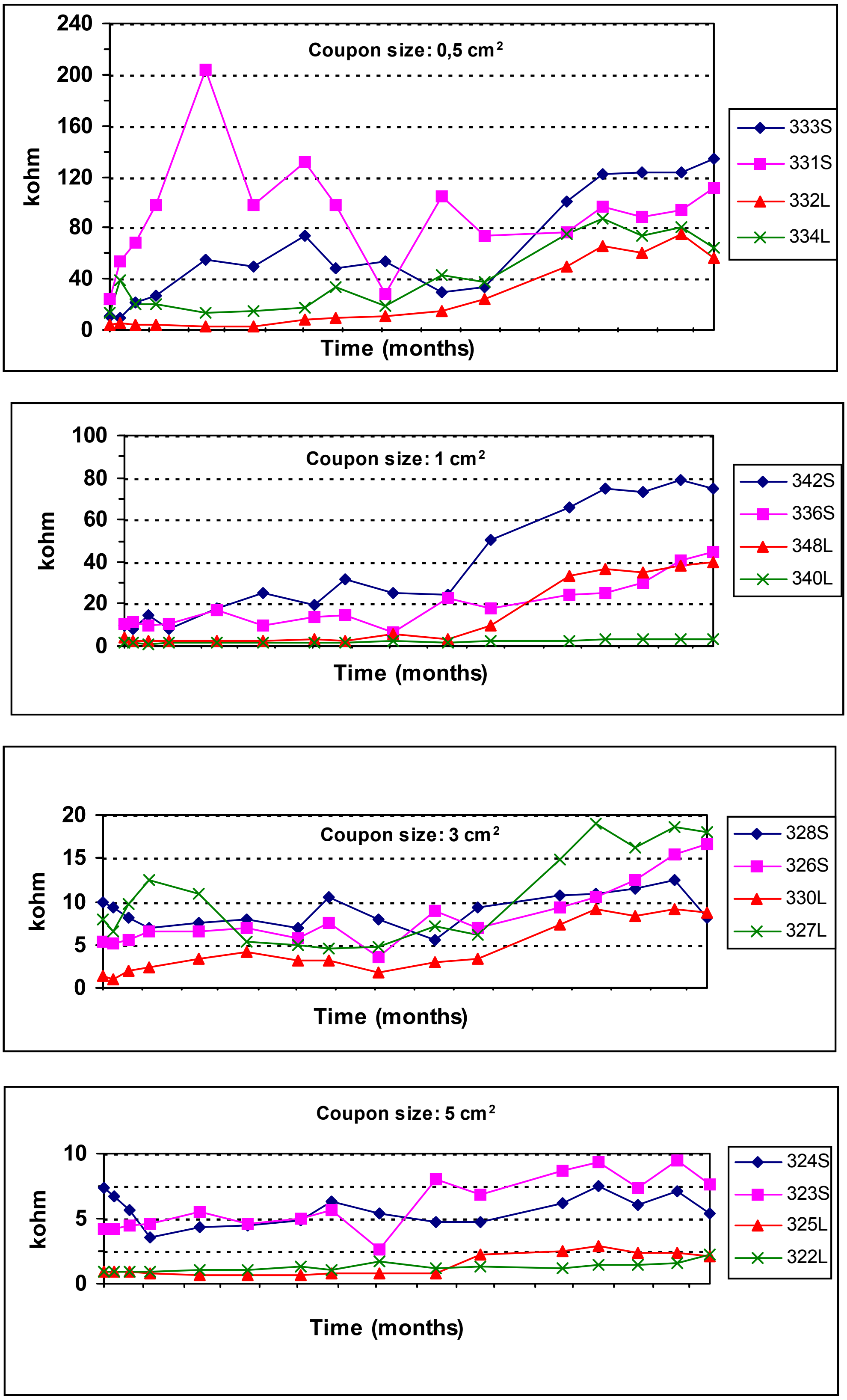

Figure 2. The grounding resistance (Rgr.), given in ohm, of every single test coupon at the twelve measurement occasions in the 5V-test series. One diagram for each size of exposed steel area.

