

MONITORING METHODS OF CATHODIC PROTECTION OF PIPELINES

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Summary

Modern techniques of monitoring cathodic protection effectiveness of the outer and inner surface of underground pipelines have been presented in brief. The methods of pipeline potential monitoring have been described taking into account the CIPS and DCVG techniques, as well as the basics of using corrosion coupons and electrical resistance probes. Examples of measurement results from pipeline operation practice have been given. The possibilities of electrochemical techniques for corrosion current determination, i.e., the corrosion rate of steel in cathodic polarisation conditions, have been presented, indicating the use of a novel harmonic synthesis method for this purpose.

Introduction

A significant number of underground pipelines is made of materials of relatively low resistance to corrosion such as carbon steel and cast iron. Pipelines made of such material are endangered by disadvantageous interaction of various types of factors. From the exterior corrosion action occurs of aggressive soil, underground water, corrosion macrocells, stray currents and microorganisms. Internal corrosion processes are affected mainly by the type and properties of transported medium and the flow character. In order to eliminate or weaken the above hazards and ensure safe operation of pipelines one should apply effective anticorrosion methods and means. Best effects are ensured by simultaneous application of two compatible complementary anticorrosion protection methods – high quality insulation coatings and electrochemical protection: sacrificial anodes or impressed current cathodic protection. Stable and effective functioning of this type of protection requires in turn application of appropriate monitoring systems, allowing systematic control of their quality during many years of operation of pipelines. In this lecture a short review has been given of monitoring techniques available today of external and internal corrosion of underground pipelines, especially in cathodic protection conditions (CP).

Mechanism of Cathodic Protection

Choice of proper techniques of monitoring of cathodically protected pipelines and correct interpretation of obtained results requires knowledge of the mechanism of this type of anticorrosion protection. Basic information on cathodic protection technology can be found in many textbooks, e.g., [1-3]. Contrary to the barrier functioning of insulation coatings, the aim of which is a possibly full separation of the steel surface from the corrosion environment, cathodic protection is an electrochemical method allowing control of the kinetics and mechanism of electrode processes proceeding on the metal/electrolyte phase boundary by DC current polarisation. The generally accepted principles of this initially empirical method can be explained by kinetics of electrode processes [4], the foundations of which are given by the Wagner and Traud mixed potential theory [5]. The principle of cathodic protection in a potential – current density system is explained in Fig. 1.

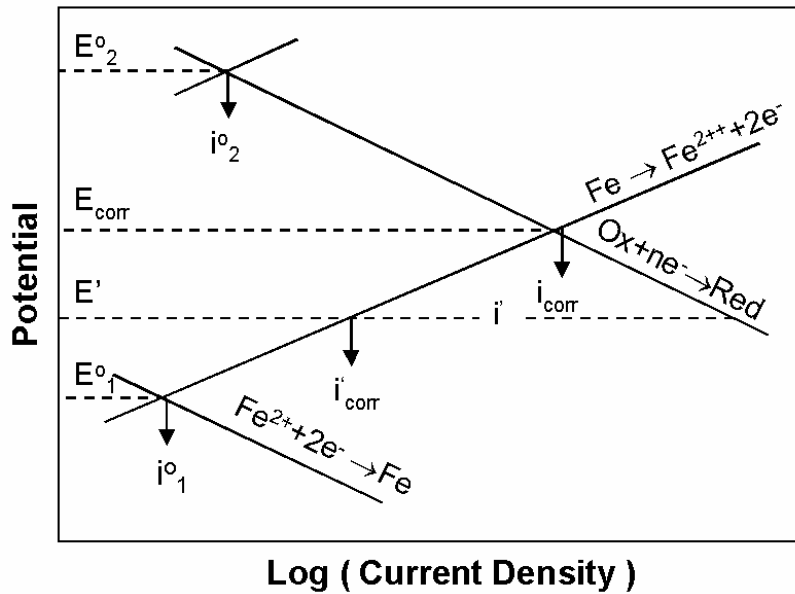


Fig. 1. Principle of cathodic protection

It presents the relation of anodic and cathodic reaction partial currents accompanying the steel corrosion process, i.e., their rate from the imposed potential. In zero current conditions an equilibrium state is established on the surface of steel, in which the anodic (oxidation) process rate is equal to the cathodic (reduction) process rate. This state is characterised by corrosion potential E_{corr} and corrosion current density i_{corr} . By cathodically polarising the pipeline with a DC current, hence appropriately changing the potential from the corrosion potential in the negative direction, one may slow down or hinder the anodic reaction of iron ionisation responsible for the corrosion process. Partial cathodic protection is ensured, for example, by polarisation of steel to potential E' with a current i' , at which the corrosion current decreases to value i_{corr}' . Full hindering of the corrosion process requires polarisation of the metal to the reversible potential of the anodic reaction E_1^0 . In that case the resulting anodic reaction rate is equal to zero, and on the steel surface only reduction processes proceed, e.g., reduction of oxygen in a neutral environment. At an even deeper cathodic polarisation another electrode process starts to proceed, i.e., evolution of hydrogen.

