

Monitoring of the External Corrosion of Buried Pipelines

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Abstract

The methods for the monitoring of various types of external corrosion of underground pipelines are investigated. The various scenarios where electrical resistance soil corrosion probes can be used for corrosion damage assessment or for the control of cathodic protection effectiveness are described. The possibilities of using hydrogen probes for the prediction of stress corrosion cracking of pipelines are discussed.

Key words: pipeline, cathodic protection, corrosion monitoring

1. Introduction

Currently, the main methods for monitoring the corrosion state of underground pipelines are electrometric diagnostics with control excavations and in-line inspection. The use of these methods requires heavy financial expenditures; hence, the development of methods for the "indirect" determination of the corrosion state and protection efficiency of pipelines is attractive. Principally, this problem can be solved by statistical analysis and mathematical simulation models relating cases of the corrosion failures of pipelines to their design features, age, operating conditions, data on geological types, chemical composition and microbial activity of the soils, and cathodic protection parameters [1]. However, the number of factors taken into account in such models is too large, and the currently available databases lack sufficient data for the development of mathematical models of high reliability. In view of this, the main goals in the development of the theory of pipe steel corrosion in soil is to determine the main factors in the origination and growth of various types of corrosion defects and to develop methods for their monitoring along the route of existing pipelines.

The common goals of corrosion monitoring (**CM**) of underground pipelines are to determine the following parameters:

- 1) The corrosivity of the soil and/or under-film electrolyte toward various types of corrosion damage to the pipe steel;
- 2) The corrosion risk for a pipeline segment, namely, the presence of galvanic macropairs, stray currents, and induced alternating currents;
- 3) The state of the isolating coating;
- 4) The efficiency of the pipeline cathodic protection (**CP**).

The following parameters are of major importance in the nucleation of local types of corrosion: the state of pipe surface, the presence of non-metallic inclusions and metallurgical defects in the pipe steel, and the magnitude and frequency of the

mechanical strains in the pipe. It is unlikely that all factors affecting the growth of various corrosion defects can be monitored on existing pipelines. Therefore, under actual operation conditions, any "indirect" diagnostic methods will provide a probabilistic estimate of the pipeline's corrosion state. However, studies on the mechanisms and kinetics of the underground corrosion of pipe steel will improve the reliability of such estimates.

An "ideal" passive pipeline protection, excluding any contact of the metal with electrolytes and preventing the origination of any corrosion defects, theoretically makes it unnecessary to know the corrosion mechanism of pipe steel in soils. The use of factory-applied coatings has made it possible to significantly reduce pipeline corrosion damage. However, some mechanical damage to the pipe insulation during transportation, pipeline assembly and operation is inevitable. "Weaker" coatings are used when insulating pipe joints under field conditions, and the protective properties of coatings degrade over prolonged pipeline operation. Hence, monitoring the pipe outer surface corrosion remains a problem of current interest, even where modern isolation pipeline coatings are used.

Determination of the state of the pipeline insulating coating is an important part of CM; however, this issue will not be covered in this communication because methods for monitoring the insulation quality are well-known and have been described [2-4].

1.1. Types of corrosion damage and general principles of their control

At the first stage of organising the CM, one needs to determine what types of corrosion damage to the pipeline outer wall are to be monitored. From the viewpoint of the electrochemical process mechanism, only three types of external pipeline corrosion can be distinguished: uniform corrosion, crevice corrosion, and stress corrosion cracking.

Uniform underground corrosion is an arbitrary term because it implies that the metal surface is equipotential, its structure is uniform, and the corrosion medium is homogeneous and has a uniform composition. None of the three conditions are met in the underground corrosion of real-life steel structures. However, the rate of uniform corrosion determined, e.g., from the mass loss of a check specimen, can be used for comparative assessment of the soil corrosivity and efficiency of the electrochemical protection.

Crevice corrosion is the most widespread type of underground corrosion of steel structures; it is impossible without a potential difference between two areas of a pipe surface. Differences in the electrode potential appear for various reasons: stray currents in the soil, operation of macro corrosion cells formed by parts of a pipeline buried in soils with differing chemical compositions or degrees of aeration, operation of galvanic elements at the level of ground waters or in a crevice between a pipe surface and a delaminated insulating coating, etc.

Stress corrosion cracking is currently the most hazardous type of underground corrosion of high-pressure gas pipelines. The origination and growth of a crevice in a metal is determined by a combination of three factors: the magnitude of mechanical stress, the alloy structure and composition, and composition of the corrosive medium.

The other known types of local corrosion, such as pitting or intergranular corrosion, are not typical in underground pipelines. It is possible that such corrosion defects appear at the early growth stages of a crack or crevice.

Local corrosion defects can be initiated either in a coating defect or under a delaminated coating. The CM methods will differ depending on the location of the corrosion defect.

At the second stage of organising the CM, methods for monitoring the possibility of the origination and/or growth rate of corrosion sites are defined. There are two

approaches to address this problem. The first one is to use methods that directly measure the metal mass loss or corrosion penetration depth. This goal is achieved using probes whose working electrodes undergo corrosion under conditions similar to the corrosion conditions of the pipe's outside wall. The second approach is to monitor the factors that cause the initiation and growth of a corrosion site, namely: the pipe potential, the chemical composition of the soil (or under-film) electrolyte, and changes in the metal properties that accompany corrosion. The second CM approach requires knowledge of the origination reasons and the growth mechanism of a corrosion site. As this knowledge is accumulated, ideas about the critical values of the factors being monitored change, and sometimes the question arises: do we monitor the right factor?

The choice of the factor to be monitored is determined not only by the existence of an unambiguous functional relationship between this factor and the external corrosion rate of the pipeline but also by the cost of the measurements. From this point of view, indirect monitoring methods are generally advantageous.

