AC CORROSION ON CATHODICALLY PROTECTED PIPELINES

Guidelines for risk assessment and mitigation measures

ANNEX N. 7

Alternating current corrosion on cathodically protected steel in soil – A long-term field investigation

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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 different a.c–densities. Two series of tests were performed, one with 10 Vac during almost two years, and another one with 30 Vac during ca. 1½ year. The corrosion rates varied widely between the test coupons in both test series. In the 10 V-series, the average corrosion rate varied between 4 and 27 µm/year and the maximum local corrosion rate between 12 and 60 µm/year. In the 30 V-series, the average corrosion rate varied between 4 and 66 µm/year and the maximum local corrosion rate between 33 and 284 µm/year. A certain correlation between the average corrosions rate and the alternating current density was observed.

Recording of the IR-free potential (OFF- potential) of the test coupons with an oscilloscope revealed that the potential varies with the alternating current, and that the potential variation seems to follow a sinus-slope. During the positive half cycle of the alternating current, the IR-free potential shifted in the anodic direction to values less negative than the limit value for cathodic protection, meaning that cathodic protection was periodically lost due to the alternating current. In many cases the potential shifted to values even less negative than the free corrosion potential, implying that the steel surface is exposed to an exiting current.

It was possible predict on-going corrosion before the withdrawal of the coupons, by using a special current interruption and potential measurement technique especially developed for this purpose.

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 and 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 400 kV-power lines. Both pipelines were provided with cathodic protection: OFF-potential ca - 1.0 V vs. saturated $Cu/CuSO_4$.

The discovery of this corrosion damage 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. This report describes the investigations in the field test installation. Sydgas AB and Vattenfall Naturgas AB have financed the investigation.

Experimental procedure

The investigation was thus carried out in a field test installation, in which cathodically protected steel coupons were exposed to different alternating current densities in soil. 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 a 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 100 meter long PE-coated steel pipe buried to a depth of 1.5 m. Se **figure 1.** The natural 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.

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 were 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. The pipe and 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.

Test series

Two test series (exposures) were 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 and 10 V in the second. Another difference, which is probably of less importance for the corrosion, was that the exposure times were for practical reasons different for different groups of coupons. In the first test series, four coupons were taken up after 1 year for a first evaluation of the corrosion. The remaining 12 coupons in this series were taken up and evaluated after 1.4 years. In the second test series, all the coupons were taken up after 1.76 years.

Since the coupons had exposed steel areas of different sizes and since the soil resistively closest to the steel surface was 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 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. 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. Ten measurements were made in the test series with 30 V_{ac} and fourteen measurements in the test series with 10 V_{ac}. 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 protective current (I_{dc}), which was then recalculated into protective current density (J_{dc}). The protective potential of the coupons with and without ohmic voltage drop (E_{on} and E_{off}), alternating voltage (U_{ac}) and grounding resistance (R_{gr}) were also measured.

Measurement of IR-free electrode potentials with an oscilloscope

For some time before the completion of the exposures, the IR-free electrode potential (potential free from ohmic voltage drop, the “OFF- potential”) was measured on each coupon with the help of an oscilloscope. The intention was to obtain a picture of how the IR- free, cathodic protective potential is influenced by the alternating current.

To ensure that the ohmic voltage drops (IR_{ac} and IR_{dc}) from the alternating and direct currents are not measured into, and do not thus falsify the measured potential, both currents were interrupted simultaneously during each measurement. The IR-free potential was then read from the saved oscilloscope picture. Potential readings were made at two different points in time in relation to the current interruption: immediately (0 milliseconds), and 3 milliseconds after the interruption. The aim of the delayed reading (3 milliseconds) was to investigate what effect the slight delay would have on the IR-free potential, compared with the potential read immediately after the current interruption. The procedure with interruption and potential reading was repeated a number of times for each coupon, so that potential values were obtained corresponding to different, randomly chosen, positions on the sinusoidal slope of the alternating current.

With knowledge of the position of the current interruption with respect to time in relation to the sinusoidal slope of the alternating current, the potential values could be plotted in the same alternating current cycle and a new sinusoidal slope was adapted to these values. With the help of this new potential curve thus obtained, the maximum and minimum potentials were determined for each test coupon throughout an alternating current cycle.

By using the new potential curve, the length of time during a whole alternating current cycle that the potential of the steel surface shifted outside the limit for complete cathodic protection (in this case: > -0.95 V), i.e. the time during which the steel surface lacked cathodic protection, could be determined. The length of time that the potential shifted to values less negative than the free corrosion potential of each steel coupon was also determined in this way, that is that the time proportion during which the steel surface was exposed to a current exit was determined.

Measurement of IR-free electrode potentials with the CORREAL-system

The IR-free potential of the test coupons in the 30 V-series was also measured with the CORREAL-method. The measurement was made approximately six months after the start of the test series. Measurement according to the CORREAL-method is basically the same as with an oscilloscope. The CORREAL-equipment, however, has been developed especially for the measurement of IR-free electrode potentials on buried and cathodically protected pipelines, which are electrically influenced, (Ref. 4).

With the CORREAL- system the alternating and the direct currents are simultaneously interrupted by an automatic circuit breaker. The electrode potential is recorded 1 millisecond after the interruption, after which the currents are again switched on. Immediately before the interruption, the alternating current is also recorded. The procedure is repeated with a frequency, which is slightly greater than the network frequency 50 Hz. In that way the potential is recorded in a large number of points with different locations on the sinusoidal slope of the alternating current. If the positive amplitude of the potential slope thus obtained is more positive than the limiting value for complete cathodic protection (in this case: -0.85 V_{dc}), this is interpreted as indicating that corrosion is occurring. At the interpretation the mean value of the maximum and the minimum potential is also taken into consideration.

In normal cases of measurement with the CORREAL-equipment on a pipeline exposed to alternating current, the potential is recorded on a special steel coupon placed in the soil above the pipeline. In the measurement in this investigation, exceptions were made from this practice. The potential measurement was instead made, as mentioned above, on the test coupons included in the 30 V-series. The measurement and the interpretation were carried out by a specialist from the Belgian gas pipeline company Distrigas S.A., who had participated in the development of the measurement method.

Results and discussion

In the following, results from the test series with 10 V_{ac} and the test series with 30 V_{ac} are presented and discussed. All electrode potentials are indicated with respect to a reference electrode of the saturated $Cu/CuSO_4$ type.

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. 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.