A very important conclusion results from the presented theory, that there is no distinct boundary between the cathodic protection state and its lack, as rigorously accepted by some standards and recommendations. Each cathodic polarisation ensures at least a partial protection of steel from corrosion. However, one should avoid excessive cathodic polarisation as it is harmful. Apart from the fact that it is connected with an unjustified use of energy (high CP current), it may cause hydrogen embrittlement of the material and destruction of protective coatings as the result of excessive alkalisation of the environment. Polarisation cannot be too small, as it may not ensure the required decrease of the corrosion rate. Hence, there is an optimum cathodic polarisation range, in which the corrosion rate falls to an acceptable low level without causing side effects. The possibility of control of such a state should be ensured by modern monitoring techniques of cathodic protection effectiveness.

Monitoring Methods of the Effectiveness of Pipeline Cathodic Protection

Monitoring of Pipeline Potential

It is the oldest and most widespread method of control of electrochemically protected objects based on potential measurement of a cathodically polarised metal surface vs. a nonpolarised reference electrode. The principles of this indirect CP monitoring method are based on an empirically determined dependence between potential and corrosion rate. Such an approach results from lack of possibility of determination in field conditions of the anodic reaction reversible potential at which the corrosion rate drops to zero. This method is being applied in practice from the twenties of the last century, when the American Robert Kuhn experimentally determined that the potential $-0,85$ V measured vs. the Cu/CuSO_4 electrode is in most cases sufficient for protection of steel from corrosion in soil and natural waters. In those days instrumental corrosion rate measurement techniques were not known and the only possible solution was adopting of such a conventional potential cathodic protection criterion instead of direct control of the degree of hindering of corrosion processes.

The CP criterion introduced by Kuhn survived in spite of its limitations till today. It has found reflection in most standards determining in different countries conditions for application of cathodic protection of steel structures. However, one should keep in mind that it is not an optimum criterion and that it is frequently criticised [6,7]. There are situations when deeper cathodic polarisation is needed to ensure protection of steel, e.g., up to $-1,0$ V vs. the copper sulphate electrode, while in many cases a potential of $-0,7$ V is sufficient.

In spite of the fact that the main concept of potential measurement remains unchanged for several tens of years, in this time an immense development took place of technology and measurement apparatus. At present battery operated, inexpensive, light and accurate digital voltmeters are available of $10\text{ M}\Omega$ internal resistance or higher, allowing potential measurement with a resolution of at least 1 mV. Also microprocessor digital recorders called data loggers are being more frequently used for monitoring of potential, allowing long-term sampling and recording of potential values with a pre-programmed frequency. Equipment is used of well known international companies (e.g., MINILOG, MoData and Mini-Trans manufactured by Weilekes Elektronik, CORD-X from COREXCO, IQ from National Instruments), as well as of Polish origin (e.g., microprocessor minirecorders M-01, RP 97 and RP98 from the Technical University of Poznań, mR from L.Instruments, Warsaw, RPK 2000 from „JAK” S.C., Gdańsk) [8].

The basic disadvantage is being more effectively eliminated of the potential measurement technique, namely the participation of the IR component in the measured values. Such a component always accompanies all potential measurements due to the unavoidable distance between the reference electrode and the cathodically polarised structure. This distance causes existence of a resistance on which an ohmic potential drop is formed in the electric field of the cathodic protection installation. Many different methods have been elaborated of IR drop elimination [9,10]. One of the more frequently applied methods is the switch-off method, based on different rates of fading of ohmic and activation polarisation (order of microseconds) and concentration polarisation (order of seconds or minutes) after switching off the current [11]. Particular difficulties are caused today by potential measurements on pipelines which are factory insulated with very good quality coatings, e.g., a polyethylene coating reaching a resistance of $10^{10}\ \Omega\text{m}^2$. These problems are widely discussed in the literature, also in Polish [12, 13].

Intensive Measurements – the CIPS Technique

On the basis of analysis of exploitation data it was found that potential measurements of cathodically protected pipelines performed only in places of fitting of permanent reference electrodes in chosen measurement-control points are frequently insufficient for the correct

evaluation of CP effectiveness. Such points are usually at distances of several hundred meters and information obtained in this way is incomplete. Obtaining of correct potential measurements in chosen places does not indicate correct potentials on the whole route of protected objects. In order to increase the reliability of potential measurements the CIPS technique was elaborated in the seventies. CIPS stands for Close Interval Potential Survey, specified in some countries as the intensive measurement technique, the principle of which is illustrated in Fig. 2.