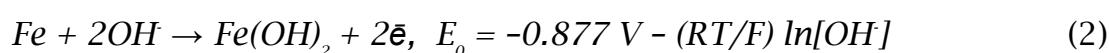
1.2. Measuring the potential of pipeline segments

Currently, the efficiency of pipeline electrochemical protection is monitored using the protective potential value. The electrode potential is an indirect parameter characterizing the metal corrosion rate; hence, the CP protective potential is also an indirect parameter that characterizes the pipeline protection level. What are the grounds for this statement?

In the first stage of the development of the scientific bases of the method for the electrochemical protection of steel structures in soils and natural waters, attempts were made to give a thermodynamic substantiation to the protective potential, i.e., to relate this value with the equilibrium potential of iron, E_0 (SHE):

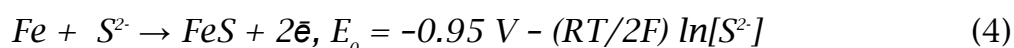
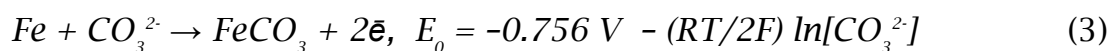


At first sight, this approach appears to be justified if one sets a permissible rate for the diffusion transfer of iron ions to the electrolyte bulk and thus defines the maximum permissible concentration of iron cations at the metal surface Baeckmann and Schwenk [5]. However, Equation (1) fails to account for the participation of electrolyte components in the iron dissolution reaction Florianovich [6] and, in particular, the possible formation of hardly-soluble corrosion products. In fact, considering that iron hydroxide is formed on the metal surface, the equilibrium potential of the anodic reaction can be determined as:



Equation (2) should occur upon alkalization of the near-electrode solution layer due to the cathodic reduction of oxygen or water.

Natural soils contain activators of iron anodic dissolution, e.g., CO_3^{2-} (HCO_3^-) and S^{2-} (HS^-) anions, which shift E_0 in the negative direction as their concentration is increased. Calculation of E_0 for the formation of iron carbonate and sulphide gives by Equations (3) and (4):



The thermodynamic substantiation of the protective potential value became even less justified after the development of the concept of the chemical coupling of partial corrosion reactions [7]. Chemical coupling implies that a fraction of the free energy produced by one reaction compensates for the energy consumption by another (induced) reaction. As a result, the quasi-equilibrium potential of the induced reaction shifts in the negative direction. A possible mechanism of chemical coupling of the partial corrosion reactions involves the participation of the intermediates of the oxidant reduction in the anodic process. Oxygen-containing oxidants (which form OH^- ions upon reduction) accelerate iron dissolution in acidic media (pH 1-3) at a constant potential, with an acceleration factor of several tens [8-

9]. In weakly- acidic and neutral electrolytes, the accelerating effect of oxygen-containing oxidants weakens or is not observed. However, even in pH-neutral media, iron dissolution would be accelerated in the presence of sulphur- or nitrogen-containing compounds that are reduced to give sulphide ions or ammonia molecules.

Thus, the metal dissolution rate is not solely a function of potential because it also depends on the composition of the corrosive medium and on the rates of other electrode reactions. The currently accepted range of protective potentials for pipelines (-0.85 to -1.15 V vs. CSE) has been established empirically, based on results of long-term practical electrochemical protection of steel structures. The effect of the corrosion medium composition on the electrochemical kinetics of iron dissolution is taken into account when establishing the minimum protective potential, which either increases (in absolute magnitude) to -0.95 V in soils with microbiological activity or decreases to -0.75 V in low-mineralised high-resistivity soils [10].

Despite the absence of theoretical substantiations of the protective potential, monitoring this value along a pipeline versus time is currently the basis for determining the electrochemical protection efficiency of underground pipelines. However, this criterion of electrochemical protection efficiency has one significant drawback: its value does not ensure a quantitative determination of the residual corrosion rate of the outside pipe wall. As a rule, this results in considerable financial expense required to maintain too negative protective potentials; however, in certain cases, the lack of knowledge of the residual corrosion rate may result in the origination of hazardous corrosion defects on the outside pipe wall in a hole of the isolating coating.

Furthermore, considerable difficulties exist in the protective potential measurements of a pipeline segment, primarily due to the compensation of the ohmic component (IR) in the measured potential value. First, due to the existence

of the IR-component, the potential that is established on the metal in real modes of electrochemical protection depends on the area of a hole in an isolating coating [11]. Second, despite the progress in the methods for elimination of the ohmic component [3] the results of the polarized potential measurements in the zones of direct and alternating stray currents are not sufficiently reliable. Third, it is difficult to measure the polarized potential in high-resistance soils (rocky, dry, or permafrost) or on pipelines with a heat-insulating coating.

It is practically useless to measure the potential of a pipeline segment to assess the initiation probability and growth rate of local corrosion defects under a delaminated coating.

Thus, to overcome CM problems, it is insufficient to measure the pipe polarized potential, and it is necessary to search for new methods for assessing the pipeline corrosion state and CP efficiency.

1.3. Determination of the pipe outside corrosion rate using electrical resistance probes

Electrical resistance probes (ER probes) are widely used to monitor corrosion rates in various technical areas. Their operating principle is based on the fact that the electric resistance of metallic conductors increases as the cross-sectional area decreases due to corrosion. In the case of pipeline CM, a corrosion probe is placed in the soil adjacent to the pipe surface and is electrically connected to the pipeline [12-15].

