The use of coupons in the field of a.c.-corrosion of pipelines

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Abstract

At the present, when preventive and mitigation measures are known and mostly successfully applied, relevant fundamentals of a.c. corrosion are still unknown. The effort to describe principles of corrosion induced by a.c. current is not negligible and laboratory and field investigations across Europe are carried out.

Coupons, which are electrically connected to and buried in the vicinity of a high voltage interfered pipeline are commonly used to investigate the a.c. corrosion risk of a pipeline /1/. Results from coupon measurements, which may be transferred to the pipeline, include a.c. and d.c. current densities, a.c. voltage and d.c. potentials, spreading resistance and - at least - the corrosion to be found on the excavated coupon.

This paper summarises results, which were obtained from co-operative a.c. corrosion project supported by Slovenský Plynárenský Priemysel, a.s. (Slovakia) and Ruhrgas A.G. (Germany). Due to big alterations of a.c. interference, which cathodically protected pipelines are exposed to, decision to run test field experiments under controlled conditions was adopted. For that purpose test field with real soil conditions was built. Throughout experiments that were carried out from 6 to 14 months 24 coupons were exposed in soil and interfered by d.c. and a.c. current maintained at constant level.

To evaluate a risk of possible corrosion attack caused by a.c. current from coupon to soil potential readings, off potential measurements within 2 ms after coupon disconnection from electrical source were taken. Obtained results allow to compare value of applied a.c. and d.c. current density and off potential readings to surface of coupons after their excavation. Corrosion attacks of steel under soil deposits formed on exposed surface of coupon were observed. The first part of paper is dedicated to all above results.

The second part of this paper describes the results from 66 coupons, which were installed for more than two years at a high voltage (50Hz) interfered pipeline at 5

different locations where the average a.c. voltage varied between 3.9 and 36V. The above mentioned measurements had been carried out twice a month. The results indicate that operating conditions strongly interfere the results obtained. Different coupons may behave different from each other at one location. Short term measurements, e.g. of a.c. current density, may give rise to false conclusions concerning the existing a.c. corrosion risk of the pipeline due to the strong dependence of the spreading resistance from soil conditions and cathodic protection parameters. Recommendations concerning the use of coupons and their accuracy will be provided regarding the use of the current density criterion mentioned in /2/, the long term operation of coupons, the interpretation of apparently non reproducible coupon results and their transferability to the high voltage interfered pipeline.

/Part 1/

1. Description of test conditions and installation of coupons

An unusual approach was adopted to prevent any possible interference from external stray current sources. Test field with a size approx. 30x20 m was built in Košice facility of Slovenský Plynárenský Priemysel, a.s. (SPP). The field with ability to keep a constant water level had been insulated from surrounding environment and afterwards was filled with original soil.

The field was equipped with 4 rod anodes, which were fed from an electrical source and provided a.c. and d.c. current distribution.

During the whole period of the test, 24 carbon steel coupons with 1 cm^2 exposed steel surface were installed in the soil. Coupons were divided into eight groups, 3 coupons at each. All coupons in the same group were supplied with the same d.c. and a.c. current, they were exposed in the soil a different time only.

Coupons were installed in the depth, which guaranteed their position under a ground water line. Test field was filled up with water taken from facility safety fire system.

Protective current of all coupons was equal to d.c. current density of $J_p = 1\ A/m^2$. Alternating current (50Hz) for various groups was adjusted to level of a.c. current density $J_{a.c.}$ from 0 up to 240 A/m^2. A.c. and d.c. current of a coupon was maintained constant throughout the whole period of the test. Smooth deviations of pre-set current values were checked and maintained weekly. For detailed parameters of the coupons see Table 1.

Table 1: Basic parameters of coupons

group number	coupon number	E_n [mV]	J_p [A/m^2]	$J_{a.c}$ [A/m^2]
I.	955	-818	-	-
	4	-815	-	-
	3	-818	-	-
II.	954	-806	1	20
	2	-817	1	20
	1	-814	1	20
III.	956	-807	1	40
	5	-795	1	40
	6	-828	1	40
IV.	957	-806	1	80
	8	-798	1	80
	7	-798	1	80
V.	960	-810	1	120
	10	-814	1	120
	9	-814	1	120
VI.	958	-818	-	20/100
	11	-798	-	20/100
	12	-798	-	20/100
VII.	13	-798	-	-
	961	-811	1	20/100
	14	-798	1	20/100
VIII.	959	-806	1	240
	15	-826	1	240
	16	-826	1	240

E_n - Corrosion free potential

Coupons 955, 3 and 4 were not connected to AC&DC source e.g. bare steel was exposed to soil conditions and impact, without any external polarisation (neither d.c. nor a.c.). Coupons 958, 11, 12 and 961,14 were exposed to variable a.c. current interference (daily: 8 hours of 100 A/m^2 + 16 hours of 20 A/m^2). Results obtained from coupon 13 were considered useless, due to a coupon failure.

2. Measurements

Long-term test field investigations started in July 2000 and finished in September 2001. Throughout the period following parameters had been measured:

- corrosion free potential E_n of coupons before connection to AC&DC source,

a) weekly measurements

- a. c. voltage $U_{a.c.}$, on potential E_{on} (by multimeter) and off potential E_{off} of coupons (by MoData HighSpeed meter)

b) monthly measurements

- spreading resistance of coupons

c) continuous measurements

- data recording measurements of currents, which polarised coupons

All potential measurements were related to $Cu/CuSO_4$ reference electrode. Measuring reference electrode was placed in a close vicinity of measured coupon to avoid big ohmic drop error.

Off potential readings were taken by MoData HighSpeed meter in a moment of 2 ms after disconnection of a coupon from the AC&DC source.

Spreading resistance of the coupons were measured by meter in 3 pin arrangement.

Required constant values of a.c. and d.c. polarizing currents were monitored by data logger.

3. Soil and water environment characteristics

Soil in the test field was clay-sandy character. Soil resistivity into the depth of 1 m was assessed to 36 Ohm.m, into the depth of 1,5 m it was 44 Ohm.m. Factor pH of the soil was in a range between 6,4 - 6,7.

Some of previous investigations have indicated how important was to know a chemical composition of soil or water environment, which bared steel was exposed to /3/, /4/. According to published experiences an analysis to assess total and carbon hardness of soil and water solution was made. Achieved results are described in Table 2.