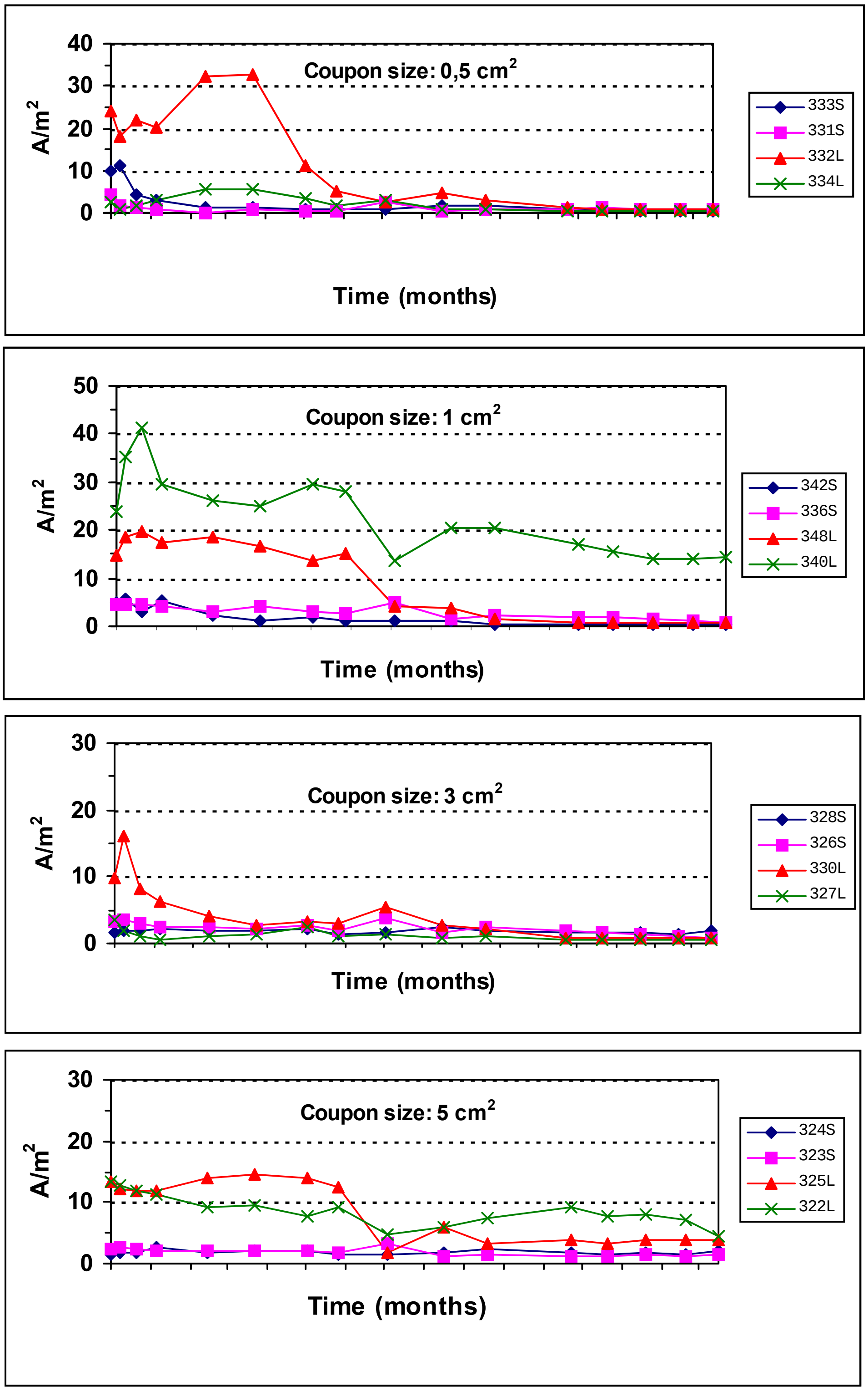

Figure 3. The alternating current density (Jac), given in A/m^2, of every single test coupon at the twelve measurement occasions in the 5V-test series. One diagram for each size of exposed steel area.

