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IMPROVEMENT OF ELECTROCHEMICAL PROTECTION OF OIL AND GAS PIPELINES

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Abstract- In the implementation of electrochemical protection of pipelines from destruction under the influence of stray currents, it is necessary to solve a whole range of complex problems, which include, first of all, the determination of the possible destruction rate, the optimal degree of protection of the pipeline, the protective potential, the equivalent circuits of protective equipment and their redundancy. Great difficulties in solving these problems are due to the fact that the metal-insulation-soil system is a very complex heterogeneous system. The article proposes a methodological basis for determining the optimal degree of protection based on technical and economic data and probabilistic relationships between the number of corrosion failures, environmental parameters, insulation and operating conditions.

Keywords: Corrosion Failures, Soil Electrical Resistivity, Electrical Protection of Oil and Gas Pipelines, Environment Settings.

1. INTRODUCTION

The metal of the structure is steel of various grades. As you know, steel is an alloy, the main, alloying and impurity elements of which are distributed unevenly in the volume. The crystal structure of steel is not uniform. Different faces of crystals may appear on the surface, and a significant number of crystals are damaged or deformed, and, consequently, have different electrochemical characteristics. The steel surface has a different degree of roughness, as well as other types of heterogeneity, determined by their purely mechanical nature (for example, various degrees of work hardening). Since the steel surface undergoes oxidation during pipe manufacturing and pipeline construction, areas covered with oxide layers of various compositions and thicknesses appear on it [1, 6].

Heterogeneities on the micro- and macro scale cause areas with different internal energy. In addition, pitting and pitting, cyclic deformations caused by pressure changes in the pipe, flow turbulence and cavitation are also possible. A change in the temperature of the transported product not only affects the stress state of the metal, but also causes a change in the heat flux through the metal-environment interface. All this, taken together, causes a change in the electrochemical parameters of the metal.

Insulation is mainly characterized by the heterogeneity of through defects in their area and shape. The range of defect sizes is very wide. The form of defects can be very diverse - from cylindrical pores to cracks and irregularly shaped exposures. Soil and ground conditions are distinguished by a particularly pronounced heterogeneity, which consists of the heterogeneity of three phases: solid, liquid and gas. The solid phase is heterogeneous in composition, size, shape of particles, their packing, porosity, permeability, and the presence of crystalline hydrates [2, 3 11]. The liquid phase varies over a wide range in terms of the filling of the threshold space (humidity), the composition and concentration of dissolved salts and gases, the distribution over the volume of the soil, acidity, alkalinity and pH. Significant changes also occur in the colloidal properties of the soil.

The gas phase varies both in composition (the content of oxygen, carbon dioxide, hydrogen sulfide, and other gases) and in the percentage of threshold space filling. Seasonal phenomena have a great influence on the state of the liquid and gas phases. Consequently, the heterogeneity of the solid, liquid, and gas phases determines the heterogeneity of the soil both in general and in terms of such important integral indicators as diffusion characteristics, oxygen content, and electrical resistivity of the soil. As can be seen from the analysis of the main components of the environmental study object, taking into account the operating conditions, the metal-insulation-soil system is a sharply heterogeneous system. The change in the factors of this system is random. In this regard, the assessment of the aggressiveness of the conditions and the protection of the metal is a probabilistic problem.

2. SPECIFIC FEATURE OF CORROSION DAMAGE

Let us note a specific feature of corrosion damage. Knowledge of average corrosion rates or protective potential is not sufficient. The pipeline fails in sections where not average, but the highest corrosion rates are realized [1, 4, 8]. Let us consider the possibility of predicting corrosion failures and their dynamics during operation. The heterogeneity of the metal-insulation-soil system is largely manifested in the heterogeneity of the soil.

This is confirmed by the distribution of corrosion failures on gas pipelines (Figure 1) depending on the electrical resistivity of the soil ρg. Corrosion failures are plotted along the ordinate (Figure 1) as a percentage of their total number, taking into account the share of each soil category.