Table 2 - pH and hardness of water & soil solution

	pH	total hardness [°dH]	carbon hardness [°dH]
(water&soil) # 1	7,91	21,56	13,44
(water&soil) # 2	8,13	19,04	12,37
water	6,96	12,04	1,29

4. Assessment of coupons after excavation

After finishing long-term field measurements coupons had been carefully excavated and checked. Coating applied on coupons as well as soil deposits, which had been formed on the steel surface, were removed. At the deposits, which formed compact layer, thickness of the layer was measured and a content of single chemical components was assessed by EDX analysis.

For thoroughly removal of corrosion and soil deposits, coupons were chemically cleaned in Clark’s solution. Afterwards a detailed photo documentation of the coupons had been done. After they have been weighted, a maximum corrosion depth of steel surface was measured by CNC scanning machine /5/, /6/. An example of the surface profile measured on coupon 7 is enclosed in Annex 1.

5. Results

Selected achieved results of performed measurements and identified maximum corrosion rates of the coupons are described in Table 3.

Table 3: Selected results of the test

group number	coupon number	J_p [A/m^2]	$J_{a.c}$ [A/m^2]	$U_{a.c.}$ (average) [V]	exposure time [days]	max. corr. depth [mm]	max. corr. rate [mm / year]
I.	955	-	-	-	187	0,014	0,027
	4	-	-	-	269	0,041	0,056
	3	-	-	-	456	0,013	0,010
II.	954	1	20	5	183	0,041	0,082
	2	1	20	16	259	0,149	0,210
	1	1	20	8	446	0,053	0,043
III.	956	1	40	9	183	0,129	0,257
	5	1	40	8	256	0,051	0,073
	6	1	40	8	443	0,058	0,048
IV.	957	1	80	16	183	0,086	0,172
	8	1	80	33	256	0,106	0,151
	7	1	80	31	443	0,173	0,143
V.	960	1	120	25	183	0,102	0,203
	10	1	120	22	254	0,126	0,181
	9	1	120	29	441	0,149	0,123
VI.	958	-	20/100	9/43	183	0,106	0,211
	11	-	20/100	6/28	204	0,035	0,063
	12	-	20/100	5/26	391	0,040	0,037
VII.	13	-	-	-	coupon failed	-	-
	961	1	20/100	6/26	183	0,073	0,146
	14	1	20/100	7/32	391	0,118	0,110
VIII.	959	1	240	35	183	0,014	0,028
	15	1	240	50	254	0,123	0,177
	16	1	240	59	441	0,176	0,146

Corrosion free potentials (see Table 1) of the coupons were quite high and approx. equal, with maximum variance among single coupons of 33 mV, what may indicate a similar starting conditions of the coupons.

Development of spreading resistance of majority of the coupons had a slightly rising trend. Behaviour of coupons 2, 7, 960 and 12 was quite unstable, what in parameter of spreading resistance meant noticeable changes of the values.

In circumstances of the test, when a.c. and d.c. coupon polarising currents were maintained on pre-set level, each change of spreading resistance of the coupon resulted in a change of a.c. voltage. Two coupons (2 and 956) out of three ones with the highest corrosion rates reached an average value of $U_{a.c.}$ equal to 16 and 9 Volts. The maximum a.c. voltage of 107 V (rms.) was measured on coupon 9.

It was supposed, that potential measurements, which were measured weekly with MoData High Speed meter, would predict if the single coupons achieved a potential criteria given by /2/ in a full time period of a.c. voltage sinus wave. A final comparison of MoData potential results against surface condition of excavated coupons showed a contradiction in between. Example: According to potentials given by MoData High Speed measurements, coupons of Group III. were the ones, which should have been sufficiently cathodically protected, however corrosion rates from 48 to 257 µm/year were observed. In vice-versa, the coupon 959 (120 A/m^2) with the 30% of unprotected time (U_{off} > -850 mV) according to the results of HighSpeed measurements was stated as almost sufficiently protected. Conclusions published in /3/ about unreliability of MoData High-Speed measurements in specific conditions of Calcium soil layers created on steel surface were confirmed, although the interference of measuring cabling on measured results was not clearly ruled out.

Visual inspection of exposed steel surface mostly showed a presence of compact mineral layers with dominating content of Fe, Ca and Si.

In several cases, the layers were characterised by high adhesion to steel surface, what was the reason of their harder mechanical removal from surface. Even though compact layers were found on steel surface of the coupons, the coupons were not sufficiently protected. Big corrosion attacks were distributed along a circumference of bared steel surface, what seemed as a common link for several coupons. In some particular cases uneven formation of mineral layers on the steel might have caused an uneven surface current concentration, which possibly resulted in local substantial increase of current density.

Corrosion attacks of the steel were identified as small pits uniformly distributed across the coupon surface or as singular, small by area but deep pits on an otherwise uncorroded surface or as noticeable corrosion maps with a significant impact. Majority of „advanced“ attacks tended to create a rounded shape.

A visual inspection and measuring of corrosion depth demonstrated an insufficient level of corrosion protection with corresponding d.c. current density J_P = 1 A/m^2. The minimum corrosion rates 10 and 27 µm/a were identified on the coupons 3 and 955 belonging to Group I. e.g., the group without any d.c. and a.c. polarisation. Corrosion rates of the coupons 12, 11 (without cathodic protection but with a.c. interference) achieved the level of 37 and 63 µm/a. Every coupon exposed to a.c. interference and cathodic protection achieved higher corrosion rates, than the coupons of the Group I. (no a.c. nor d.c. load). Coupons of Group II. that were constantly exposed to $J_{a.c.}$= 20 A/m^2 were identified corroded, with the maximum corrosion rates from 43 - 210 µm/a. Identified corrosion rates of all coupons were in a range of 10 - 257 µm/a. A bar graph interpretation is enclosed in Annex 2.

Substantial differences in corrosion rates of the coupons in Groups II., III., VI. and VIII. came up. However, we attempted to establish equal conditions for all coupons formed a group by manageable influencing parameters.

Based on the comparison of the results, it was stated, that coupons 2, 956, 958 with substantial higher corrosion rates within its own group reached higher spreading resistance values than the rest of the coupons of the group in comparable exposure time.

/Part 2/

6. Introduction and coupon test sites

In order to find out how coupons have to be used when assessing the a.c. corrosion risk of a pipeline a field test at a high voltage interfered pipeline had been carried out. Fig. 1 shows a schematic sketch of the pipeline and the high voltage line (50Hz) which is parallel routed over some ten km.