The grounding resistance and alternating current density of the test coupons

Results from the repeated measurements of electrical parameters in the test series with 30 Vac are shown in **table 2** and from the test series with 10 Vac in **table 3.** Each parameter is shown as a mean value of all the single values obtained during the exposure period. In spite of a constant alternating voltage throughout the exposure, however, 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 also occur, see **figures 2- 5.** The exceptionally high alternating current density on test coupon No 286 may be incorrectly calculated, because it is not clear how large an area of steel was exposed to the alternating current. See further in the next section.

The variations in the grounding resistance with time are not, however, the same for all the coupons. In the 10 V-series, the grounding resistance increased markedly in half of the coupons during the latter half of the exposure while the resistance of the other half of the coupons hardly changed with time. The increase in the grounding resistance corresponds to a decrease (although not as apparent) in the alternating current density on these coupons. In the 30 V-series, there was also a tendency towards an increase in grounding resistance of some coupons, but the increase was not as marked as that in the 10 V-series.

The variations in the grounding resistance may be due to several factors. 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 have had an influence. Finally, the increase with time of the effective steel area to which the corrosion gives rise may have contributed to a slight decrease in the grounding resistance, especially in coupons with a small exposed steel area.

The appearance of the corrosion

The appearance of the corrosion could be divided into three groups:

o Small point-shaped attacks evenly distributed across the surface (uneven surface)
o Large point-shaped attacks evenly distributed across the surface (rough surface)
o A few large deep local attacks on an otherwise uncorroded surface (“pocked” surface)

Examples of the three types of corrosion are shown in **figure 6.** On coupons with local corrosion attacks on an otherwise uncorroded steel surface, the cathodic protection has obviously been active locally on the uncorroded surfaces.

On two of the coupons in the 30 V-series (coupons No 282 and 286) and on one coupon in the 10 V-series (coupon No 305), corrosion also occurred at a distance in under the PE-tape. These attacks may have been caused by alternating current corrosion, crevice corrosion or by both these forms of corrosion. Evidence of alternating current corrosion having taken place under the tape on coupon No 286 is the fact that the appearance of the corrosion attack is similar to that on the free steel surface. This also means that part of the alternating current may have passed through the steel surface inside the crevice. The alternating current density of this coupon (calculated for the freely exposed steel surface area of 0.5 cm^2 on the basis of the measured alternating current, 47 mA) is exceptionally high (940 A/m^2) compared with the current density on other coupons. If an alternating current has also flowed under the tape, the calculation has then been based on too small an area and this has given an incorrect and too high value of the alternating current density on the freely exposed steel area. For test coupons No. 282 and 305, it is more difficult to prove such a conclusion.

Corrosion rates

The corrosion rates, expressed as average corrosion and maximum local corrosion, on coupons in the 30 V-series are shown in **table 2** and on coupons in the 10 V-series in **table 3**. The corrosion rates are also shown in histograms in **figure 7**, where they are ordered from left to right according to increasing average corrosion rate.

Because corrosion on three of the coupons (coupons No 282, 286 and 305) took place also under the PE-tape, where other corrosion conditions had existed than on the free steel surface, no value of the average corrosion rate is shown for these three coupons.

The corrosion rates are higher in the test series with an alternating voltage of 30 V_{ac} than in the test series with 10 V_{ac}. However, the corrosion rates vary widely between the test coupons in both test series. In the 10 V-series, the average corrosion rate varies between 4 and 27 µm/year and the maximum local corrosion rate varies between 12 and 60 µm/year. In the 30 V-series, the average corrosion rate varies between 4 and 66 µm/year and the maximum local corrosion rate varies between 33 and 284 µm/year. In the 30 V-series, the difference between the maximum local corrosion rate and the average corrosion rate is remarkably larger than it is in the 10 V-series.

Correlation between corrosion rate and alternating current

As was shown in the previous section (se **figure 7**), there is thus a relationship between corrosion rate and alternating voltage level. Especially, the maximum local corrosion rate is much higher at the higher alternating voltage.

A certain but not unambiguous correlation also seems to exist in both test series between the average corrosion rate and the alternating current density (mean value of current densities measured at the different measurement occasions). The average corrosion rate increases with increasing alternating current density, see **figure 8**. It is possible that the correlation would have been more evident if the current measurements would not have been carried out as repeated measurements of the instantaneous current value, but instead as a continuous recording of the accumulated amount of current.

IR-free potentials measured with oscilloscope and with the CORREAL- system

The maximum and minimum IR-free potentials recorded with oscilloscope and with the CORREAL-system on each single coupon 0, 1 and 3 milliseconds after current interruption are shown in **table 4.**

It seems that the potential readings at 0 milliseconds (oscilloscope) and 1 millisecond (CORREAL) after current interruption in many cases give unrealistic values of the maximum and minimum potentials. The reason for this is unclear, but it might be because capacitive charges have not had time to be discharged from the steel surface during the short time period to the potential reading, and that this thus gives incorrect values of the electrochemical potential. Potential reading after 3 milliseconds (oscilloscope) seems to give more realistic potentials. On the other hand, both a certain anodic and cathodic depolarisation might have had time to take place during the 3 milliseconds before the potential reading, which would mean that the read potential values are too small. If that is the case, the measured potentials still show that the cathodic protection is periodically lost due to the alternating current during the a.c. positive half-cycle. It seems, however, that the optimum choice of time after current interruption for a potential reading, which will show the true

IR-free potential, is a matter for further discussion.

Assessment of on-going corrosion with the CORREAL- system

The interpretation of the measurement results obtained on coupons in the 30 V-series with the CORREAL-system indicated that corrosion occurred on all test coupons on which measurement could be performed. The strongest corrosion was judged to occur on coupon No 286. This is interesting because of the high alternating current on this coupon. Regarding the measured corrosion rates, the assessment according to the CORREAL-method was correct in this case.

Effect of the alternating current on the IR-free potential

Figure 9 shows two examples of a sinusoidal slope, which is adapted for the IR-free protective potential, measured with oscilloscope. The unbroken curve represents the potential read immediately (0 milliseconds) after interruption of the currents, and the broken line represents the potential read 3 milliseconds after the interruption. The curve fit is in both cases reasonably good, and the potential thus seems to follow a sinusoidal slope. However, a reservation must be made for the possible unrealistic values of maximum and minimum potentials discussed above.

The proportion of the time during which the protective potential is less negative than the free corrosion potential of each single coupon, and less negative than the limiting value of - 0.95 V_{dc} for complete cathodic protection (which is practised in low-resistive soils) is shown in **table 5.** These proportions of time, when complete cathodic protection is lacking and when the steel surface is exposed to a current exit, is based on potential readings 0 milliseconds after current interruption, so that the indicated time periods are probably too long, (see discussion above). A calculation based on potential readings 3 milliseconds after interruption would probably give shorter proportions. However, no such calculation has been made up to now.