1.4. Assessment of the possibility of hydrogen induced stress cracking of a steel pipeline

The possibility of the origination of such hazardous corrosion as hydrogen induced stress cracking (HISC) of pipe steel can be monitored using hydrogen probes. The dissolution of atomic hydrogen in steel can result in hydrogen

embrittlement and, hence, in the stress corrosion cracking (SCC) of steel. A crack grows when the hydrogen concentration in the metal exceeds a certain critical value. The critical concentration values are reached at critical rates of hydrogen permeation into steel [16-17]. The rates of hydrogen permeation into steel can be measured under field conditions using hydrogen probes [16].

In this paper, the opportunity to assess the pipeline corrosion state and CP efficiency using ER probes and hydrogen probes are discussed.

2. Experimental procedure

2.1. Design of electrical resistance probes

The corrosion penetration depth (Δd) is calculated either from an increase in the working element (WE) resistance (for general corrosion) or from the time until WE rupture (for local corrosion). The general corrosion rate is determined as:

$$\Delta d = d_0(1 - R_0/R_\tau)/\tau, \quad (5)$$

where d_0 is the initial thickness of WE; R_0 is the initial WE resistance; and R_τ is the WE resistance upon exposure time, τ .

By simultaneously recording the WE and thermal sensor resistances, it is possible to bring the WE resistance to a standard temperature. Then, the observed changes in the readings from ER probe can be attributed to corrosion effects.

The surface (S) and thickness of the ER probe's WE are selected based on the following conflicting requirements:

- The d_0 value should be large to ensure a long life of the probe. It has been determined experimentally that the following requirement should be met when the rate or uniform corrosion is determined: $\Delta d < 0.5 d_0$ [18].
- High sensitivity (or improvement of the probe response time) requires

either a small d_0 or high-precision measurements of WE resistance; however, the latter approach considerably increases the cost of the measuring instrument;

- High reproducibility of ER probe readings requires a sufficiently large area of metal contact with the heterogeneous medium (soil).
- The power consumption for electrochemical protection with a probe connected to the pipe is minimised by decreasing S . However, at too low S values, the probe potential in the real pipeline CP circuits will be more negative than the metal potential in the coating holes [11] hence, S should not be smaller than the maximum area of a coating defect on the pipeline segment being monitored.
- The probe design should allow it to be located as close as possible to the pipeline; however, installation of a probe directly on the pipe surface generally makes mounting more expensive.

Furthermore, the dimensions and configuration of the working element should allow assessment of the crevice growth rate based on the rupture time, τ_{rup} .

All of the above requirements cannot be achieved in a single sensor. In view of this, a number of ER probe types have been developed by [12, 13, 19, 20], and the use of a specific probe in a CM system depends on the intended purpose. Below described results were obtained by using two types of ER probes (Table 1).

Table 1. Dimensions and uses of WEs in corrosion ER probes.

Probe type	WE thickness, μm	WE surface area, cm^2	Probe application
DK	100	30 - 330	Monitoring the pipeline corrosion rate in insulating coating defects; assessment of cathodic protection performance
VIK	0.1 - 0.2	4.5	Express analysis of soil corrosivity; assessment of cathodic protection performance

DK probe is a cylindrical corrosion probe equipped with a built-in resistance thermometer. The working element of DK probe is a 100 μm thick steel foil band,

3 mm wide, arranged on a plastic tube in the form of a one-layer winding with a 1.5 mm step. The length of WE can be varied from 1 to 11 m. The chemical composition (wt %) of WE steel is as follows: C: 0.05, Mn: 0.38, Si: 0.03, Cr: 0.05, Cu: 0.15, S: 0.04, P: 0.035, Al: 0.16, Ni: 0.09.

The working element of the VIK probe consists of a 0.1 - 0.2 μm iron layer thick vapour-deposited on a dielectric support by decomposition of iron pentacarbonyl. It is used for the express assessment (within 1 to 2 days) of soil corrosivity and for monitoring the parameters of the electrochemical protection of pipelines. VIK probe is characterised by high sensitivity and fast response (approximately 30 min), but its lifetime is as short as several days. The reliability of corrosion rates obtained using the VIK was confirmed by the gravimetric method using steel specimens [19].

2.2. Design and operating principle of the hydrogen probe

The DH-1 hydrogen probe was developed by [21]. The probe operation is based on the use of the Devanathan-Stachurski's cell. A probe's 100 μm thick steel membrane is electrically connected to a pipe, and its outside surface has the same potential as the pipe. Hydrogen formed on the outer membrane surface partially enters into the metal and diffuses to the internal membrane surface. On the internal membrane surface, a potential is maintained at which atomic hydrogen is oxidised. Under steady-state conditions, hydrogen concentration in the metal (C_{H}) can be calculated from the current of the hydrogen penetration through the steel membrane, i_p (Equation 6):

$$C_{\text{H}} = i_p L M / F \rho D, \quad (6)$$

where L is the membrane thickness, M is the atomic mass of hydrogen, F is the Faraday constant, ρ is the specific density of the steel, and D is the hydrogen diffusion coefficient in the steel. Thus, i_p can be considered as a criterion of the steel hydrogen embrittlement hazard.

2.3. Design of the CM point

Typical CM point was equipped with several ER-probes or hydrogen probes, reference electrode (CSE), data logger with satellite transmitter for collecting and transmitting of data (Fig. 1). All probes have electric contact with the pipeline except ER-probes which were used for determination of corrosion activity of soil. The probes were installed into ground close (not far 5 cm) to pipe surface.