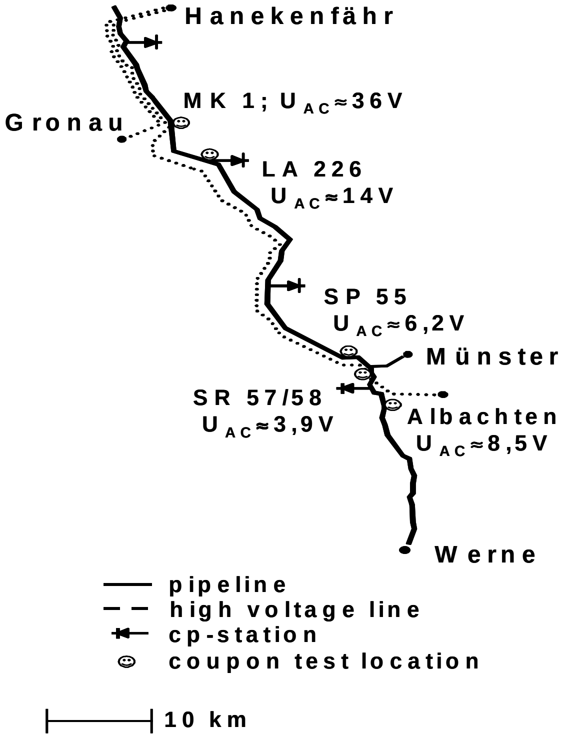


Fig.1:
A sketch showing the parallel routing between the high voltage line and the inductively interfered pipeline. Five test locations, named MK 1, LA 226, SP 55, SR 57/58, and ‘Albachten’, for coupons had been selected. The a.c. voltages given reflect the average pipe/soil a.c. voltage over two years (this was the scheduled duration for coupon tests). The pipeline had been constructed in 1966 and is bituminous coated.

For a period of two years 66 coupons, free steel surface 1cm^2, had been installed at these locations. Tab. 4 in Annex 3 gives the details and summarizes the results from the measurements, which had been carried out twice a month (location MK1, SP 55 and ‘Albachten’) or continuously by data logger (SR 57/58 and LA 226).

The goal of these investigations was to describe the conditions under which the results from coupon measurements may be considered to be reliable and representative for the corrosion process at a real coating fault and thus for the a.c. corrosion risk of the interfered pipeline.

To achieve this the following questions had to be answered:

How many coupons should be installed per site?
How long shall coupons be operated?
How to conclude to corrosion rate from coupon measurements?

7. A.c. current density and spread resistance

Fig 2a, 2b and 3a, 3b and 4a, 4b show a.c. current density and spread resistance of coupons installed at “Albachten”, SR57/58 and MK1 for two years respectively.

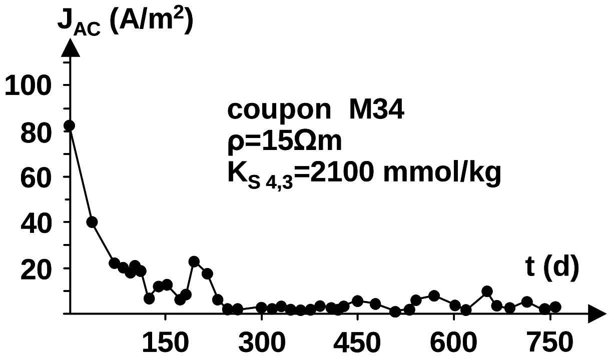


Fig 2a:
A.c. current density of coupon M34 installed at ‘Albachten’ with time. Due to the increase of spread resistance the current density gradually decreases. Short term measurements, e.g. during 3 months, will provide falsified results regarding the a.c. corrosion risk. After two years corrosion was negligible (see table 4).

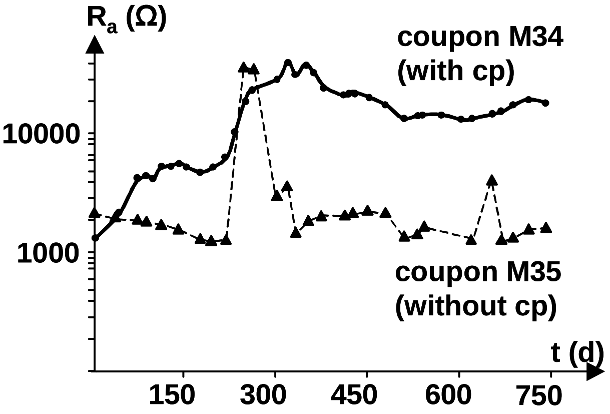
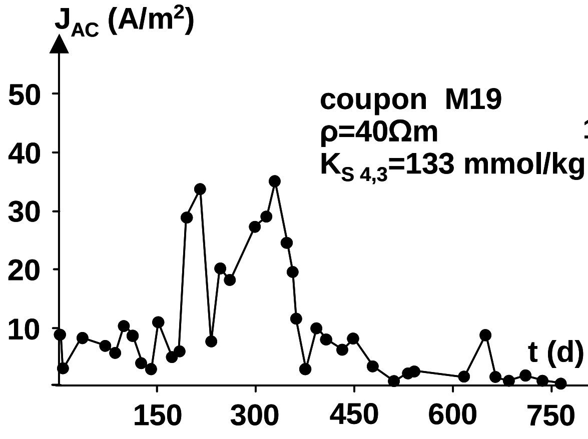


Fig 2b:
Spread resistance of coupon M34 with time. For comparison the spread resistance of coupon M35, installed at the same location but operated without cp is also given. Although the soil resistivity is low (ρ=15Ωm) the spread resistance is governed by the bicarbonate content in the soil, indicated by the high level of acidic capacity ($K_{S\ 4,3}$), which will – in combination with cp - give rise to the formation of calcareous surface layers (see also /3/).