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 10.** 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

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 recording of the IR-free potential (OFF- potential) of the test coupons with an oscilloscope reveals that the potential varies with the alternating current, and that the potential seems to follow a sinusoidal slope.

- During the positive half cycle of the alternating current, the IR-free potential shifts in the anodic direction to values less negative then the limit value for cathodic protection, meaning that cathodic protection is periodically lost due to the alternating current. In many cases the potential shifts to values even less negative than the free corrosion potential, meaning that the steel surface is exposed to an exiting current. However, a reservation is made for certain unrealistic high and low potential values obtained.

- It was possible to predict on-going corrosion on a group of test coupons before the withdrawal, by using a special current interruption and potential measurement technique especially developed for this purpose.

- The appearance of the corrosion varies between the coupons, from small point-shaped attacks evenly distributed across the steel surface (“uneven” or “rough” surface) to large deep local attacks on an otherwise uncorroded steel surface (“pocked” surface).

- The corrosion rates were higher at the alternating voltage level 30 V than at 10 V, even if the corrosion rates vary widely between the test coupons at both voltages. However, some rather high corrosion rates appear also at the comparatively low alternating voltage level 10 V.

- At the 30 V_{ac}-level, the difference between maximum local corrosion rate and the average corrosion rate is remarkably larger than it is at the 10 V_{ac}-level.

- There is a certain but not unambiguous correlation between the average corrosion rate and the alternating current density.

- In spite of a constant alternating voltage throughout the exposures, the grounding resistance and thereby also the alternating current density varied between different measurement occasions, probably due to changes in soil resistivity and in chemical conditions closest to the steel surfaces. Long-term changes in the grounding resistances also occurred.

- 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.

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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
Clay	7,8 - 8,1	28 - 68	2 400 - 2 500	120 - 230	25 - 37	< 10
Sand	8,0 - 8,3	10 - 34	660 - 1 300	28 - 65	8 - 21	< 10

Table 2. Mean value of the electrical parameters measured on the test coupons at ten occasions in the 30 Vac-series, and the average corrosion rate (”average”) and the maximum local corrosion rate (”max”) of each coupon.

Coupon nr	Exp. area (cm^2)	Soil	Exposure (year)	Eon (V)	Eoff (V)	Uac (V)	Idc (mA)	Jdc (A/m^2)	Iac (mA)	Jac (A/m^2)	Rgr (ohm)	Corrosion rate	
												average (μm/y)	max (μm/y)
272	4,9	Clay	1,4	-1,36	-1,09	30,0	0,174	0,36	62,56	127,7	1570	17	72
273	4,9	Sand	1,4	-1,37	-1,07	31,0	0,069	0,14	13,44	27,4	6904	7	46
274	4,9	Clay	1,0	-1,37	-1,09	31,0	0,248	0,51	59,56	121,6	569	23	225
275	4,9	Sand	1,4	-1,39	-1,1	31,0	0,552	1,13	43,56	88,9	1316	13	83
276	3,1	Clay	1,4	-1,36	-1,09	31,0	0,163	0,53	40,00	129,0	998	24	52
277	3,1	Sand	1,4	-1,37	-1,1	31,0	0,058	0,19	10,33	33,3	7138	4	119
278	3,1	Clay	1,0	-1,37	-1,08	31,0	0,548	1,77	47,00	151,6	1438	44	284
279	3,1	Sand	1,4	-1,39	-1,09	31,0	0,087	0,28	17,67	57,0	3305	19	194
280	1,1	Clay	1,4	-1,36	-1,09	31,0	0,128	1,16	13,56	123,3	3384	34	77
281	1,1	Sand	1,4	-1,37	-1,08	31,0	0,076	0,69	4,18	38,0	18191	12	39
282	1,1	Clay	1,0	-1,37	-1,1	31,0	0,358	3,25	4,89	44,5	6094	1)	64
283	1,1	Sand	1,4	-1,38	-1,08	31,0	0,572	5,20	10,24	93,1	2249	66	121
284	0,5	Clay	1,4	-1,37	-1,09	31,0	0,078	1,56	2,01	40,2	28809	7	78
285	0,5	Sand	1,4	-1,38	-1,1	31	0,059	1,18	1,21	24,2	34865	12	81
286	0,5	Clay	1,0	-1,37	-1,08	31,0	0,548	10,96	47,00	940,0	33400	1)	48
287	0,5	Sand	1,4	-1,37	-1,08	31,0	0,040	0,80	1,36	27,2	57643	6	33

1) Corrosion attack under PE-tape

Table 3. Mean value of the electrical parameters measured on the test coupons at ten occasions in the 10 Vac-series, and the average corrosion rate (”average”) and the maximum local corrosion rate (”max”) of each coupon.

Coupon nr	Area (cm^2)	Soil	Exposure (year)	Eon (V)	Eoff (V)	Uac (V)	Idc (mA)	Jdc (A/m2)	Iac (mA)	Jac (A/m2)	Rgr (ohm)	Corrosion rate	
												average (μm/y)	max (μm/y)
290	4,9	Clay	1,76	-1,49	-0,94	10,45	0,06	0,12	1,53	3,12	51324	8	51
291	4,9	Sand	1,76	-1,50	-1,09	10,29	0,08	1,03	3,75	12,11	3835	4	40
292	4,9	Clay	1,76	-1,51	-0,99	10,28	0,07	0,15	3,57	7,29	19849	6	19
293	4,9	Sand	1,76	-1,51	-1,08	10,32	0,07	1,84	3,62	11,69	3181	8	60
294	3,1	Clay	1,76	-1,50	-1,07	10,34	0,11	0,83	4,25	13,70	2907	6	60
295	3,1	Sand	1,76	-1,50	-1,09	10,29	0,08	1,03	3,75	12,11	3835	5	19
296	3,1	Clay	1,76	-1,51	-1,08	10,32	0,07	1,84	3,62	11,69	3181	13	31
297	3,1	Sand	1,76	-1,51	-0,99	10,28	0,07	0,15	3,57	7,29	19849	6	34
298	1,1	Clay	1,76	-1,45	-1,04	10,28	0,08	2,21	1,79	16,27	10668	19	36
299	1,1	Sand	1,76	-1,51	-1,11	10,36	0,03	3,73	1,72	15,61	25460	10	37
300	1,1	Clay	1,76	-1,49	-1,16	10,39	0,02	1,46	0,85	7,71	17250	20	20
301	1,1	Sand	1,76	-1,51	-1,04	10,28	0,02	2,35	1,37	12,49	57725	10	12
302	0,5	Clay	1,76	-1,51	-1,11	10,42	0,02	2,57	0,64	12,77	29955	17	24
303	0,5	Sand	1,76	-1,51	-1,11	10,25	0,02	1,27	1,23	24,69	57205	27	36
304	0,5	Clay	1,76	-1,51	-1,05	10,29	0,02	0,82	0,70	14,02	30857	17	21
305	0,5	Sand	1,76	-1,51	-1,04	10,25	0,02	1,82	0,42	8,50	33829	1)	22