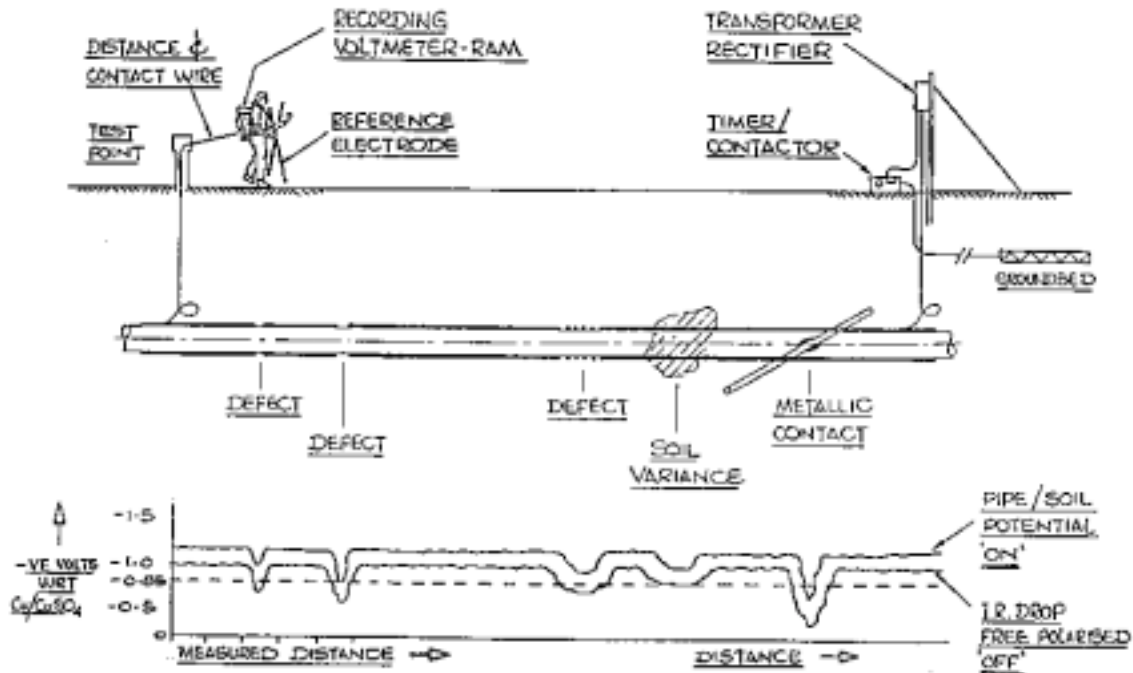


Fig. 2. Schematic diagram of CP monitoring of a pipeline by the CIPS method

The CIPS method is based on connecting a thin, strong cable to a monitored pipeline and performing of frequent (e.g., every several m) potential readings along the route vs. a portable reference electrode [14]. The scaled cable wound on a drum is used for measurement of distance with an accuracy of approx. 1%. One may also apply satellite localisation giving the measurement point co-ordinates with an accuracy of 1 m (GPS system). Simultaneously values are recorded on several channels of the recorder of the „ON” (switch-on) potential, „OFF” (switch-off) potential and the distance. For synchronisation one may use quartz clocks, time radio signals sent out, for example, from Frankfurt or GPS clocks, which may be used in the whole World. Special computer software is applied for recorded data processing. Results can be stored as a database and the cathodic polarisation degree can be compared of pipeline protection during consecutive measurements.

Gradient Methods – the DCVG Method

The DCVG method (short for Direct Current Voltage Gradient) enables evaluation of CP effectiveness (determination of cathodic and anodic zones) and detection of defects in insulation by determining of the zones of inflow or outflow of polarising current [15]. The potential gradient is measured in the ground with a very sensitive voltmeter and two reference electrodes placed on both sides of the investigated pipeline at distances of 1-2 m from each other. The principle of the method is shown in Fig.3.