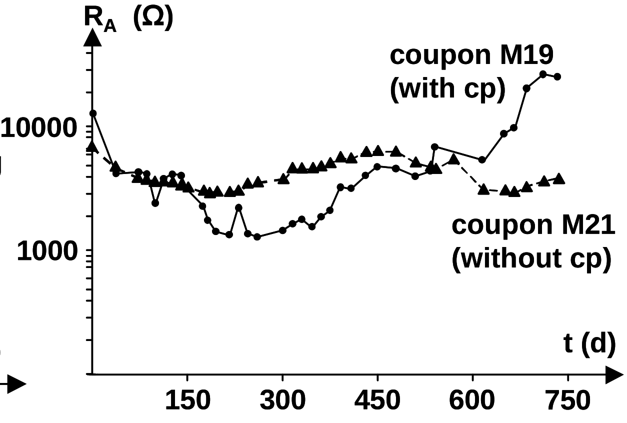
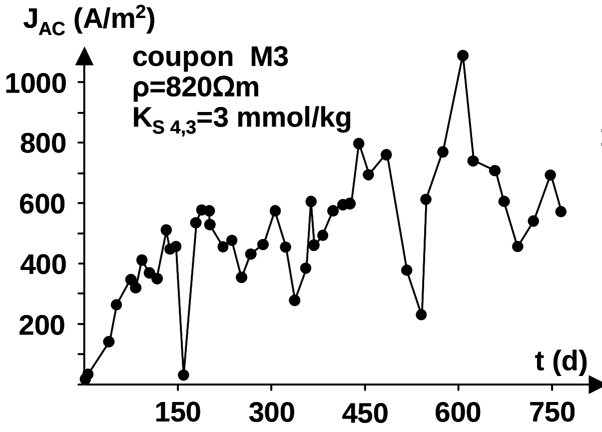


Fig 3a:
A.c. current density of coupon M19 installed at SR 57/58 with time. Mean current density is generally well below critical levels (e.g. 30A/m^2) due to the (delayed) increase of spread resistance. After two years corrosion was negligible (see table 4).

Fig 3b:
Spread resistance of coupon M19 with time. For comparison the spread resistance of coupon M21, installed at the same location but operated without cp is also given.
In combination with cp the long time characteristic of spread resistance may be described by a gradual increase, which came up afterwards a minimum had been achieved after app. ½ year.



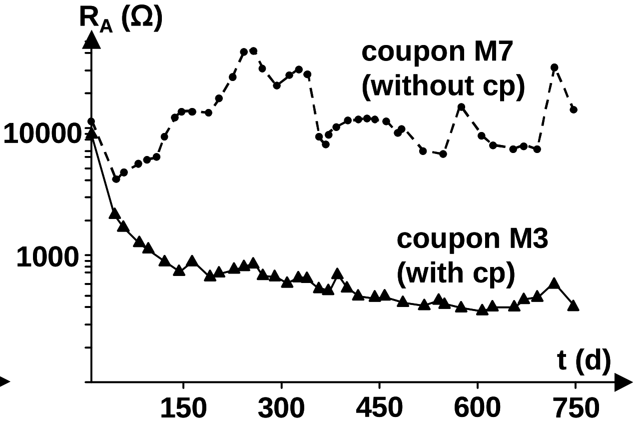


Fig 4a:
A.c. current density of coupon M3 installed at MK1 with time. After installation the current is low due to the high soil resistivity (although U_{ac} is high, see table 4). This is a good example that current density measurements using probes, which are only temporarily, e.g. minutes, in contact with soil may result in a clear underestimation of a.c. corrosion risk as current density remarkably increases due to reduction of spread resistance. After two years the steel surface of the coupon was uniformly corroded and the pit depth was 0.35mm (see table 4).

Fig 4b:
Spread resistance of coupon M3 with time. For comparison the spread resistance of coupon M7, installed at the same location but operated without cp is also given.
In this case the combination with cp results in a remarkable decrease of spread resistance although the soil resistivity is high.
The low acidic capacity ($K_{S\,4,3}$=3 mmol/kg) indicates low concentration of bicarbonate and thus a negligible ability to form surface layers.

From these results it is concluded that coupons should be operated for at least one year. After this time corrosion which may be found – or not found – on the coupon may be considered to be representative for the pipeline.

8. Corrosion rate and 'reproducibility' of coupon results

Fig. 5a and fig. 5b show the results of corrosion rate measurements from two series of coupons, which had been installed at SR57/58 and MK1 respectively.

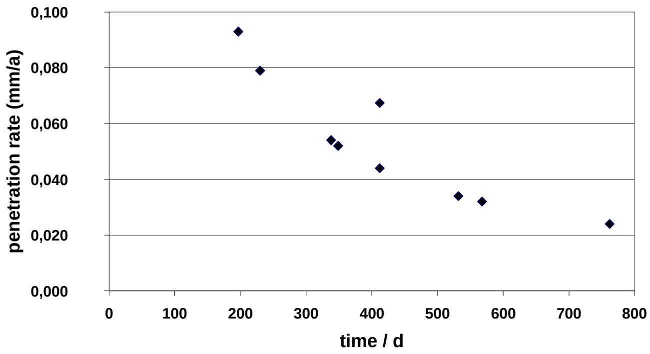


Fig 5a:
Penetration rate as a function of time for different coupons buried at SR57/58; each data point represents one coupon.
The coupon installed for more than 700d is M19 (see fig. 3a,b). Corrosion rate decreases with time, suggesting a well defined and similar corrosion system among all coupons. Results like these are rarely found with coupon measurements.

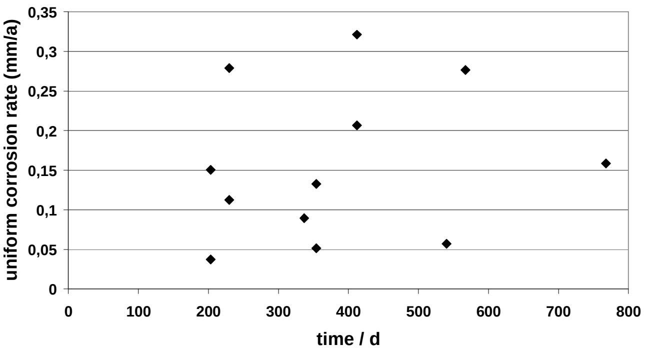


Fig 5b:
Uniform corrosion rate as a function of time for coupons buried at MK1; each data point represents one coupon. The coupon installed for more than 700 days is M3 (see fig. 4a,b). No defined relation may be found in this case, which suggests the strong impact of any parameter, which cannot be governed by experimental effort. This is a typical result which should be expected from a.c. corrosion coupon measurements (see also /3/).