As can be seen from the figure, in soils with high and very high corrosive activity (electrical resistivity $\rho_g \leq 10$ Ωm), 66-79% of lesions occurred, with an increase in the specific electrical resistance of the soil ρ_g, the number of lesions decreases: in soils with $\rho_g = 10 \div 20$ Ωm, from 11.9 to 24.9% of lesions are noted, with $\rho_g = 20 \div 100$ Ωm, 6.2÷6.5% and with ρ_g more than 100 Ωm, 2.6÷3.1%.

The analysis shows that the magnitude of the specific electrical resistance can not only assess the conditions, but even predict the number of failures in the design of a structure for a long period of its operation, i.e., determine the frequency spectrum of pipeline destruction rate [5, 7].

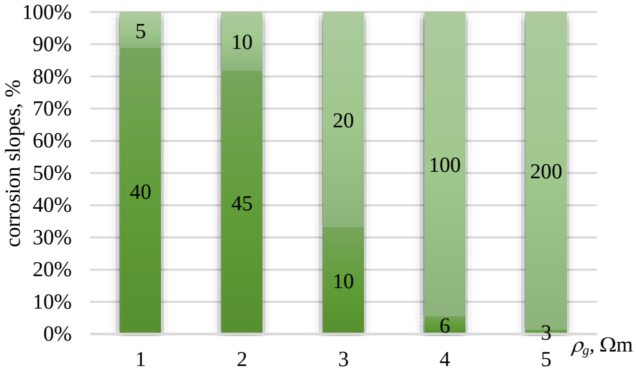

Figure 1. Distribution of corrosion damage depending on the electrical resistivity of the soil ρ_g for different soil corrosivity is: 1- very high; 2- high; 3- increased; 4- average; 5- low

As noted, the soil is a sharply heterogeneous system, the parameters of which are stochastic. The electrical resistivity of such a medium is naturally an averaged value, since a four-electrode installation is used to measure the electrical resistivity of the soil (averaging occurs over a volume approximately equal to the cube of the distance between the supply electrodes, i.e., over the volume of the soil at least several tens of cubic meters).

As measurements of the electrical resistivity of saline soil in the same place, but with different distances between the supply electrodes, show, the value of ρg varies quite widely according to the lognormal law (Figure 2). Characteristically, in soils with a low average resistivity, the dispersion is less than in soils with a high average resistivity. Since in saline soils the electrical resistivity of the soil is determined mainly by moisture content, the higher the moisture content, the more homogeneous the soils are.

At low humidity, a high average resistivity is observed, however, 20-30% of measurements (Figure 2) indicate the presence of inclusions with a lower (more than 10 times) electrical resistivity. This effect can explain the appearance of cases of high destruction rate in soils with electrical resistivity of more than 20 Ωm and even more than 100 Ωm.

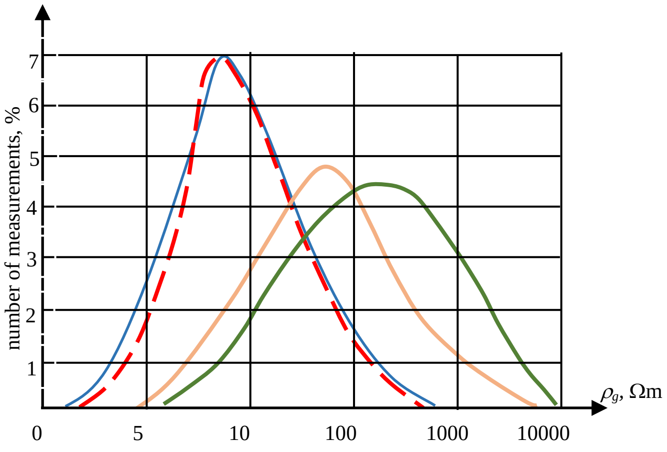

Figure 2. Distribution of soil resistivity ρ_g in various pits on the gas pipeline

The processing of experimental data, taking into account the maximum values of the depth of caverns, showed that with a decrease in the electrical resistivity of the soil, the magnitude of the cavern increases, while the longer the period of operation, the more noticeable this dependence. However, there are opinions, supported by experimental data, about the inexpediency of using electrical resistivity as a criterion for assessing corrosion conditions [2, 11, 13].