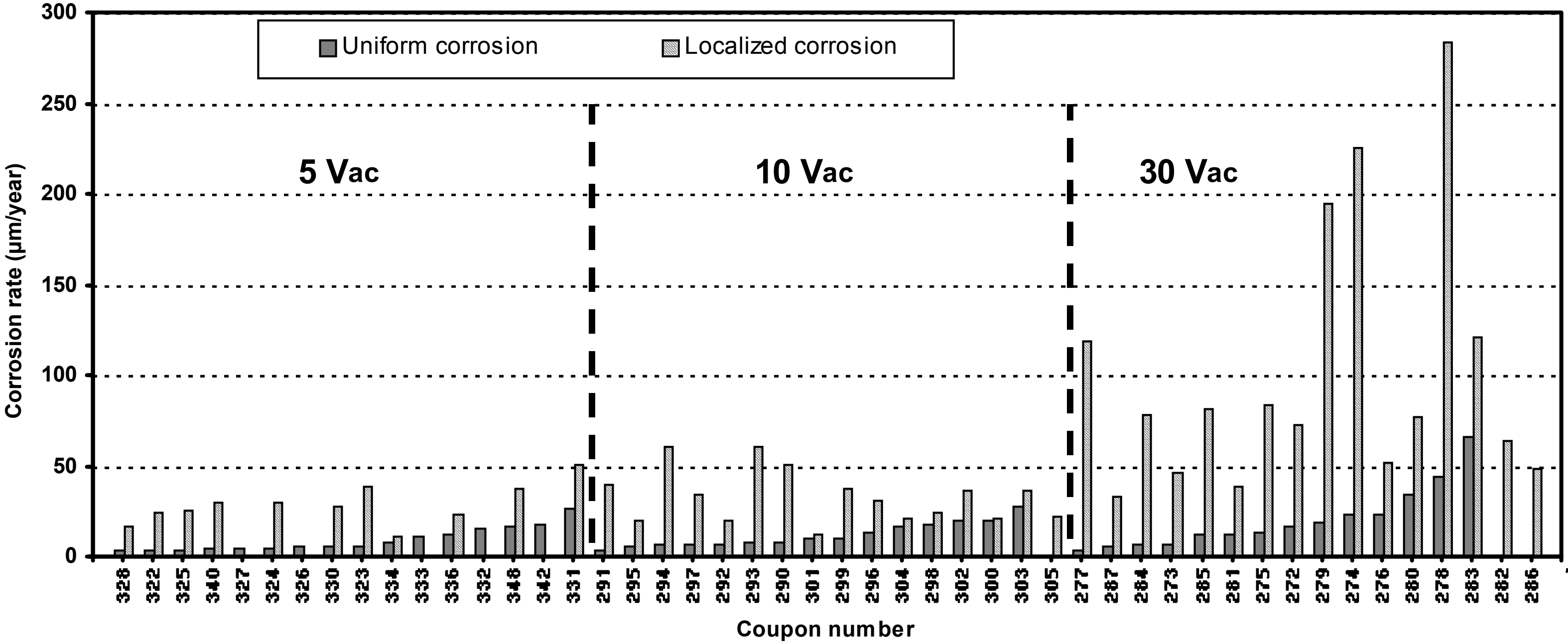

Figure 4. Average corrosion rate and maximum local corrosion rate of all test coupons in the 5V-, 10V- and 30V-test series. The corrosion rates are ordered from left to right according to increasing average corrosion rate. Average corrosion rate for coupon no. 305 (10V-test series), 382 and 386 (30V-test series) is false and therefore not given, because of corrosion under the tape cover.

Comparison with other field trials of alternating current corrosion

The alternating voltage on the pipe and the test coupons was kept constant throughout the exposure period, and this investigation differs in this respect from other field trials of alternating current corrosion. In these latter investigations, the corrosion conditions are usually studied on test coupons buried and electrically connected to a pipeline, which is electrically influenced by an alternating current plant, e.g. a power line or the contact line of an a.c. railway. In such field trials, the alternating voltage of the pipes and coupons therefore varies with time in an uncontrolled way, because of operational variations in the electrically influencing high voltage source.

Examples of the diurnal variations in the induced alternating voltage in a natural gas pipeline in southern Sweden in the summer and in the winter are shown in **figure 5.** The alternating voltage of the pipeline is induced from a 400 kV-power line, which runs parallel to the pipeline. The alternating voltage of the pipe is highest in the morning and evening and almost twice as high in the winter as in the summer, because the alternating current in the phase conductor of the power line is highest during these periods.

In this field trial, the electrical conditions have thus been more controlled, which may be of importance in attempts to find a relationship between the alternating current corrosion and other parameters and in an attempt to find a suitable measurement criterion for AC-corrosion on cathodically protected pipelines.