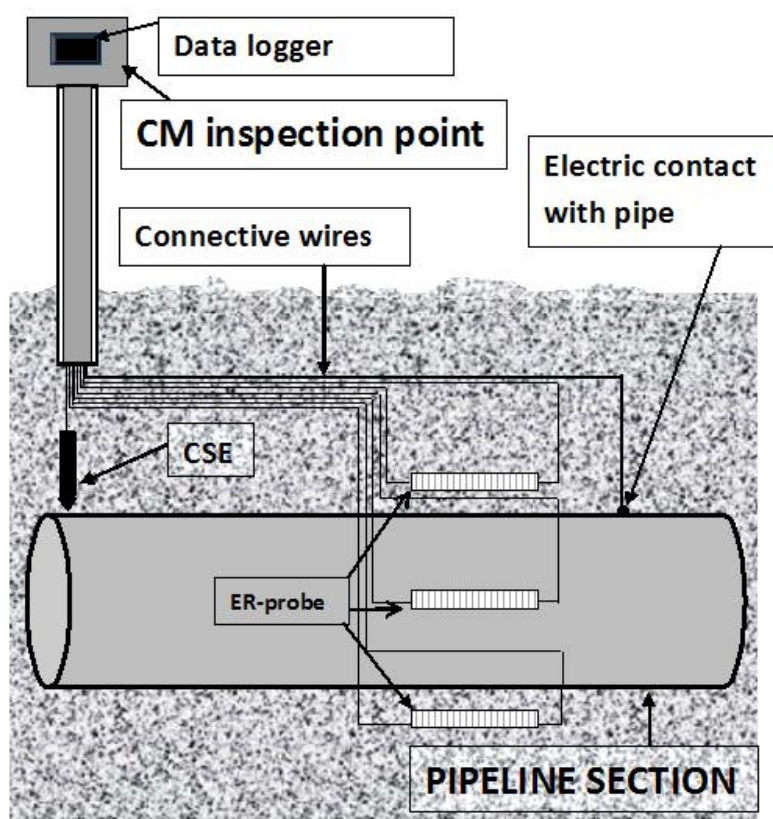


Fig. 1: Design of typical CM point.

2.4. Data collection

IR probes were monitored at least 2 times per day for the first month. Thereafter, the monitoring frequency was decreased, but it was not less than one reading per month. Hydrogen probes were monitored at least 4 times per day for the test

period.

3. Results and discussion

3.1. Use of ER probes for the measurement of the "residual" corrosion rate in the case of CP operation

Figure 2 shows the thickness variation (Δd) of working elements in DK probe (Figure 2a) and VIK probes (Figure 2b) *versus* time. The probes were connected to an operating gas pipeline at the drainage point of the cathodic station. The pipeline polarized potential was -1.15 V (CSE). An approximately constant Δd in the VIK probes is established within 15 hours and that in DK probes, within 2-5 days. The subsequent variations of Δd during the entire test (22 days) are insignificant. The measured steel corrosion rate under these conditions is negligibly small (below 10 $\mu\text{m}/\text{year}$), which proves the efficiency of the pipeline cathodic protection. The surface area of the working element in DK is approximately 20 times larger than that in VIK. This is why it takes much longer for a protective potential to be established on DK probes in comparison with VIK probes.

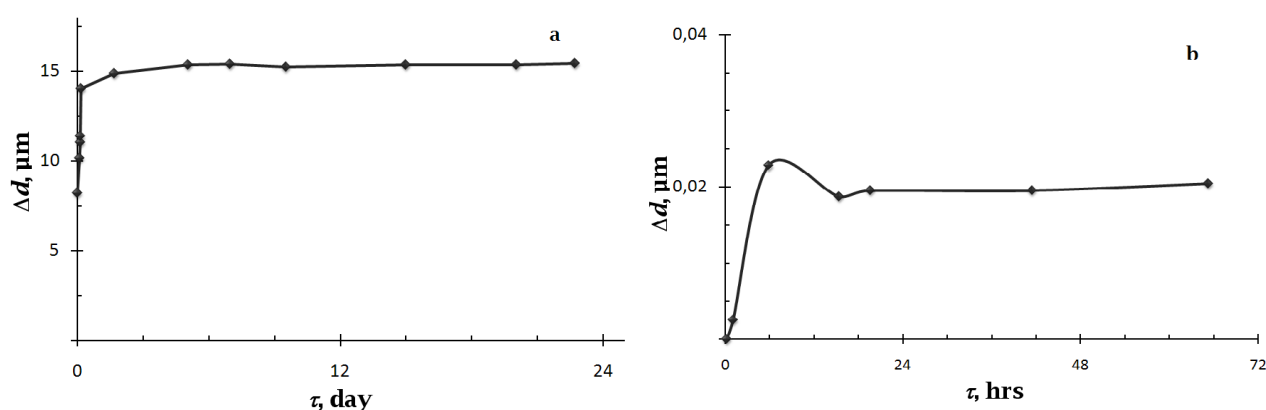


Fig. 2: Variation of WE thickness of two DK probes (a) and a VIK probe (b) at the pipeline cathodic protection potential.

3.2. Corrosion rate measurement in a coating defect with disconnected CP

A DK probe was installed on a segment of a working gas pipeline. The CP was temporarily disconnected. Figure 3 shows the variation in time of the thickness of the probe working layer. The initial test period (~1 hour) was not taken into account in the corrosion rate calculations. The corrosion rate measured by the probe was approximately 0.5 mm/year, which classifies this gas pipeline section as a high corrosion hazard.