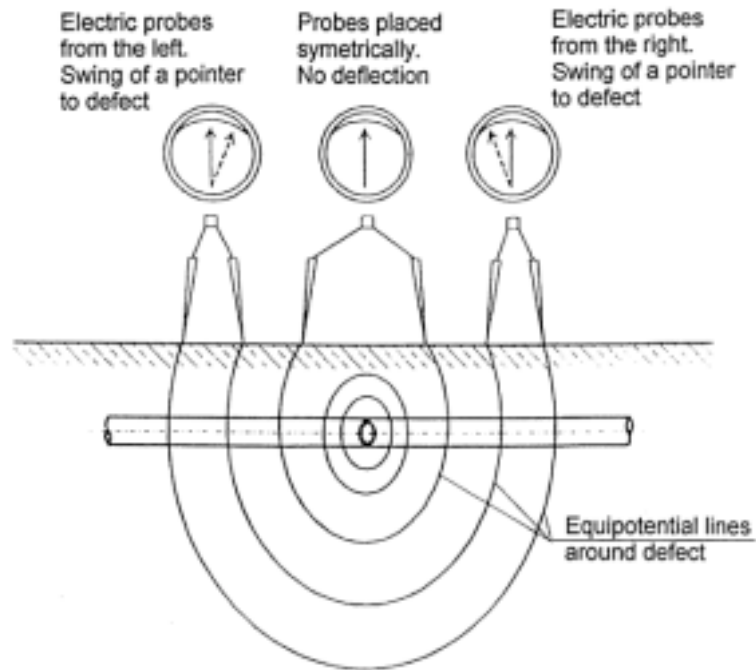


Fig. 3. Principle of the DCVG method

The defects can be localised with an accuracy of 10÷15 cm on pipelines laid on depths up to 6 m. Conclusion as to the shape and size of the defects are made from potential gradient graphs and soil resistivity measurements in the vicinity of the epicentre. During measurements the CP station works in the ON/OFF regime, for example with a frequency of 1.1 Hz (switch-on time 0.3 s / switch off time 0.6 s).

Sometimes combined methods are used (e.g., CIPS and DCVG) such as the method of intensive measurements described by Weßling [16]. The worker walking along the pipeline route records the distance as well as switch-on and switch-off potential changes at small intervals vs. the portable reference electrode. The measurements are supplemented with ON/OFF potential gradients in one or two directions perpendicular to the pipeline. The method requires synchronous switching off of all DC current sources polarising the tested pipeline section. This type of measurement allows determination of the CP effectiveness and detection of insulation leakages (places of increased potential). Other variants of potential gradient measurements on pipelines, as the voltage summing method, the three-electrode method, the IFO (**I**ntensive **F**ehlstellen**o**rtung) method are described during this seminar by Weßling [16]. Practical implementation of the above field methods significantly decreased the number of breakdowns of underground pipelines. More information on field insulation tests is given, amongst others, by Matocha [17].

In recent years complex computer software has started to be used in field measurements based on mathematical models of cathodically polarised underground or underwater structures [18]. The finite element method (FEM) and the boundary element method (BEM) are being used allowing prediction of current and potential distribution on pipelines and correct interpretation of obtained results. However, electrochemical measurements in low conductivity soils can cause additional difficulties connected with the ohmic potential drop.

CP Monitoring with the Use of Simulation Probes

Simulation probes (corrosion coupons) are usually used in the form of steel electrodes of a strictly determined shape and surface area, protected by cathodic protection together with the pipelines. They allow obtaining of additional information on cathodically protected objects on the basis of performed electric and electrochemical measurements. The schematic diagram of simulation probe connection to a cathodically protected pipeline has been shown in Fig. 4.

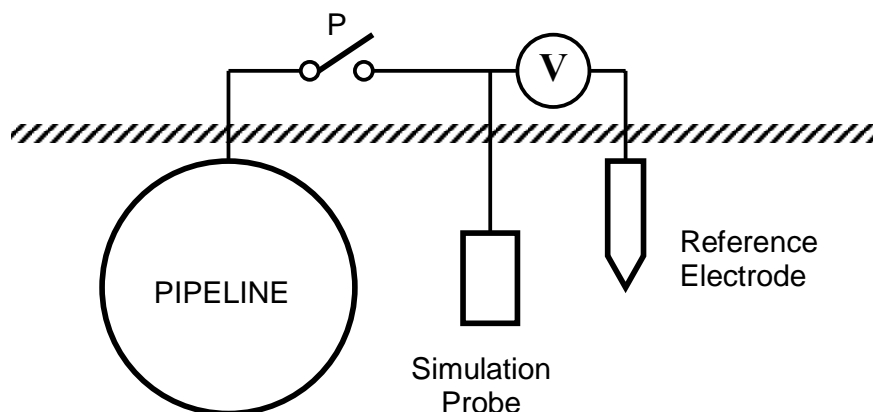


Fig. 4. Method of CP monitoring with a simulation probe

Such a probe allows measurement of the switch-off potential (by disconnecting the P switch) without interrupting pipeline cathodic protection. Different types of simulation probes are described in the literature [19,20] and they find wide application. They enable, amongst others:

- More accurate potential measurement of cathodically protected structures with IR component elimination,
- Determination of the local polarising current density,
- Minimisation of interference on neighbouring underground structures,
- Determination of the mean unit insulation coating resistance,
- Measurement of the corrosion rate in cathodic polarisation conditions,
- Determination of polarisation resistance,
- Measurement of depolarisation rate,
- Determination of the CP level of pipeline sections in casing pipes.