From these results it is concluded that coupon measurements should generally be considered to exhibit a considerable amount of uncertainty, i.e. they might suggest corrosion rates, which are too low compared to the corrosion rate, which may appear within a coating fault on the pipeline. The conclusion, which had been drawn for Ruhrgas practise is that three coupons per site will be installed if a.c. corrosion risk of a pipeline has to be investigated.

9. A.c. current density, d.c. current density and corrosion rate

Fig. 6a and 6b show the relation between uniform corrosion rate and penetration rate as a function of the average a.c. current density as measured on all coupons installed.

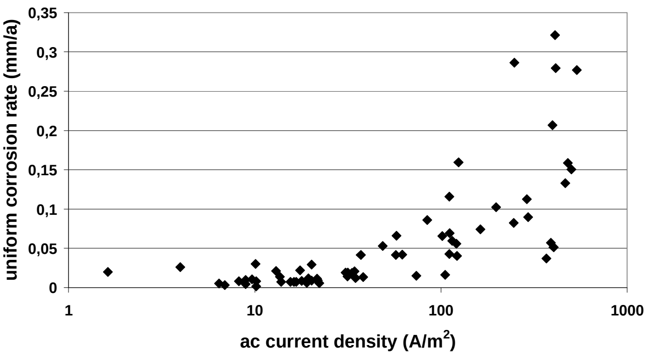


Fig 6a:
Uniform corrosion rate as a function of mean a.c. current density. It may be concluded from this diagram that corrosion rate shows a tendency to increase more rapidly if current density exceeds a level of app. 30A/m^2.

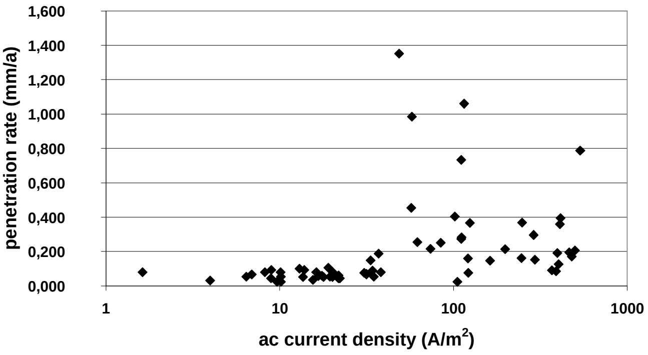


Fig 6b:
Penetration rate as a function of mean a.c. current density. Corrosion rate shows a tendency to increase if a.c. current density exceeds a level of app. 30 A/m^2.

The results suggest that a considerable uncertainty exists when predicting the corrosion rate from a.c. current density measurements, i.e. the corrosion rate may be heavily overestimated even if a.c. current density is higher than 100 A/m^2. As a conclusion for future coupon measurements at high voltage interfered pipelines it has been decided to excavate coupons after app. one year of operation and to base further decisions on the mass loss and/or on the maximum pit depth which is found on the corroded coupon.

The final question to be answered in the course of each a.c. corrosion investigation is related to the origin of any mass loss or pits, which are found on coupons, i.e. it has to be certified that corrosion is due to alternating current and not to the action of differential aeration or galvanic elements or d.c. stray currents. For this purpose fig. 7 shows the relation between mean a.c. current density and mean d.c. current density (i.e. cp current density). D.c. current density is well above 0.2 A/m^2 for those coupons showing a.c. current densities higher than 10 A/m^2, which is generally considered to be sufficient for cathodic protection. From this it is concluded that corrosion on coupons is due to a.c. (Note: The pipeline (see fig. 1) is not interfered by d.c. stray currents). For future coupon measurements it is recommended to ensure the proper function of cathodic protection, e.g. by monitoring the current output of cp rectifiers and by measuring their IR-free potential.

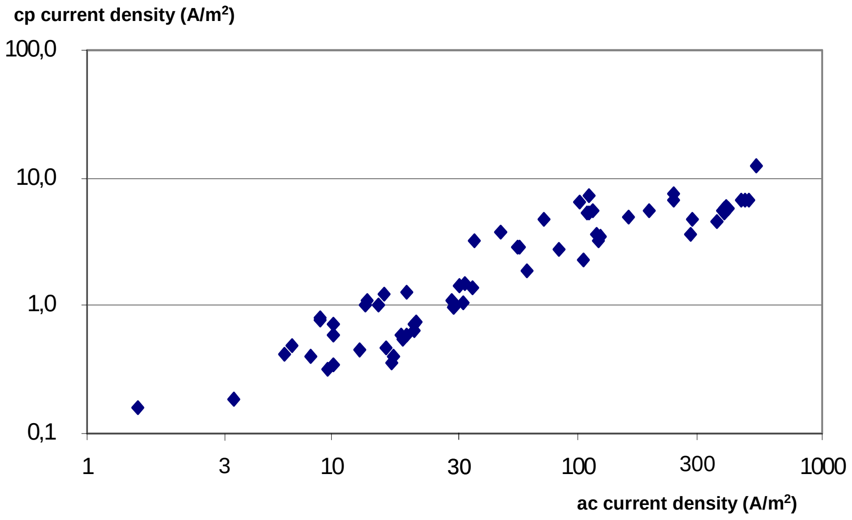


Fig. 7
Relation between mean a.c. current density and cp current density for all coupons installed. The data suggest the decreasing spread resistance of those coupons showing both high cp and a.c. current densities.

10. Conclusion

Summing up the particular results following conclusions can be described:

- experience from the test indicates, that coupons installed in the same soil conditions may behave different; for practical applications it is recommended to install at least 3 coupons per site in order to increase the probability for identifying “the worst case conditions”,
- a substantial factor, which determines the corrosion conditions on the phase boundary between soil and exposed steel, is chemical composition of soil deposits and its consistency,
- achieved results in Groups III., IV.,V and VI. demonstrated that in case of coupons with the shortest exposure time, maximum corrosion rates were identified. It may be concluded, that the fastest progress of attack is related to initial stage of „uncovered“ steel surface. In some particular cases of a real pipeline in operation, where a.c. interfering source (power line or traction) came to its vicinity afterwards, and coupons were applied as evidence of up-to-date a.c. corrosion status, an „hurried“ conclusions of possible corrosion risk can be adopted. However, possible substantial changes throughout the exposure period should be taken in to the consideration,
- the assessment of corrosion rate from coupon a.c. current density measurements may result in significant under or overestimation. It is therefore recommended to measure weight loss and/or pit depth of excavated coupons after sufficient exposure time.