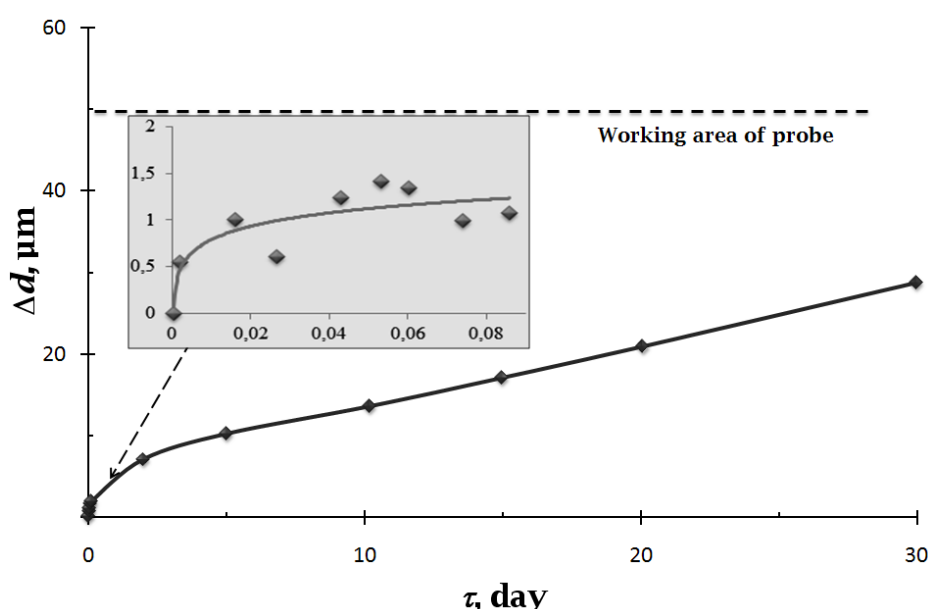


Fig. 3: WE thickness variation in a DK probe with disconnected CP.

The accuracy and reliability of corrosion rate measurements increase as either the probe exposure time or the measurement frequency increase. Figure 4 shows the Δd vs. time plot obtained on a DK probe that was connected to an operating oil pipeline not equipped with a CP system. The resistance of the probe's WE was measured every hour. Although the measured Δd values are scattered, the variation of these values in time can be fitted by a linear equation with a high correlation factor; and the calculated corrosion rate equals 0.2 mm/year. This

corrosion rate remained almost unchanged for 40 days at this pipeline section.

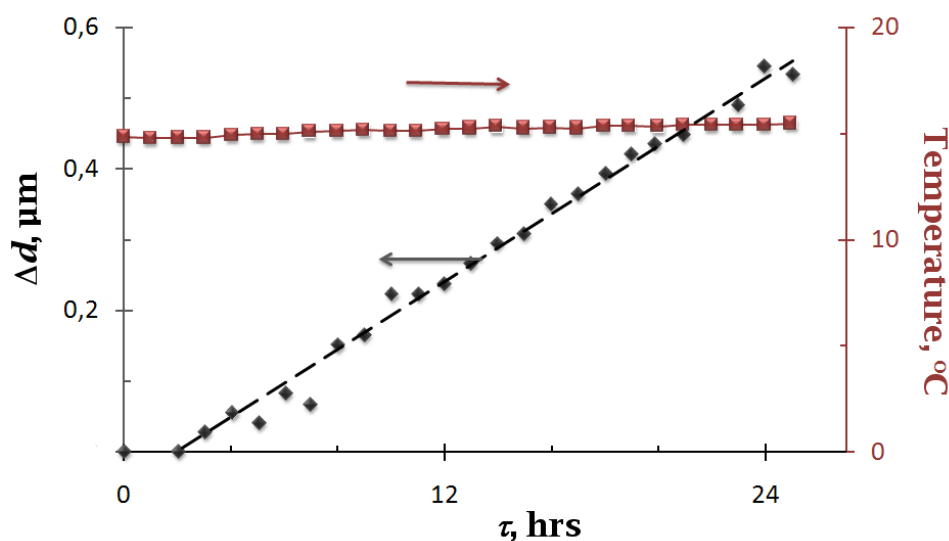


Fig. 4: Time variation of the WE thickness in a DK probe at a field oil pipeline segment without CP.

3.3. Soil corrosivity measurement

Probes can be used to assess the soil corrosivity expressed in corrosion rate units. Express assessments can be performed by means of VIK probes, using a resistance meter with a measurement accuracy of 0.1 Ohm as the measuring tool.

Figure 5 presents the variation of WE thickness vs. time in three VIK probes at the free corrosion potential. The corrosion rate calculations were performed without consideration for the initial test period (~20 min), during which the probe's WE acquires a constant temperature and potential. Figure 4 shows that after 20 hours of testing, the Δd significantly exceeds $0.5d_0$, whereas the $\Delta d - \tau$ plot strongly deviates from linearity. This confirms the limited lifetime of the probe, during which its corrosion rate can be considered constant. The mean corrosion rate calculated over a period of up to 20 hours equals 45 $\mu\text{m}/\text{year}$.

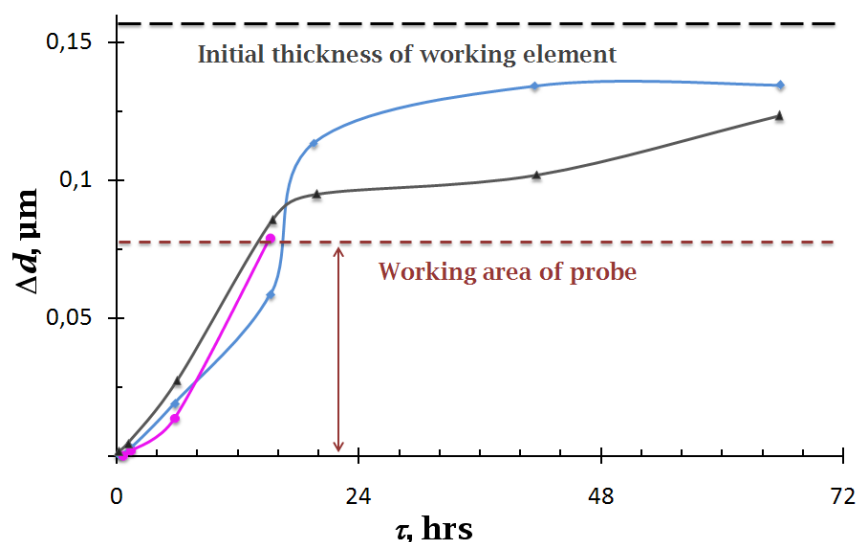


Fig. 5: Variation of the WE thickness in VIK probes not connected to a pipeline.