A lot of attention has been recently devoted in USA to simulation probes. Dan Stears et al. [21] describes a pipeline transporting oil in Alaska. Over 400 probes were used, placed in different geological conditions on a route of approx. 1300 km. Obtained results were positively assessed. It was stated that probes placed near the pipeline really allowed a more accurate evaluation of effectiveness of applied CP than other classic potential measurements.

Monitoring of the Corrosion Rate in CP Conditions

For several tens of years mainly potential measurements were used for control of CP effectiveness. In spite of their continuous improvement they give limited information on the state of protected objects. Results of potential measurements (thermodynamic data) are assessed in two categories only: fulfilled/unfulfilled standard CP criteria. Nothing is known on their basis of the real corrosion rate.

A more advantageous solution would be introduction of the so called kinetic CP criteria, which would allow maintaining of the metal structure corrosion rate on a given level depending

on actual requirements. Their introduction depends, however, on elaboration of effective and reliable corrosion rate measurement methods in polarised systems.

A list of methods, applied or tested in this scope, is presented in Fig. 5.

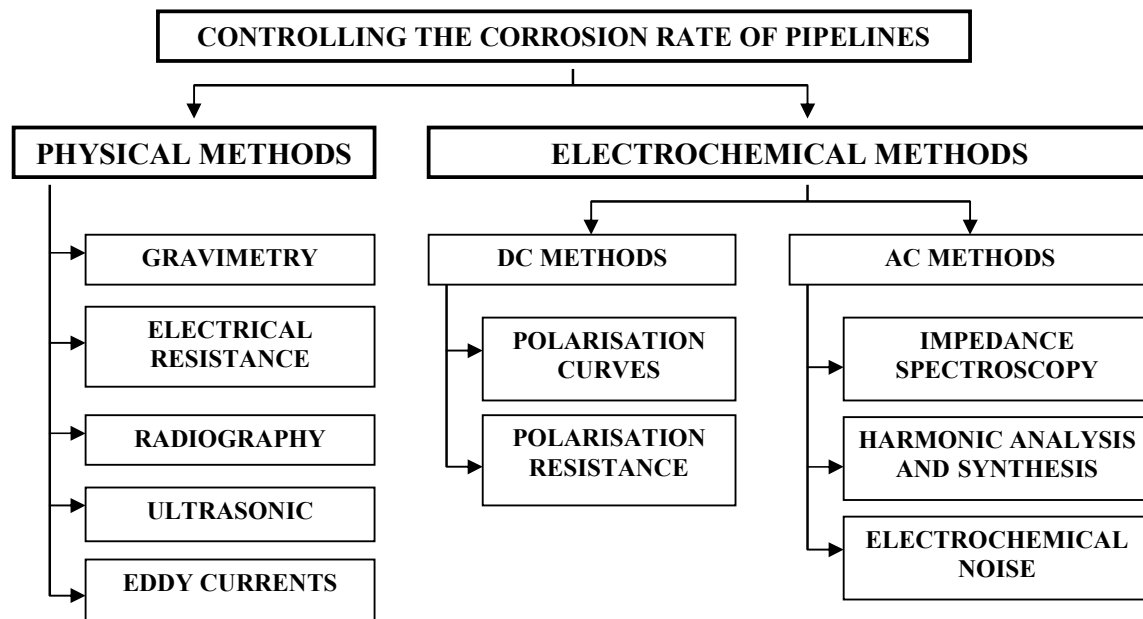


Fig. 5. List of pipeline corrosion rate control methods

Some of them already have been tested with a positive result (physical methods), some have not been positively verified (DC electrochemical methods), some are in the phase of testing (AC electrochemical methods – impedance spectroscopy, harmonic analysis and synthesis) [22,23], while remaining methods (e.g., electrochemical noise) were not investigated up till now. A wider discussion of the possibilities of electrochemical methods in the scope of corrosion rate monitoring of cathodically polarised systems has been given in reviews [24, 25]. Below examples are given of corrosion rate measurement results of cathodically protected industrial structures with the use of gravimetric, electrical resistance and harmonic synthesis methods.