1) Corrosion attack under PE-tape

Table 4. Maximum and minimum potential, and the mean value of maximum and minimum potential recorded with oscilloscope and with the CORREAL-system on each test coupon 0, 1 and 3 milliseconds after current interruption

Voltage	Coupon	Off-potentials (Vdc) recorded								
		with oscilloscope after						with CORREAL after		
		0 milliseconds			3 milliseconds			1 millisecond		
U_{ac}	nr	Emax	Emin	Emean	Emax	Emin	Emean	Emax	Emin	Emean
30 V	272	1,11	-3,76	-1,33	-0,94	-1,54	-1,24	-	-	-
	273	1,43	-3,42	-1	0,86	-1,5	-1,12	-0,69	-1,75	-1,21
	274	0,55	-3,18	-1,32	-0,92	-1,22	-1,07	10,24	-10,24	-1,14
	275	0,86	-3,77	-1,46	-0,9	-1,46	-1,12	9,95	-1,69	-1,15
	276	0,88	-3,97	-1,55	-0,68	-1,89	-1,29	-0,22	-2,21	-1,17
	277	0,68	-3,91	-1,62	-0,8	-2,01	-1,41	-0,55	-1,79	-1,17
	278	-	-	-	-	-	-	-0,69	-1,63	-1,15
	279	0,65	-2,4	-0,88	-0,82	-1,58	-1,2	-0,79	-1,7	-1,24
	280	1,95	-5,4	-1,73	0,61	-3,31	-1,35	-0,58	-1,53	-1,03
	281	2,44	-5,58	-1,57	-0,03	-2,41	-1,21	0,08	-2,46	-1,2
	282	-	-	-	-	-	-	10,24	-10,24	-1,15
	283	1,18	-5,09	-1,96	-0,53	-2,18	-1,35	-0,36	-7,04	-1,27
	284	3,22	-5,68	-1,23	-0,41	-2,38	-1,4	1,67	-4,36	-1,23
	285	3,55	-8,65	-2,55	1	-3,14	-1,07	2,28	-3,82	-1,19
	286	-	-	-	-	-	-	10,24	-10,24	-0,48
	287	2,79	-6,61	-1,91	0,22	-2,63	-1,2	3,71	-5,96	-1,05
10 V	290	1,1	-4,71	-1,8	0,3	-2,17	-0,94			
	291	0,85	-3,65	-1,4	-0,23	-2,33	-1,23			
	292	1,2	-4,22	-1,51	0,14	-2,18	-1,02			
	293	1,05	-4,28	-1,61	-0,18	-2,82	-1,5			
	294	0,63	-2,93	-1,15	-0,84	-1,33	-1,08			
	295	0,53	-2,98	-1,23	-0,74	-2,29	-1,51			
	296	0,68	-3,85	-1,56	-0,44	-2,44	-1,44			
	297	1,08	-3,8	-1,36	-0,36	-3,02	-1,34			
	298	0,44	-3,73	-1,64	-0,75	-1,18	-0,96			
	299	0,5	-3,38	-1,44	-0,65	-1,08	-0,86			
	300	0,65	-3,9	-1,63	0,12	-3,03	-1,45			
	301	1,33	-4,63	-1,65	0	-1,98	-0,99			
	302	0,85	-3,8	-1,48	-0,86	-1,27	-1,07			
	303	1,28	-3,92	-1,32	-0,12	-1,5	-0,81			
	304	0,79	-3,85	-1,53	-0,58	-1,64	-1,11			
	305	0,87	-3,8	-1,47	-0,63	-1,26	-0,94			

Table 5. Proportion of time when the IR-free potential is less negative than the limit value for complete cathodic protection, and less negative than the free corrosion potential.

Potential limit	Proportion of time, in % , when IR-free potential is less negative than limit value	
	10 Vac	30 Vac
Free corrosion potential	29 - 43	34 - 42
Complete cathodic protection (– 0.95 Vdc)	39 - 47	39 - 52

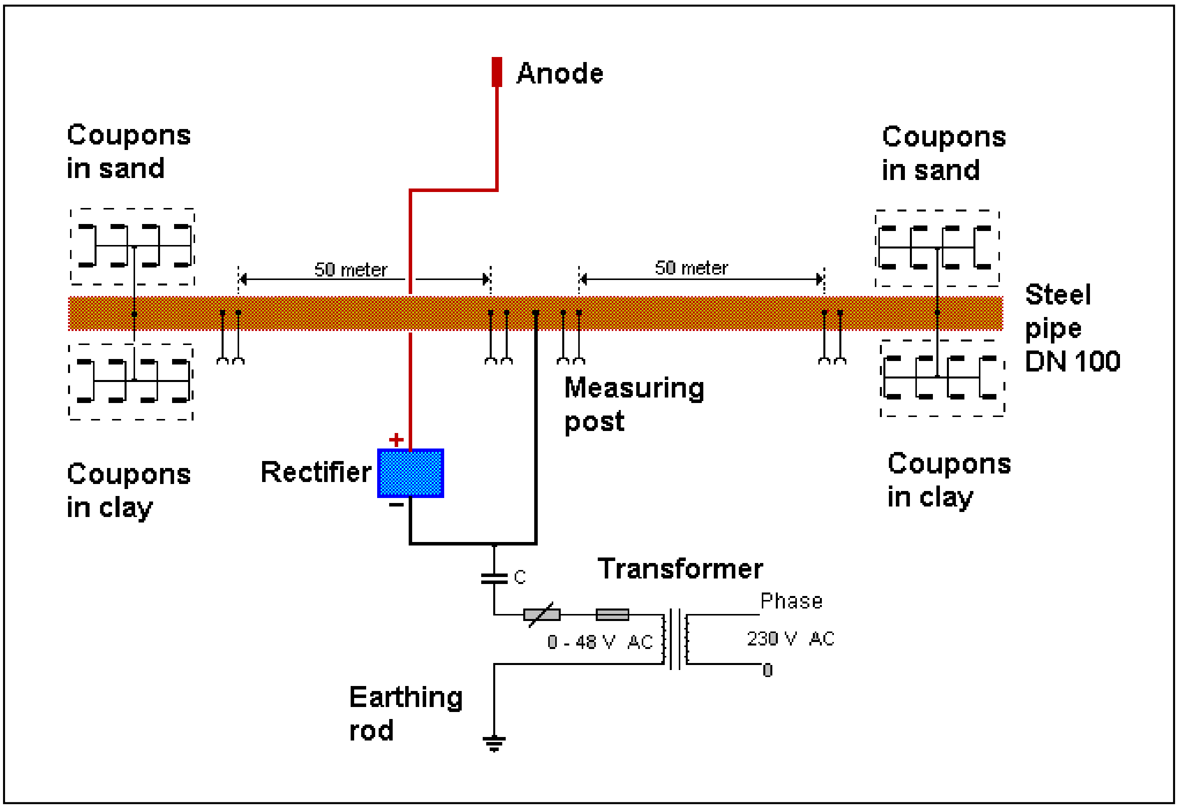

Figure 1. The field-test installation.