Thus, within certain limitations, VIK probes can be used to assess the free corrosion rate of steel in a specific soil (*i.e.*, its corrosivity), the assessment duration being one day. If longer-term problems are to be solved, for example, to assess the effect of seasonal factors (variation of soil electrical resistance, temperature, humidity, and chemical composition) on the corrosion kinetics of underground structures, it is recommended to use DK probes that provide more adequate integral estimates of the steel corrosion rate.

3.4. Assessment of local corrosion rates

The corrosion rate calculated from the electrical resistance variation is an averaged quantity. For example, Figure 6 provides the thickness profiles of certain sections of a working element (steel band with $d_0 = 100 \mu\text{m}$) in a DK probe installed at a distance of 1 km from an operating CP device. Based on the results of a one-year exposure, the mean corrosion rate was 0.017 mm/year). The corrosion of the probe's working element is distributed rather uniformly, though in certain places, Δd is up to 50 μm , and the local corrosion rate is approximately three times higher than the mean value.

The ratio of the penetration depths of the crevice corrosion (Δd_L) and the tentatively uniform corrosion (Δd) depends on many factors, including the composition of the corrosive medium. Repeated attempts have been made to assess this ratio for the corrosion of carbon steels in soils; this was also reflected in certain standards [22]. As noted above, the rate of crevice corrosion can be assessed from the probe's WE rupture time (Equation 5)

$$\Delta d_L = d_0 / \tau_{\text{rup}} \quad (5)$$

Although τ_{rup} depends on the probe WE's thickness and width. However, comparison of the Δd_L values determined using probes of the same type provides certain information on the degree of non-uniformity of the external corrosion on the pipeline segment being monitored.

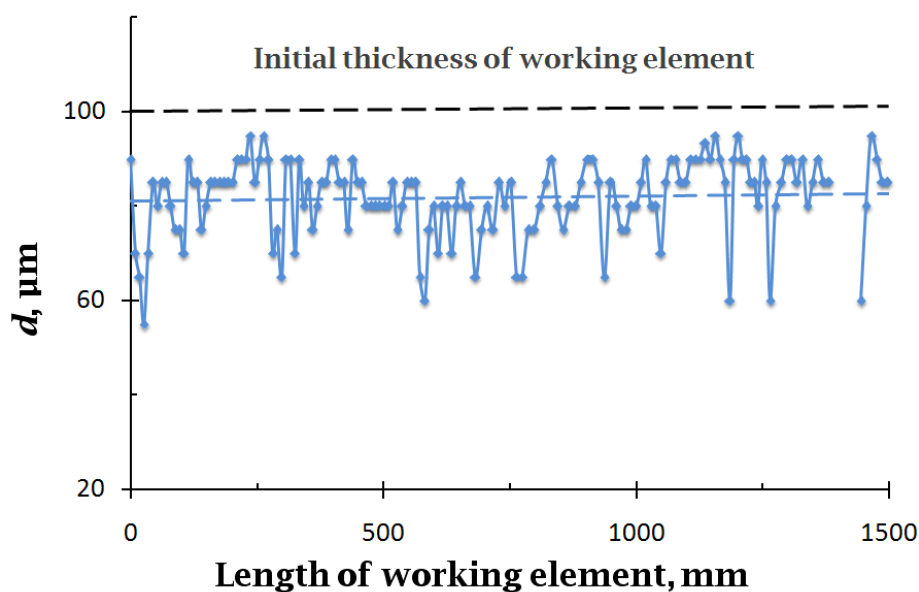


Fig. 6: Thickness profile of a DK probe's WE after 12 months of exposure at the gas pipeline CP potential.

For example, Table 2 lists average values of Δd , Δd_L , and their ratios measured using DK probes on operating field oil pipelines without CP. The pipe walls of these pipelines had been repeatedly ruptured; as result, the adjacent soil has been

salted with water and has acquired a high corrosivity. Corrosion macropairs formed in locations where the pipeline crossed the boundaries of natural and salted soils, which explains the high corrosion rates of the probe WEs. As follows from Table 2, the local corrosion rates are up to 2.7 mm/year, whereas the $\Delta d_L/\Delta d$ ratio varies from 9.7 to 1.9; the mean $\Delta d_L/\Delta d$ value at the monitored pipeline sections amounts to 3.6. The corrosion rates at the pipeline sections located in soils with lower corrosivity are several times smaller, but the mean $\Delta d_L/\Delta d$ ratio is also approximately 3. However, upon longer exposure of the probes, the measured corrosion rates should decrease, and the $\Delta d_L/\Delta d$ ratio should increase.

Table 2. Uniform corrosion and crevice corrosion rates and their ratios ($\Delta d_L/\Delta d$) measured at pipelines in the absence of CP.