Gravimetry and Electrical Resistance Technique

Gravimetric measurements are the simplest, at the same time the most reliable, method of determination of CP effectiveness based on corrosion rate measurements. They were applied in the initial period of implementation of this technology. They are based on exposure together with the cathodically protected structure of appropriate metal samples, so called coupons, connected by an electric cable in order to ensure the same potential. The mass difference of samples determined before and after exposure gives the corrosion loss, and also the corrosion rate of the protected structure. Knowing the corrosion rate of the unprotected metal in the same conditions, one may determine quantitatively the effectiveness of cathodic protection according to formula:

$$S_{CP} = \frac{M_0 - M_1}{M_0} \cdot 100\%$$

where: M_0 – corrosion loss of unprotected steel,

M_1 – corrosion loss of cathodically protected steel.

The monitoring technique of corrosion process rates with the use of electric resistance measurements is now, apart from electrochemical techniques, one of the most widely applied methods of metal corrosion rate determination in various industrial installations. The technique is a development of the gravimetric method with the difference that instead of determining the corrosion loss by weighing, it is calculated on the basis of the measured electric resistance increase of corroding samples [26]. To attain this an appropriate probe is placed in the corrosion environment, the measuring element of which is made of the controlled corroding metal (usually steel). A change of probe resistance is connected with dissolution of the metal and its transition into corrosion products (oxides or hydroxides) of low electric conductivity. This causes increase of resistance of the probe with exposure time. Control of the magnitude of resistance changes in time allows precise determination of the corrosion rate. Contrary to the weighing method, resistance measurements can be performed at a desired frequency, which at appropriate apparatus sensitivity, allow practically continuous monitoring of the corrosion rate. The measured resistance changes are usually very small and require application of very sensitive measurement methods. Most frequently bridge methods are used with the use of AC currents.

In order to control the cathodic protection effectiveness of industrial structures appropriate resistance sensors are installed, which are electrically shorted in order to equalise the potential with the protected structure. Systematic resistance measurements allow evaluation of the protection degree of the structure from corrosion. In paper [27] application has been shown of electrical resistance (ER) technique for monitoring of cathodic protection effectiveness of underground structures. In this paper chosen results have been presented obtained by the gravimetric and ER techniques, which allowed control of the effectiveness of anticorrosion protection of the internal surface of large-diameter cooling water pipelines at one of the Polish electric power stations (Elektrownia Łaziska) [28]. A view of the mounted corrosion coupons, resistometric sensors (ER probes) and reference electrodes inside the pipeline has been shown in Fig. 6. Examples of ER measurements have been given in Fig. 7.



Fig. 6. View of corrosion coupons (3 pieces), ER probes (2 pieces) and reference electrode mounted on the internal surface of water pipeline