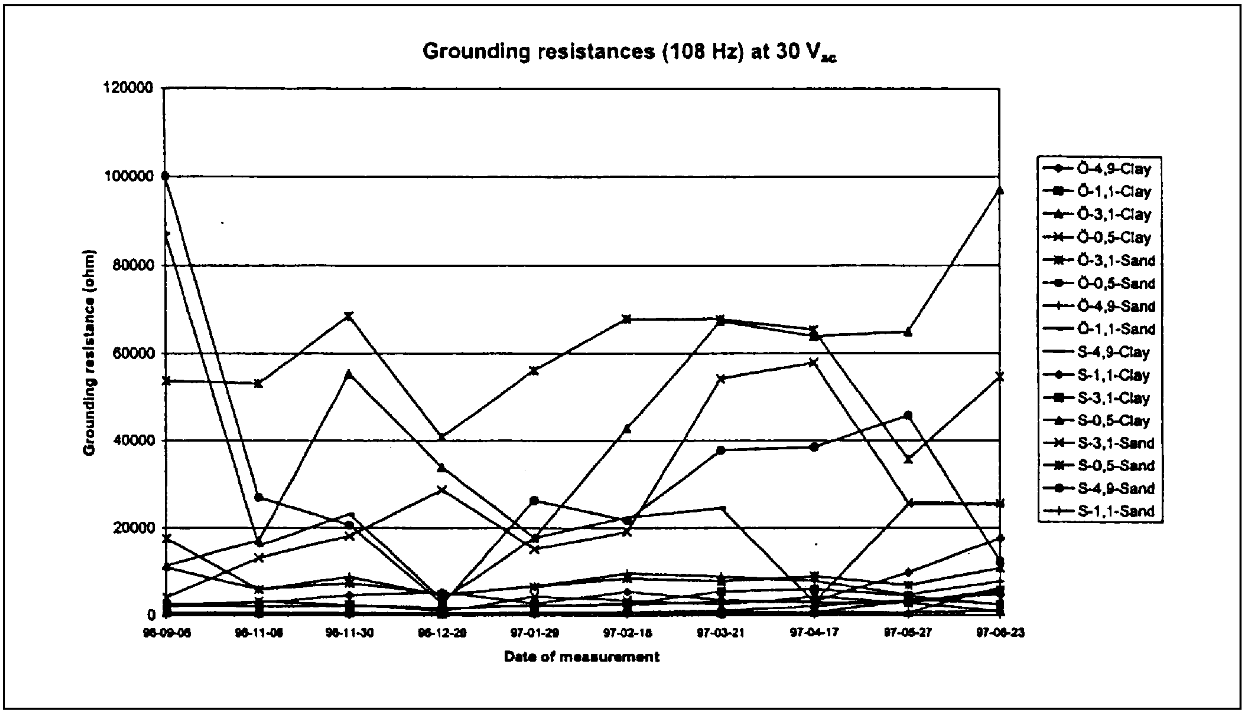

Figure 2 The grounding resistance (Rgr) of the test coupons at the measurement occasions in the 30 Vac-series.

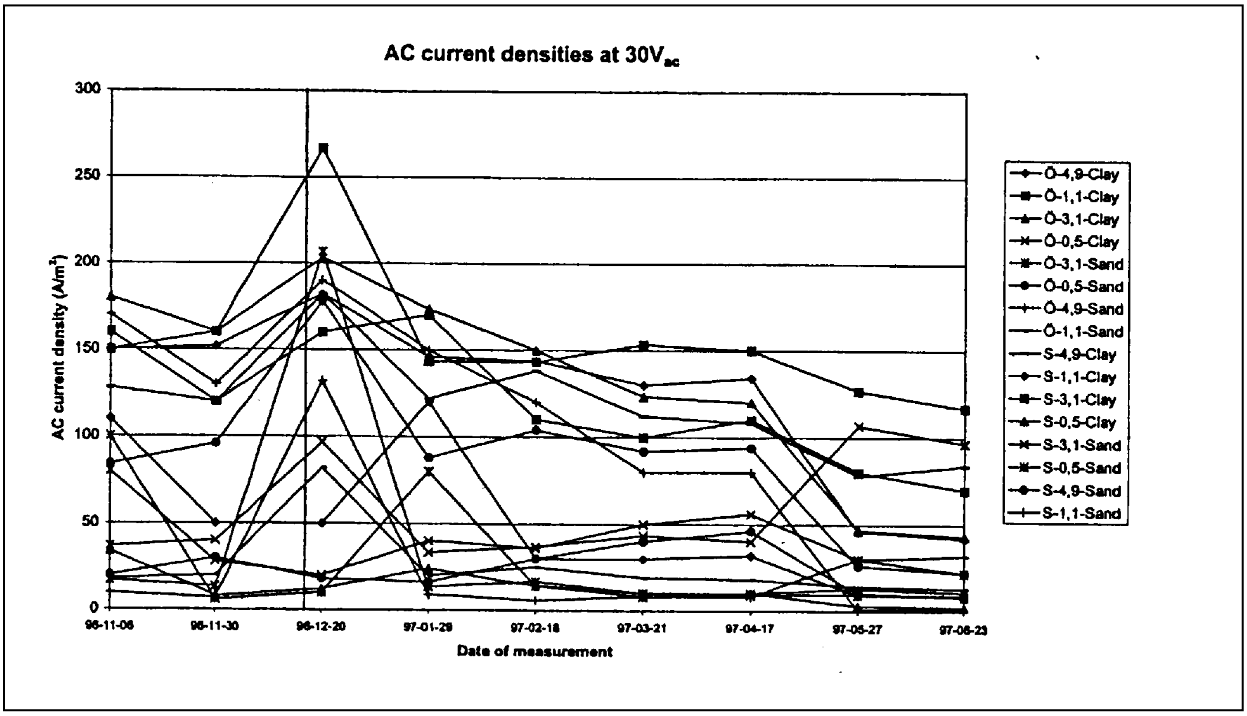

Figure 3. The alternating current density (Jac) of the test coupons at the measurement occasions in the 30 Vac-series.