Literature:

/1/ CEOCOR; AC-corrosion on cathodically protected pipelines; 2001

/2/ EN 12954; Cathodic protection of buried or immersed metallic structures – General principles and application for pipelines

/3/ Stalder F., Büchler M., Voute C.-H., Bieler J. - Messmethoden zur Feststellung der durch Wechselstrome verursachten Korrosionsgefährdung an kathodisch geschützten Rohrleitungen; final report of FOGA-project 0055, 2001

/4/ Voute C.-H., Stalder F. - Einfluss der Bodenzusammensetzung auf den Ausbreitungswiderstand und die Wechselstromkorrosion von kathodisch geschützten Messproben. CEOCOR - Brussels 2000

/5/ Tuleja S., Kocich J., Hornák P., Ševcíková J. - Štúdium korózneho poškodenia ocelových vzoriek. Hutnícka fakulta TU Košice, 2001

/6/ Tuleja S., Kocich J., Hornák P., Ševcíková J. - Štúdium korózneho poškodenia ocelových vzoriek II. Hutnícka fakulta TU Košice, 2001

Annexes:

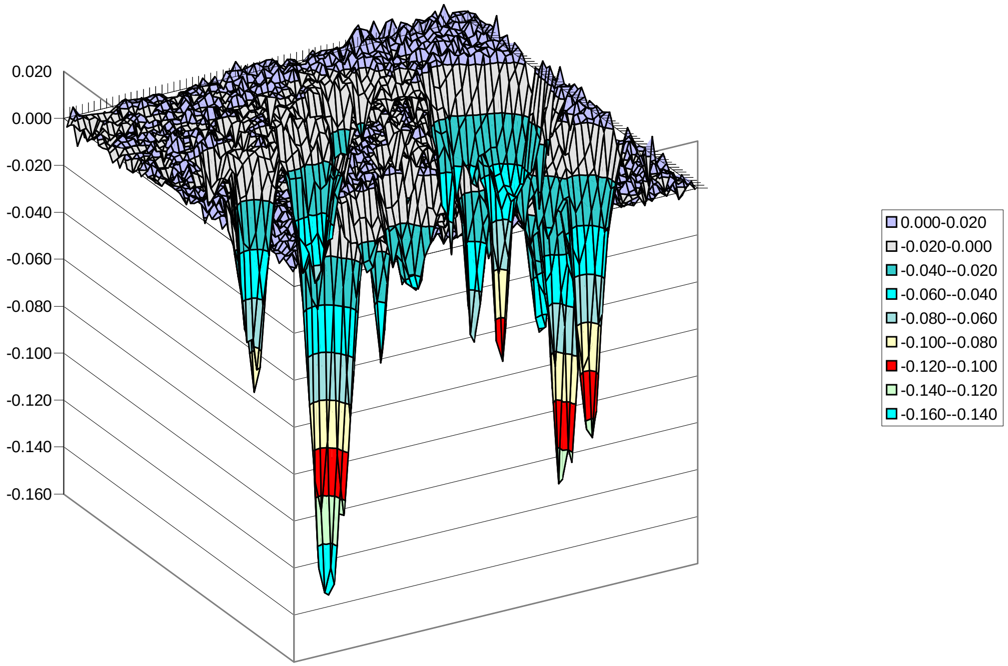
1 - Coupon 7 - Surface profile

2 - Bar graph - Maximum corrosion rates of the coupons

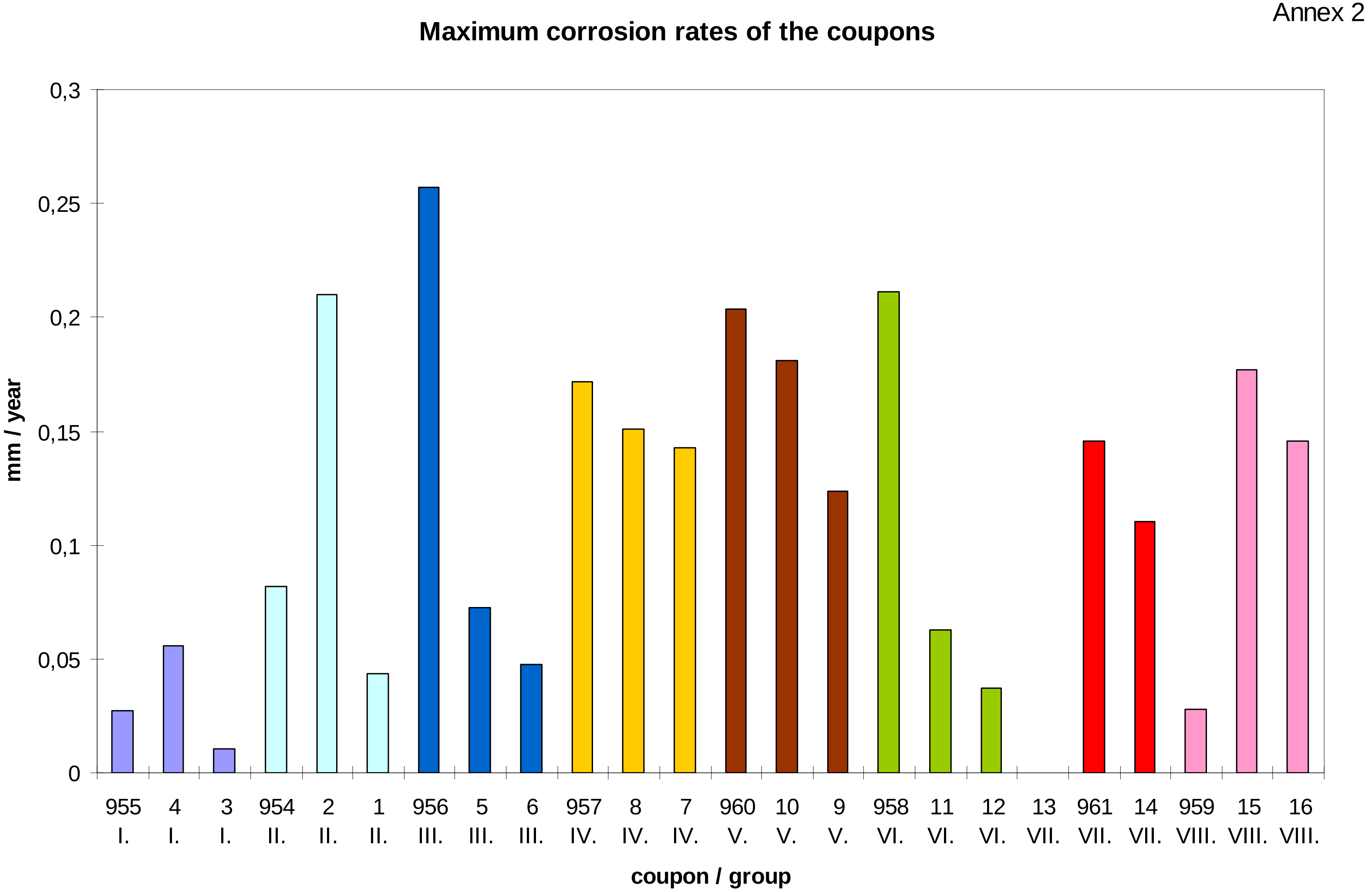
3 - Table - Data from coupons installed at a high voltage interfered pipeline