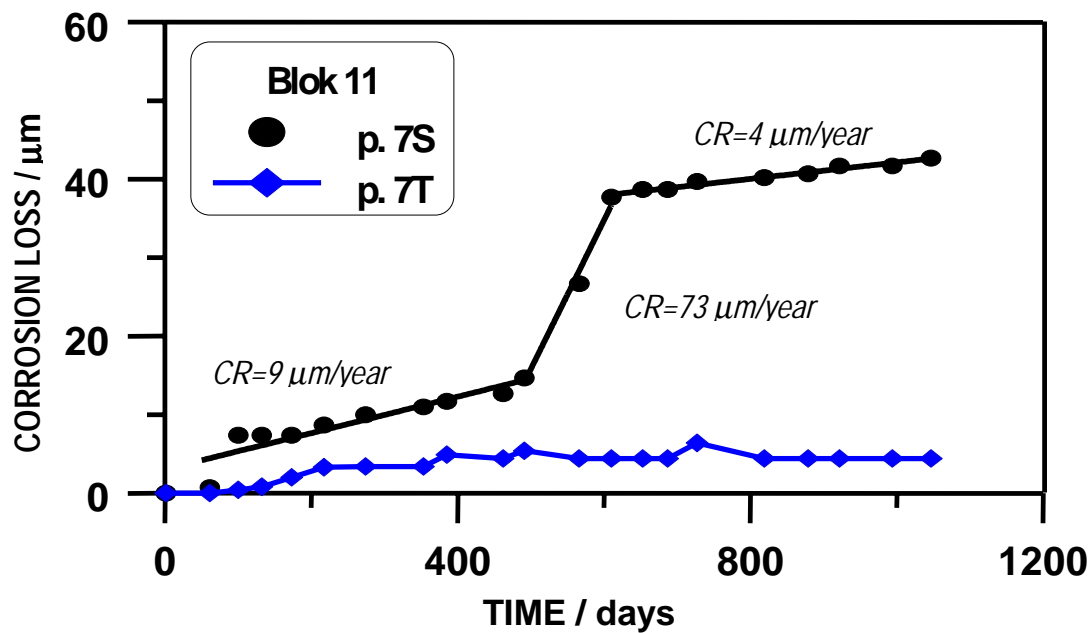


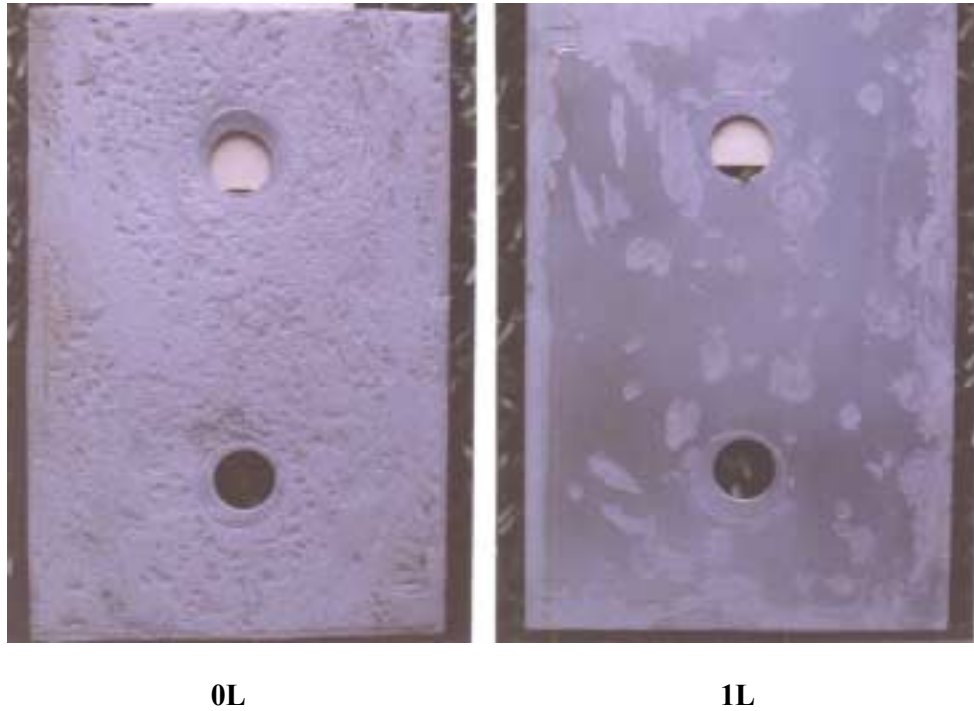
Fig. 7. Corrosion loss of steel determined by the ER technique on a cathodically protected internal surface of cooling water pipelines in Elektrownia Łaziska power station

It shows how corrosion losses of steel probes changed in a period of approximately 3 years of operation of cathodic protection installation. This graph allows performing of quantitative evaluation of the effectiveness of applied anticorrosion protection, as the corrosion rate is proportional to the inclination angle of the determined $\Delta G=f(t)$ function. As results from given data the suction pipeline (point 7S) corroded in the first period (up to 500 days) with a rate of approx. 0.009 mm/year, after which its corrosion rate increased several times to approx. 0.073 mm/year. This was caused by the repair period and temporary switching off of the protection installation. In a further operation period (after 600 days) its corrosion rate was again limited due to restarting of CP to a negligibly small value of approx. 0.004 mm/year. During this time another pumping pipeline (point 7T) showed a minimum corrosion loss at a level of 1.4 $\mu\text{m}/\text{year}$, indicating full cathodic protection.

The corrosion coupon technique, additionally applied for comparison, confirmed the high effectiveness of cathodic protection of internal surfaces of cooling water pipelines. Cathodically polarised coupons dismantled from the installation after an exposure time from half a year to three years showed a small destruction degree in relation to coupons not protected from corrosion. A view of both types of coupons has been presented in Fig. 7, while corrosion rates determined on their basis have been given in Table 1.

Table 1
Corrosion Rate of Cathodically Protected Pipeline Measured by Weight Loss Method

Coupon Designation	Type of Coupon	Weight Loss [g]	Corrosion Rate [$\mu\text{m}/\text{year}$]	CP Effectiveness [%]
0P	without CP	15,8415	134,5	-
1P	with CP	1,0777	9,2	93,2
2P	with CP	0,8460	7,2	94,6
9P	with CP	0,9500	8,1	94,0



*Fig. 8. View of steel coupons dismantled from the cooling water pipeline after 6 months exposure:
0L – without CP, 1L – with CP.*

The applied simple and convenient electrical resistance technique allowed obtaining of relatively accurate quantitative data on the effectiveness of anticorrosion protection of monitored pipelines (above 90%) with a discrepancy of approx. 5% in comparison with gravimetric measurements. Performed investigations confirmed high suitability of the ER technique for monitoring of cathodic protection effectiveness. The technique allows obtaining of more accurate information on the anticorrosion protection degree of cathodically protected structures than traditional potential measurements, delivering accurate quantitative data on their corrosion rates. Availability, wide choice and high quality of corrosimeters and ER probes manufactured at present should favour their wider application also in the pipeline cathodic protection technology, especially where potential measurements are unreliable.