Inspection station number	Uniform corrosion rate, mm/year	Crevice corrosion rate, mm/year	$\Delta d_L/\Delta d$
1	0.325	1.30	4.0
2	0.316	1.33	4.2
3	1.00	2.68	2.7
4	0.312	0.63	2.0
5	0.112	1.09	9.7
6	0.208	0.39	1.9
7	0.660	1.40	2.1
8	0.275	0.74	2.7
9	0.445	1.25	2.8

Thus, corrosion probes can be used efficiently to achieve the following goals in monitoring the external corrosion of underground pipelines:

- measurement of "residual" corrosion rates at the protective potential, i.e., determining the performance of CP;
- corrosion rate measurements in a coating defect and ranking of pipeline sections by corrosion hazard, taking into account the effect of stray currents and currents of extensive macropairs;
- measurement of soil corrosivity with respect to uniform and crevice corrosion.

3.5. Assessment of the possibility of HISC of a steel pipeline in the operating zone of cathodic stations

The measurement of the hydrogen permeation rate on operating pipelines was part of a program of RAO Gazprom in 1995-1997 aimed at investigating the causes of corrosion failures previously observed on the pipelines of the Krasnoturyinsk district, Sverdlovsk region, Russia [23]. To this end, control sites were arranged at CP drainage points, with four to six DH-1 hydrogen probes installed on each. Figure 7 shows the results of the i_p measurements at one of the sites taken over 1.5 years. One can see that the maximum flux density of hydrogen into the steel did not exceed 12 - 13 $\mu\text{A}/\text{cm}^2$, mainly in the summer months. The gas pipeline potentials measured without correction for the ohmic drop ranged from -2.5 to -3.5 V (CSE).

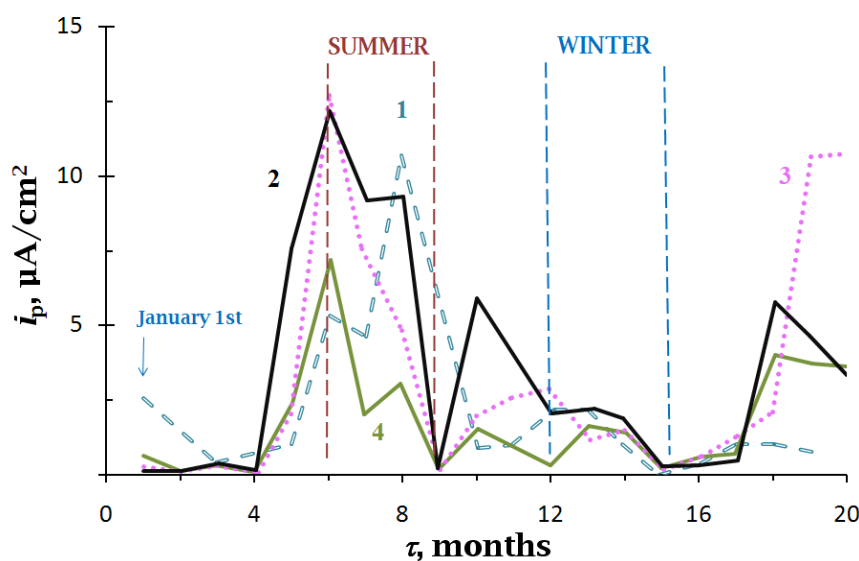


Fig. 7: Plot of the current densities measured by hydrogen probes at control site; 1 - 4 - parallel gas pipelines.

The critical i_p values, at which crack growth by the steel hydrogen embrittlement mechanism is triggered, were determined by laboratory experiments on specimens with pre-formed cracks. The ambiguous effect of cathodic polarisation on the

crack growth rate was used for this purpose [24]. Cathodic polarisation would slow down the growth of corrosion cracks by the mechanism of local anodic dissolution of metal and accelerate the growth by the hydrogen induced stress corrosion mechanism HISC.

In laboratory tests, HISC becomes the major crack growth mechanism in X70 pipe steel at current densities of hydrogen penetration through membrane above $100 \mu\text{A}/\text{cm}^2$ (at $L = 100 \mu\text{m}$) [17]. The hydrogen probes did not give such readings at any pipelines in the Krasnoturinsk district. It was thus concluded that cathodic protection does not stimulate the SCC of underground pipelines.

This conclusion is only correct for steels of this strength grade and for the types of soils studied. It is possible that in soils containing hydrogen absorption promoters, e.g., hydrogen sulphide, hydrogen can be accumulated in higher concentrations.

The use of X80 and X100 steels, as well as consideration for cyclic mechanical stress, may result in adjustments of the critical rates of hydrogen absorption by steel at which metal hydrogen embrittlement occurs. Furthermore, some researchers believe that the SCC of pipe steels in environments with near-neutral pH results from a synergistic effect of hydrogen and stress on local metal anodic dissolution [25-27]. It follows that cathodic protection can prevent the development of stress corrosion, but at potentials near the corrosion potential, an increase in the concentration of absorbed hydrogen can accelerate the crack growth.

3.6. Promising methods of indirect local corrosion diagnostics under delaminated pipeline coatings

Monitoring the state of the external pipe surface under a delaminated coating is the most difficult problem faced in the corrosion monitoring of pipelines. The use of ER probes was suggested for the monitoring of under-film corrosion [18].

However, the experience in application of under-film corrosion probes is rather scarce because the probes have to be installed directly onto a pipe surface, making it difficult to reproduce the conditions of under-film corrosion growth.

It is more promising to develop CM methods that allow for the prediction of the origination and growth of local corrosion defects by analysing the chemical composition of the soil electrolytes and/or by measuring the partial corrosion reaction rates on a probe placed into the soil near a pipe wall or into the under-film electrolyte. The development of such CM methods requires a deeper understanding of the local corrosion initiation centre and growth mechanism. Because stress corrosion cracking of pipe steel in soils with near-neutral pH is currently the most hazardous type of under-film corrosion, researchers have mainly focused on studies of this phenomenon [28-30].