Annex 1

Coupon 7 – surface profile



Annex 2


Maximum corrosion rates of the coupons
mm / year
0,3
0,25
0,2
0,15
0,1
0,05
0
955 I.
4 I.
3 I.
954 II.
2 II.
1 II.
956 III.
5 III.
6 III.
957 IV.
8 IV.
7 IV.
960 V.
10 V.
9 V.
958 VI.
11 VI.
12 VI.
13 VII.
961 VII.
14 VII.
959 VIII.
15 VIII.
16 VIII.
coupon / group

Tab. 4: Data from coupons installed at a high voltage interfered pipeline

Annex 3

test location	sample	time	J_{AC} min.	J_{AC} max.	J_{AC}av	J_{DC}min.	J_{DC}max.	J_{DC} av	spread resistance			potential off	Uac			uniform corrosion rate	max. penetration rate
									min	max	av	av	min	max	av		
	No.	in d	A/m^2	A/m^2	A/m^2	A/m^2	A/m^2	A/m^2	Ω	Ω	Ω	V (SCE)	V	V	V	mm/a	mm/a
MK1 coupons in ditch beside pipe soil resistivity ρ = 820 Ωm	M 1	203	16,0	600	368,6	0,4	7,8	4,6	670	2.040	993,5	-0,98	13,0	51,0	35,8	0,036	<0,090
	M 6	203	13,0	844	501,4	0,3	10,2	6,6	479	1.610	734,7	-0,95				0,145	0,207
	M 65	230	40,7	605	412,9	1,3	8,1	5,8	543	855	664,4	-0,98				0,268	0,395
	M 66	230	215,0	329	289,2	0,5	5,5	3,6	862	1.562	1076,9	-0,97				0,108	0,297
	M 43	337	30,0	659	293,9	0,5	10,2	4,7	285	5.950	1749,4	-0,91				0,086	0,153
	M 4	354	15,1	636	402,4	0,2	8,7	5,3	560	1.900	822,3	-1,03				0,050	0,126
	M 5	354	13,0	778	464,7	0,2	12,4	6,6	311	1.360	690,5	-0,99				0,128	0,196
	M 51	412	21,0	842	396,7	0,4	9,6	5,7	454	1.197	670,7	-0,99				0,199	0,192
	M 52	412	16,8	828	409,7	0,3	10,1	5,9	290	1.217	636,8	-0,99				0,309	0,360
	M 2	540	13,8	592	389,5	0,3	9,7	5,6	579	2.100	843,3	-1,01				0,055	0,084
	M 44*)	567	26,5	1008	536,6	0,4	15,7	12,3	389	1.900	638,2	-0,96				0,266	0,788
	M 3	768	14,6	1085	480,6	0,3	12,7	6,6	372	2.100	708,0	-1,02				0,152	0,172
*steel surface 3,75 cm^2	M 7	768	free corrosion						4.000	40.000	13907,7	-0,59				0,036	0,135
LA226 coupons attached to pipe soil resistivity ρ = 800 Ωm	M 8	357	5,5	348	124,1	0,2	9,9	3,5	262	23.400	5781,1	-0,97	13,0	39,0	14,2	0,153	0,367
	M 9	357	22,5	210	121,7	1,2	6,1	3,2	261	3.890	1393,4	-1,02				0,039	0,077
	M 10	357	45,0	357	198,1	2,5	10,3	5,6	262	1.070	707,5	-1,04				0,098	0,214
	M 53	418	12,9	107	61,9	0,5	3,3	1,9	1.234	4.300	1989,8	-1,08				0,040	0,254
	M 54	418	23,0	347	162,6	1,0	9,5	4,9	498	995	643,7	-1,04				0,071	0,146
	M 55	418	14,2	254	121,0	0,9	8,6	3,7	522	1.995	1084,5	-1,03				0,054	0,159
	M 11	774	22,0	562	246,2	2,2	14,0	6,7	262	1.862	606,0	-1,07				0,079	0,161
	M 12	774	23,0	274	105,5	0,5	9,2	2,3	261	2.560	1283,5	-1,13				0,016	<0,023
	M 13	774	37,0	698	247,8	2,3	19,0	7,4	260	916	519,7	-1,07				0,275	0,368
	M 14	774	free corrosion						3.000	10.000	6987,0	-0,70				0,009	0,032
SP55 coupons in ditch beside pipe soil resistivity ρ= 25 Ωm	M 22	194	15,6	232	111,3	0,8	9,7	5,3	400	782	561,8	-0,98	1,6	11,2	6,2	0,067	0,282
	M 23	194	12,5	210	110,8	0,7	9,7	5,3	447	856	582,6	-0,97				0,041	0,273
	M 67	230	0,3	7,43	1,6	0,0	1,0	0,2	3.180	56.000	31364,4	-1,22				0,019	<0,079
	M 68	230	14,0	75	38,2	1,1	8,7	3,2	139	1.655	827,9	-1,05				0,013	<0,079
	M 45	336	9,7	73	34,8	0,2	3,6	1,5	1.060	2.650	1556,6	-0,85				0,012	<0,054
	M 24	349	2,0	165	57,7	0,2	8,0	2,9	341	12.400	3837,1	-0,97				0,064	0,984
	M 25	349	2,2	230	115,0	0,1	9,5	5,5	359	902	595,0	-0,98				0,057	1,060
	M 56	411	9,7	111	48,6	1,0	7,7	3,8	145	2.010	858,1	-1,04				0,051	1,352
	M 57	411	15,0	269	111,1	1,4	11,5	7,3	140	656	361,9	-1,06				0,111	0,733
	M 27	560	1,9	143	57,2	0,2	5,6	2,9	440	16.000	2551,5	-1,03				0,040	0,454
	M 46	566	32,7	162	73,8	2,2	8,5	4,7	423	1.600	751,3	-0,99				0,015	0,217
	M 26	759	2,5	207	101,6	2,2	12,4	6,3	139	938	539,6	-1,00				0,063	0,404
	M 28	759	free corrosion						1.387	2.880	1892,9	-0,72				0,003	<0,024