Harmonic Synthesis

Especially promising results are ensured by the recently elaborated at the Gdańsk University of Technology non-invasive method of harmonic synthesis [29]. The method, contrary to the previously described gravimetric and ER methods, allows determination of the instantaneous corrosion rate of the cathodically protected metal, hence at the moment of measurement. The method is based on perturbation of a simulation probe, connected with the pipeline and cathodically polarised, with a sinusoid voltage signal of low frequency (below 0.1 Hz) of an amplitude not exceeding 50 mV. On the basis of the measured first three harmonic components of the current response synthesis is performed of the stationary section of the polarisation characteristic of a steel electrode in the potential range $E_{CP} \pm U_o$, where E_{CP} is the potential of cathodically protected pipeline, while U_o is the amplitude of perturbation signal. Numerical analysis of such a determined cathodic polarisation curve with appropriate software allows determination of the corrosion current and Tafel coefficients of steel exposed in water or soil in cathodic polarisation conditions. Their knowledge in turn, allows calculation of the

current corrosion rate of a cathodically protected steel structure in mm/year. Examples of measurement results of a cathodically protected steel pipeline section in soil obtained by the harmonic synthesis method have been shown in Fig. 9 [30].

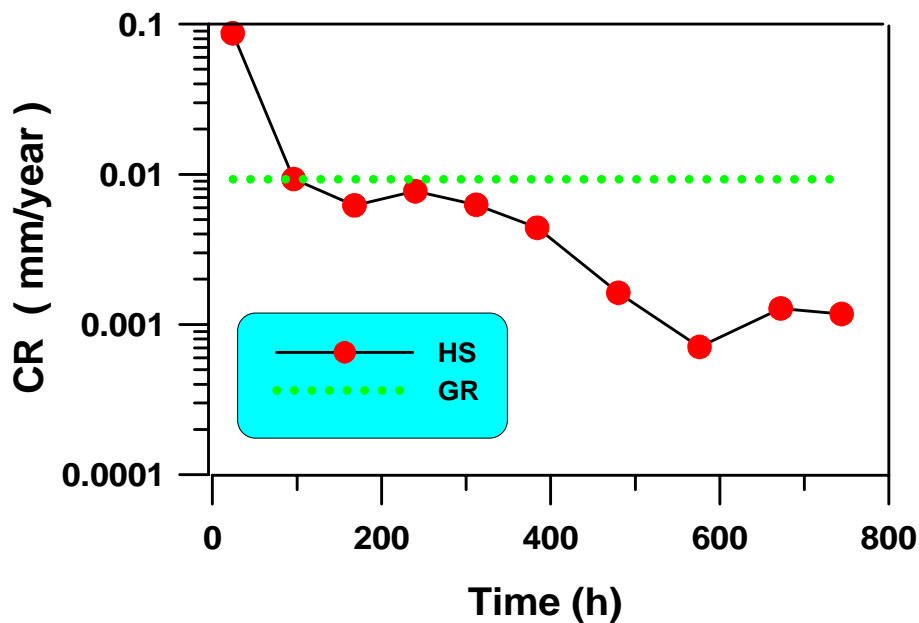


Fig. 9. Corrosion rate of cathodically protected steel pipeline in the function of time determined by the harmonic synthesis method

For comparison the straight line depicts the mean corrosion rate determined on the basis of mass loss. As can be seen good conformity has been obtained of electrochemical and gravimetric measurements. One can see systematic increase of the cathodic protection degree of the pipeline during monthly polarisation. The steel corrosion rate decreased from the initial value of 90 $\mu\text{m}/\text{year}$ to close to zero in the final investigation period.

Conclusions

The presented review of monitoring techniques indicates that at present two approaches are being developed in methods of cathodic protection effectiveness control. On one hand traditional potential measurement methods are being developed and improved, ensuring more accurate evaluation of the pipeline polarisation degree on their whole length with elimination of the IR component and drawing conclusions as to anticorrosion protection correctness on the basis of conventional potential criteria. On the other hand electric and electrochemical measurement techniques are being developed, allowing determination in chosen places of real corrosion rates of cathodically protected structures, hence realising the postulated concept of implementation of so called kinetic cathodic protection criteria. One may expect that such a cathodic protection development trend will be maintained in the nearest future as the applied measurement techniques are complementary and supplement each other in obtained information, ensuring better control of the quality of obtained anticorrosion protection of pipelines.

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