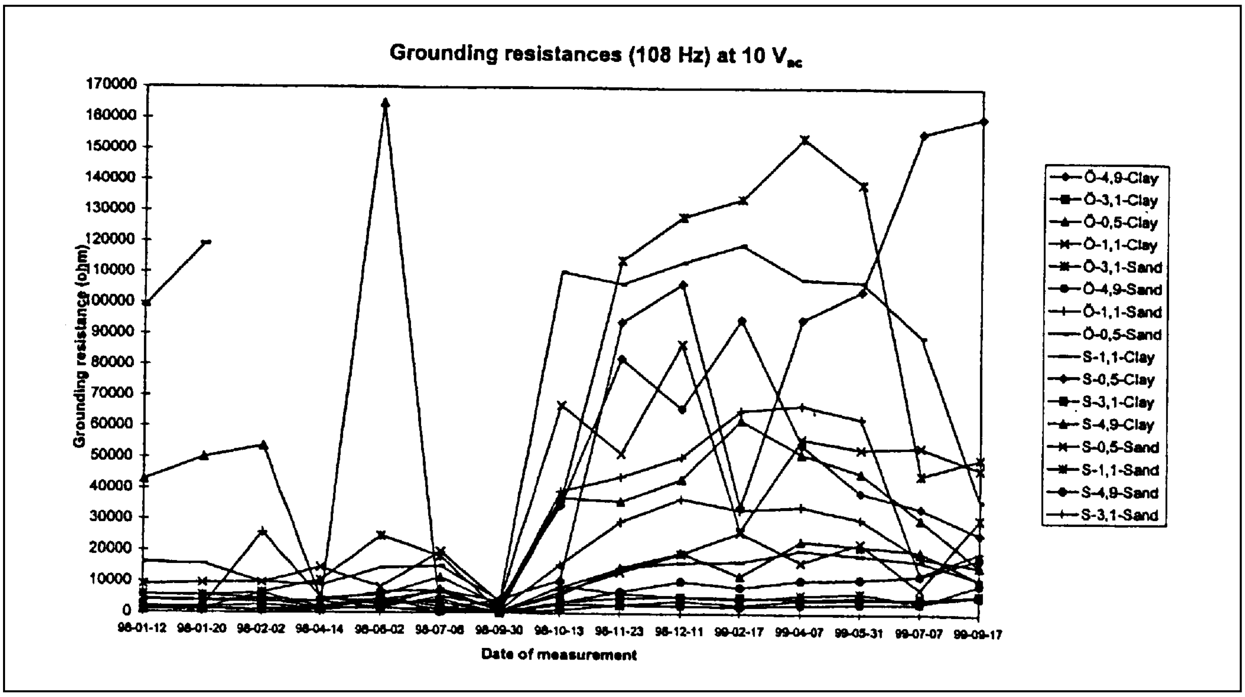

Figure 4. The grounding resistance (Rgr) of the test coupons at the measurement occasions in the 10 Vac-series.

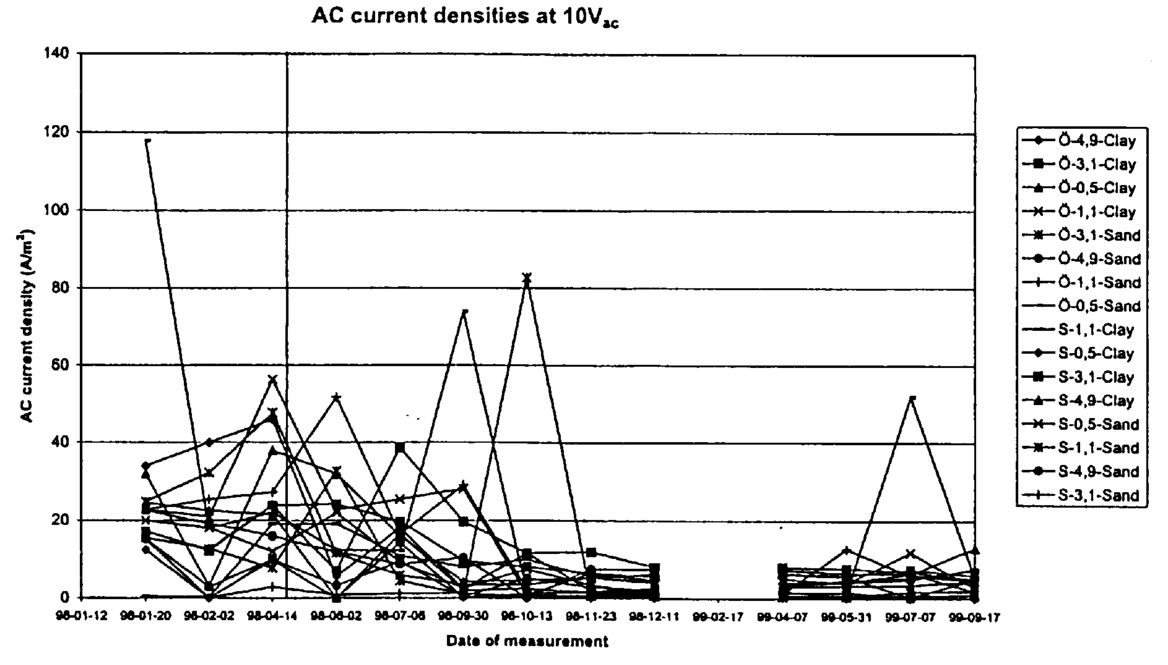

Figure 5. The alternating current density (Jac) of the test coupons at the measurement occasions in the 10 Vac-series.