In particular, the presence of CO₂ and H₂S in the corrosive medium accelerates crack growth [28-32] and shortens the time until crack appearance [33]. In addition, crack colonies on pipe walls are found in anaerobic soils that have pH values of 5.5-7.5. Therefore, it is considered necessary to monitor the soil electrolyte pH and oxygen, hydrogen sulphide and carbon dioxide levels.

Because carbonic acid and hydrogen sulphide molecules dissociate to give the respective ions, it was suggested that the composition of the soil electrolytes be determined in the field using ion-selective electrodes.

Soils at pipeline segments where crack colonies formed were found to have higher concentrations of sulphide-containing compounds (HS⁻ and S²⁻ ions) (Figure 8).

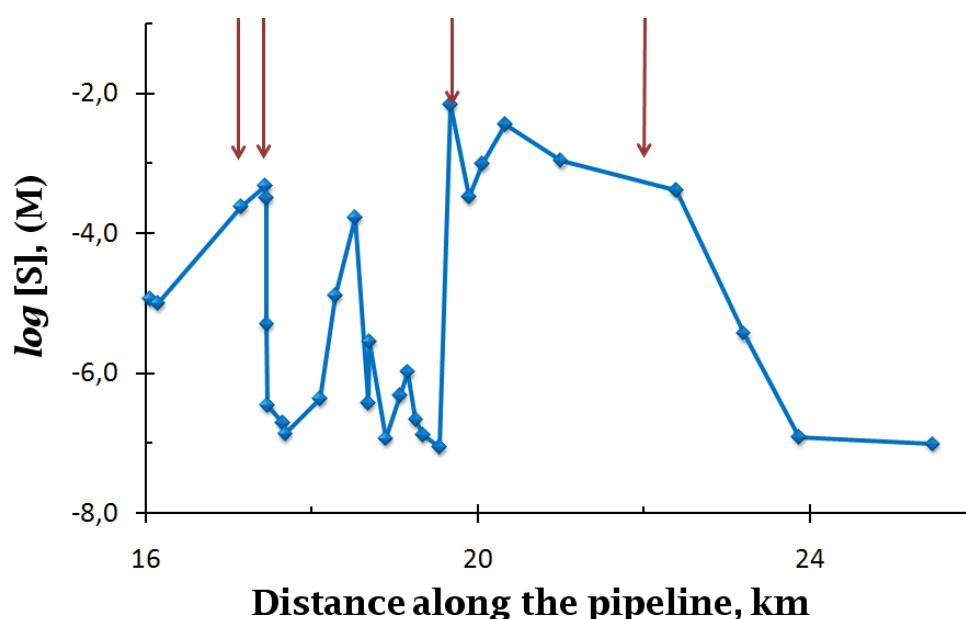


Fig. 8: Changes in the concentration of sulphide-containing compounds in a soil electrolyte at a pipeline segment. Arrows denote the locations of the crack colonies found upon control excavations.

The oxygen concentration in a soil electrolyte can be determined from the rate of its cathodic reduction on a special test electrode made of pipe steel. It is also considered reasonable to determine the hydrogen absorption rate and the kinetics of pipe steel anodic dissolution in the soil electrolyte at a pipeline being monitored. The anodic current values at a preset potential and the character of the current variation *versus* time can be indications of local steel dissolution, and therefore show the possibility of the formation of a mechanical stress concentrator on the pipe surface.

Measurements made using special probes, which include ion-selective electrodes and electrodes made of pipe steel, should improve the reliability of the existing method for the discovery of pipeline segments potentially prone to stress corrosion. Further research on the impact of the composition of the soil electrolytes on pipe steel SCC should lead to the establishment of new criteria for determining the possibility of crack initiation and assessment of the growth rate

of cracks in pipe steel under delaminated coatings.

4. Conclusions

Currently, the most urgent goals of underground pipeline external corrosion monitoring include: 1) assessment of the CP efficiency by determining the "residual" corrosion rate, 2) ranking pipeline segments by the metal corrosion rate in a through coating defect in the absence of CP, and 3) predicting the development of hazardous corrosion defects (cracks and crevices), primarily under a delaminated coating. The first two CM goals can be achieved using various ER probes.

Determination of the "residual" corrosion rate complements the existing CP efficiency monitoring that is based on polarized potential measurements. Hence, corrosion sensors should be installed in areas with unstable temporal variation of the potential (zones of stray or induced currents) or where measurements of potential are complicated (high-resistance soils, heat-insulated pipelines). The main problem that remains unresolved involves the measurement of the efficiency criterion of the pipeline protection, i.e., the "residual" uniform corrosion rate. At the moment, we can agree with the authors of [18] that a rate of uniform corrosion below 25 $\mu\text{m}/\text{year}$ measured over a period of one year is an indicator of efficient CP, but it is impossible to make a final decision on the magnitude of this criterion without the large-scale use of corrosion sensors.

Ranking pipeline sections based on the use of corrosion sensors provides grounds for decreasing (in absolute magnitude) the CP protective potential at pipeline sections with low corrosion susceptibility, or otherwise strengthening the corrosion protection (by CP installation, changing the operating modes of the cathodic stations, pipeline re-insulation) at pipeline sections with high corrosion susceptibility.

Prediction of the origination of hazardous corrosion defects under delaminated

pipeline coatings remains the most difficult problem of CM. However, the progress made in understanding the stress corrosion mechanism in pH-neutral soils and the development of express methods for determining the chemical composition of soil electrolytes and electrode reaction rates leading to the growth of cracks, allows one to expect a substantial improvement in the reliability of the methods for diagnostics of potentially hazardous pipeline segments.

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