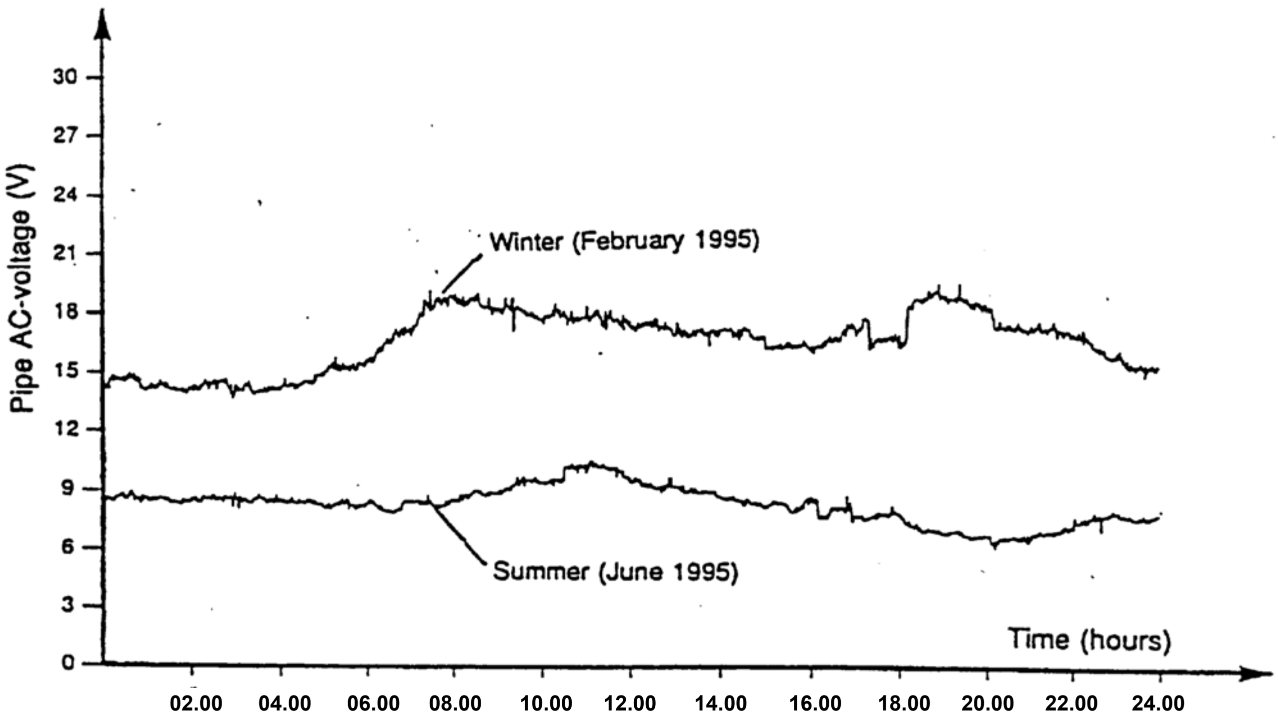

Figure 5. Diurnal variations in the induced alternating voltage in a natural gas pipeline in the summer and in the winter. The alternating voltage of the pipeline is induced from a nearby and parallel 400 kV-power line.

Conclusions

From the field investigation of alternating current corrosion on cathodically protected steel in soil, the following conclusions can be drawn

- Alternating current of high current density can cause corrosion attacks on steel in soil, despite the steel surface being provided with cathodic protection.

- The corrosion rates (both average and local corrosion) varied widely between the test coupons in all three test series. The measured average corrosion rates in the 5V-test series were, surprisingly, of the same magnitude as those in the 10V-test series. The average corrosion in the 5V-series was 3-26 μm/year and in the 10V-series 4-27 μm/year. The average corrosion rates were, however, higher in the 30V-test series, 4-66 μm/year. This is the same for the local corrosion in the three test series. In the 30V-series there appeared some extremely high corrosion rates. In this series four coupons showed a local corrosion of 120 – 285 μm/year.

- There seems to be a tendency of increasing local corrosion rate the higher the influencing AC-voltage is.

- The corrosion rates, which were measured in the 5V-, 10V- and 30V-test series, can be used in the discussion whether a fixed AC-voltage can be used as a measurement criterion for AC-corrosion on cathodically protected steel pipelines. This is because of the comparably large number of test coupons and the controlled experimental conditions.

- In spite of a constant alternating voltage throughout the test series, the grounding resistance and thereby also the alternating current density varied strongly on a short-term up and down between different measurement occasions, primarily due to weather and seasonal changes in soil resistivity and in chemical conditions closest to the steel surfaces due to the cathodic polarisation of these.

  Long-term changes in the grounding resistances also occurred and there seemed to be a tendency of increasing grounding resistance, and decreasing AC-current density, with time. The increase in resistance and decrease in alternating current seems to be larger for coupons with small exposed steel areas (0,5 and 1 cm^2).

- The observed short-term and long-term variations and changes in alternating current densities complicates the use of this parameter as a criterion for AC-corrosion on cathodically protected pipelines.

- In this field investigation, the electrical conditions have been more controlled than what usually is the case in other field investigation of alternating current corrosion, where coupons are connected to a pipeline which is AC-influenced from a high voltage power line or an electrified AC-railway.

Acknowledgement

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