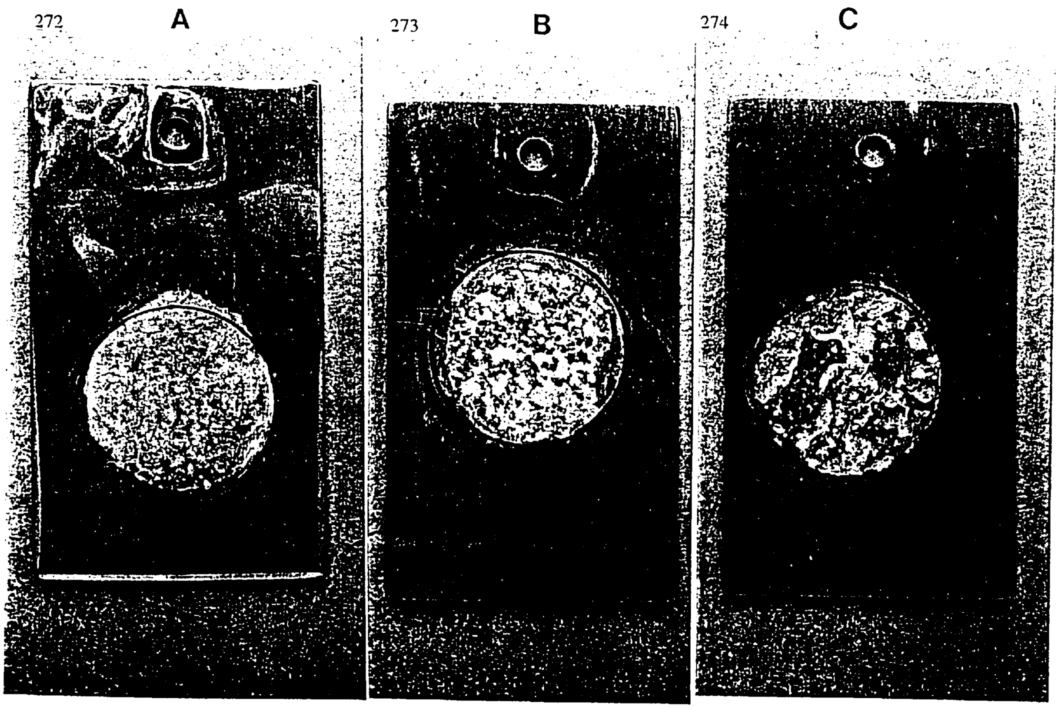

Figure 6. Examples of the appearance of the corrosion attack on the test coupons. A= "uneven surface", B= "rough surface", C= "pocked surface"

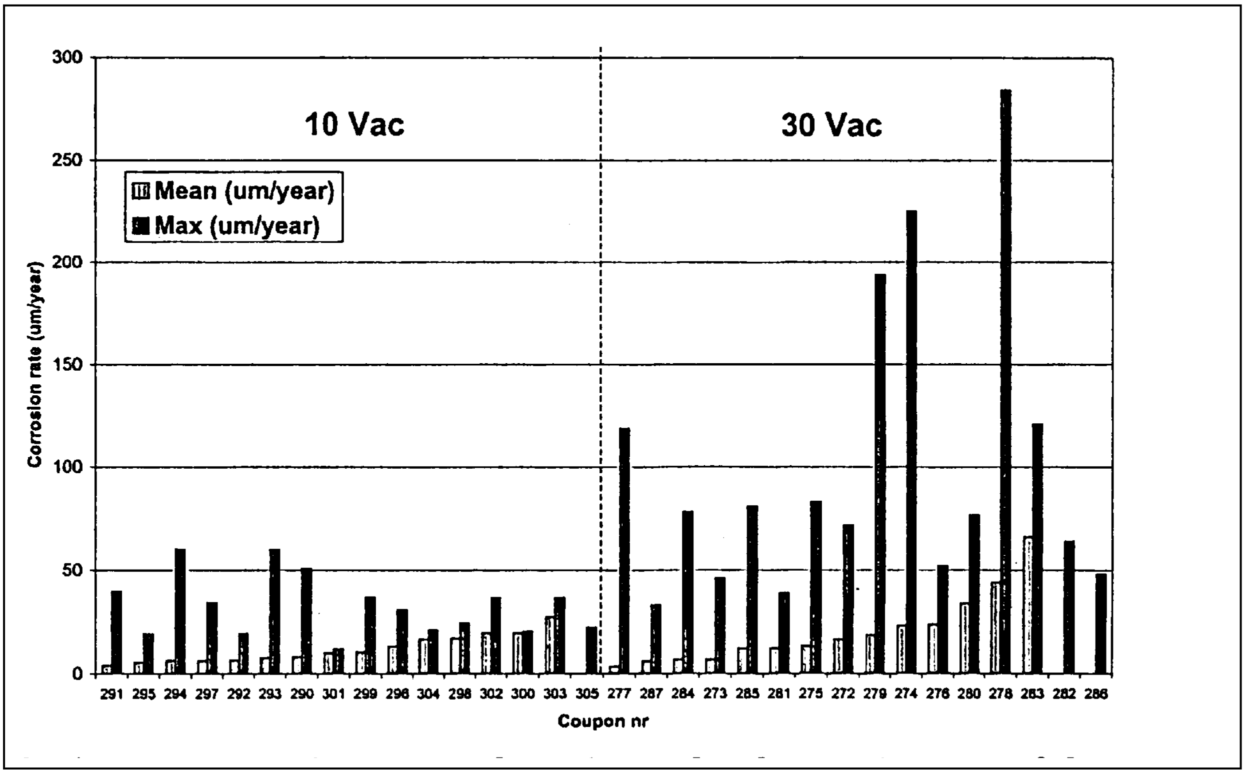

Figure 7 Average corrosion rate and maximum local corrosion rate of the coupons. The corrosion rates are ordered from left to right according to increasing average corrosion rate.