Table 4: Continued

test location	sample	time	J_{AC} min.	J_{AC} max.	J_{AC}av	J_{DC}min.	J_{DC}max.	J_{DC} av	spread resistance			potential off	Uac			uniform corrosion rate	max. penetration rate
									min	max	av	av	min	max	av		
	No.	in d	A/m²	A/m²	A/m²	A/m²	A/m²	A/m²	Ω	Ω	Ω	V (SCE)	V	V	V	mm/a	mm/a
SR57/58 coupons in ditch beside pipe soil resistivity ρ= 40 Ωm	M 15	197	3,3	23	8,9	0,4	1,7	0,8	1.700	6.500	3531,5	-1,07	1,2	11,5	3,9	0,009	<0,093
	M 17	197	4,5	39	13,9	0,4	1,8	1,1	1.130	2.640	1706,9	-1,07				0,007	<0,093
	M 69	230	4,4	58,8	16,3	0,6	2,4	1,2	1.570	4.980	2809,0	-1,09				0,007	<0,079
	M 70	230	2,3	29	10,1	0,1	1,0	0,6	2.700	4.700	3477,8	-1,12				0,029	<0,079
	M 47	338	1,1	21,2	6,4	0,2	1,0	0,4	3.000	15.800	8371,1	-1,06				0,005	<0,054
	M 18	349	2,7	41,5	13,7	0,2	2,7	1,0	1.131	4.600	2438,0	-1,01				0,013	<0,052
	M 16	349	2,9	55	20,2	0,5	2,6	1,3	1.049	6.300	2287,8	-1,06				0,009	<0,052
	M 58	412	1,2	42,4	8,9	0,4	2,1	0,8	2.440	6.300	4139,0	-1,05				0,004	<0,044
	M 59	412	0,9	24,1	6,9	0,3	1,0	0,5	4.000	8.000	5420,5	-1,09				0,003	0,067
	M 20	532	3,0	40,7	15,5	0,4	2,3	1,0	1.173	5.700	2517,5	-1,13				0,007	<0,034
	M 48	568	1,1	16,8	4,0	0,0	0,8	0,2	2.670	48.200	14333,8	-1,10				0,025	<0,032
	M 19	762	0,2	35	10,2	0,0	2,1	0,7	1.350	27.000	5248,4	-1,06				0,008	<0,024
	M 21	762	free corrosion						2.940	6.900	4301,5	-0,72				0,005	0,058
'Albachten' coupons in ditch beside pipe soil resistivity ρ= 15 Ωm	M 29	194	10,5	111	37,1	0,5	4,9	1,4	685	4.600	2825,0	-1,08	5,0	28,0	8,5	0,040	0,188
	M 30	194	5,1	69,8	19,1	0,2	2,3	0,6	1.700	7.200	5132,3	-1,09				0,006	0,105
	M 71	232	9,3	98	33,3	0,6	3,6	1,4	955	6.950	2897,5	-1,04				0,018	0,148
	M 72	232	0,7	44	8,2	0,0	2,3	0,4	874	89.500	36744,4	-1,07				0,008	<0,079
	M 50	337	0,7	125	10,2	0,1	3,9	0,3	1.050	38.000	22479,5	-1,01				0,002	<0,054
	M 31	348	6,5	78,7	20,2	0,2	2,7	0,6	1.190	10.600	5617,1	-1,06				0,028	0,082
	M 32	348	6,0	77,8	17,9	0,2	2,6	0,4	1.540	12.900	6289,5	-1,10				0,008	<0,052
	M 60	412	3,2	63	21,8	0,3	2,2	0,7	1.200	6.500	3878,8	-1,05				0,008	0,060
	M 61	412	3,1	79,7	21,8	0,3	2,9	0,7	1.070	7.700	4549,6	-1,04				0,009	<0,044
	M 33	529	1,5	84	13,0	0,1	3,5	0,4	1.000	25.000	11261,9	-1,04				0,020	0,101
	M 49	569	5,6	121	21,6	0,3	3,9	0,6	1.100	6.950	4562,5	-1,05				0,011	0,049
	M 34	761	1,3	82,2	9,7	0,0	2,8	0,3	1.350	42.000	16212,3	-1,05				0,010	<0,024
	M 35	761	free corrosion						1.300	37.000	3878,7	-0,65				0,026	0,083
'Albachten' coupons attached to pipe soil resistivity ρ= 15 Ωm	M 37	348	8,9	104	31,5	0,4	3,5	1,0	980	9.900	3911,0	-1,07	5,0	28,0	8,5	0,014	0,066
	M 38	348	6,3	103	30,7	0,2	3,7	1,1	945	8.280	4359,8	-1,08				0,018	0,077
	M 39	348	6,5	135	34,3	0,3	5,7	1,1	564	6.200	3615,4	-1,08				0,020	0,088
	M 62	411	1,6	56	16,7	0,1	2,2	0,5	840	10.350	5668,8	-1,08				0,007	0,057
	M 63	411	2,0	86,4	22,2	0,1	3,2	0,8	956	16.700	6916,4	-1,03				0,006	<0,044
	M 64	411	0,6	96	17,5	0,0	2,0	0,4	712	46.000	13661,4	-1,09				0,021	0,059
	M 40	759	4,1	132	31,6	0,3	5,2	1,0	590	6.450	3686,9	-1,06				0,019	0,071
	M 41	759	1,5	610	84,5	0,2	11,7	2,7	241	11.500	4224,5	-1,07				0,083	0,252
	M 42	725	3,0	80,2	19,4	0,1	2,6	0,6	1.150	5.700	4147,1	-1,08				0,012	0,053