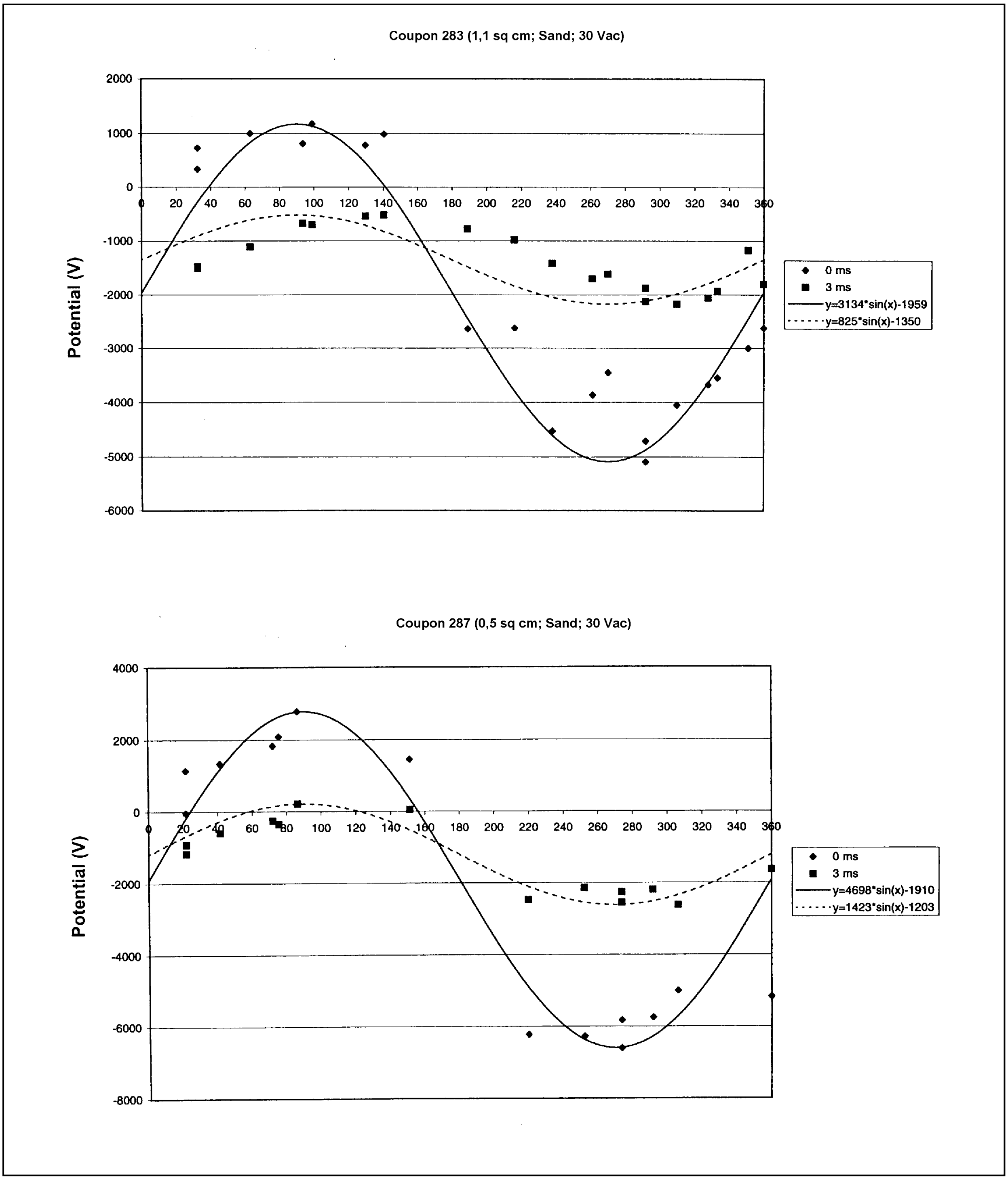

Figure 8. Two examples of sinusoidal slopes fitted to IR-free potentials, recorded with an oscilloscope. The unbroken line represents the potential read immediately (0 milliseconds) after current interruption, and the broken line represents the potential read 3 milliseconds after the interruption. (Coupons Nr. 283 and 287).

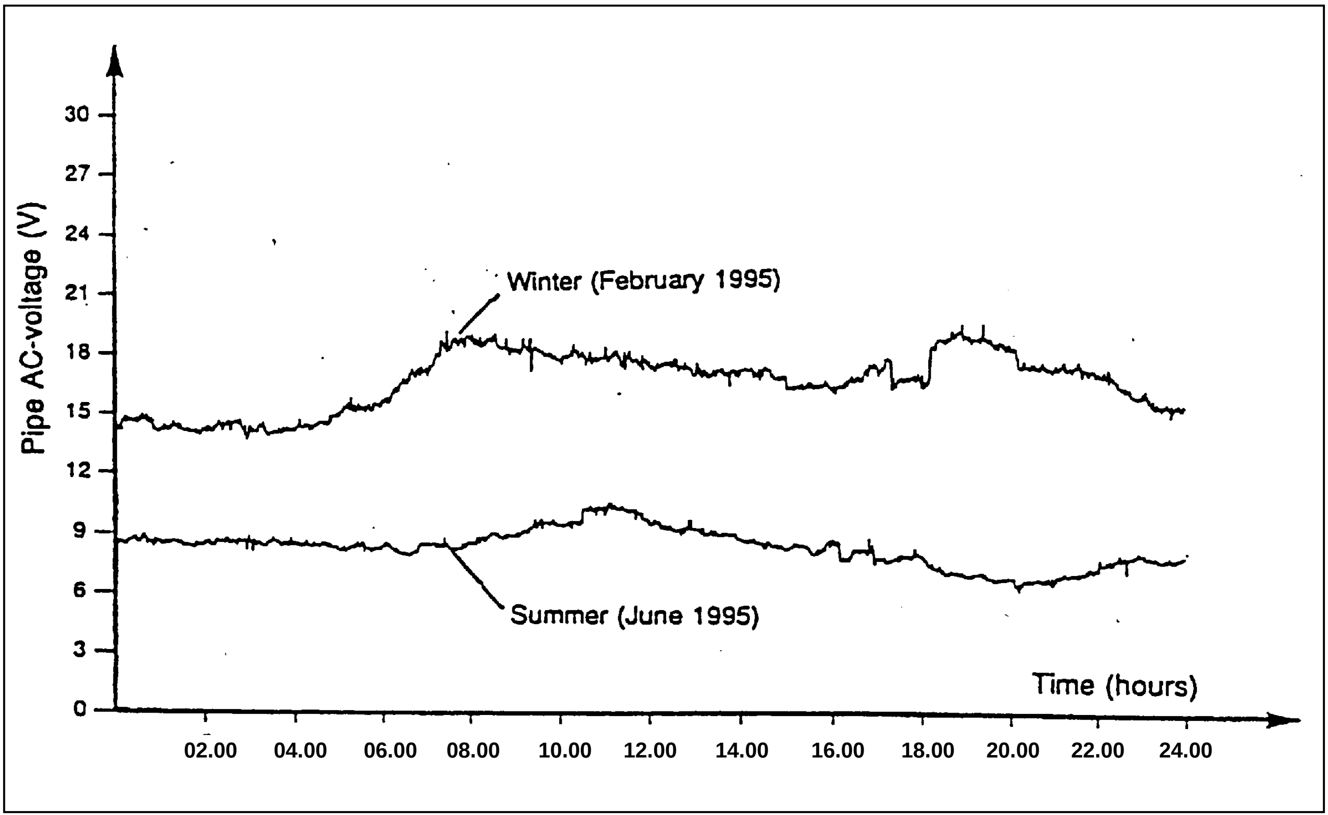

Figure 9. Diurnal variations in the induced alternating voltage in a natural gas pipeline in southern Sweden in the summer and in the winter. The alternating voltage of the pipeline is induced from a parallel 400-kV-power line.