It is probably incompetent to classify the whole variety of soil conditions according to any one criterion. In a number of areas, the specific electrical resistance of soils correlates well with the rate of pipeline destruction. These are areas in which the soil contains a sufficient amount of soluble mineral salts, and above all chlorides, which activate the corrosion process. In such areas, evaporation of moisture is approximately equal to precipitation (arid, desert and semi-desert regions).

In other areas, where the amount of precipitation prevails over evaporation, and consequently, there is a constant washing out of soluble salts from the soil, the destruction process cannot be activated (for example, by chlorides, due to their very low concentration). In this case, diffusion limitation of oxygen acts as a criterion for corrosion hazard. Of course, in both regions, the main depolarizer of the cathodic reaction is oxygen; therefore, the limiting oxygen current can serve as a general criterion for assessing corrosion conditions.

The study of the corrosion process of steel in various low-mineralized soils (sand, clay, peat) showed that, in a wide range of changes in soil moisture, the corrosion rate V is directly proportional to the limiting current density for oxygen j_l [1, 2].

$$V = 0.626 \times j_i \tag{1}$$

The average deviation of the experimental data from those calculated by Equation (1) does not exceed 8.3%. In dry and arid regions, where the soil moisture is low, the electrical resistivity of the soil can serve as a criterion for assessing the corrosion rate. Statistical analysis of damage in these areas made it possible to derive an equation for determining specific number of corrosion failures [2, 9]:

$$n_0 = \frac{K_U}{e^V \rho_g^B \left(L + L'\right)} \tag{2}$$

where, K_U is coefficient depending on a number of conditions and, above all, on the state of the insulating coating; V is corrosion rate, mm/year; ρ_g is soil electrical resistivity, Ωm; L is distance between the considered point of the gas pipeline and the compressor station, km; B is exponent; L' is constant value for given operating conditions.

As can be seen from Equation (2), the probability density of corrosion damage to the gas pipeline is inversely proportional to e^V, ρ_g^B and L, i.e., the higher the corrosion rate, the less the number of cases of damage to the gas pipeline at such a rate, in other words, the corrosion of a pipe with an extremely high corrosion rate is observed much less frequently than its damage at a lower rate.

An increase in the electrical resistivity of the soil leads to a decrease in the probability of corrosion at a given rate. With distance from the compressor station, the probability of corrosion failure decreases. The calculation results according to Equation (2) are in good agreement with the actual data of the corrosion survey (Figures 3 and 4). As can be seen from Figure 3, the actual data in the coordinates ln, n_0, V are easily approximated by straight lines with different values of ρ_g. The standard deviation between the actual and calculated values does not exceed 20% [7, 10, 11].

A similar picture is observed when comparing the partial dependence $n_0 = \dfrac{K_U}{e^V \left(L + L'\right)}$, with actual data in Figure 4. In this case, the standard deviation is less than 25%.

The actual and calculated data were compared within the corrosion rate from 1.25 to 6 mm/g. A lower rate was not taken into account, because their volume was not representative due to the fact that the lower the corrosion rate, the longer through rusting. This explains the decrease in the density of corrosion failures at relatively low corrosion rates.

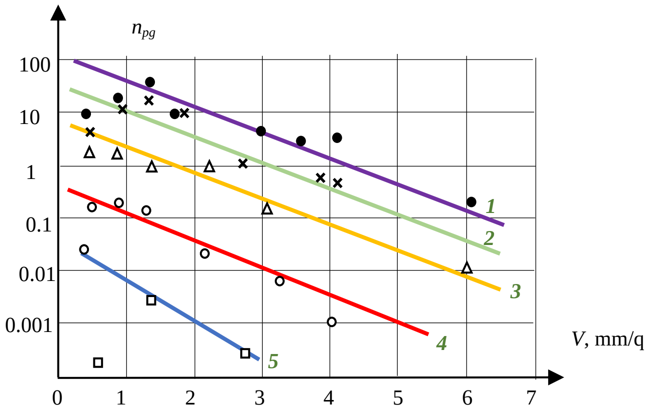

Figure 3. Distribution of the specific number of corrosion failures n according to the corrosion rate V at various specific soil resistances ρ_g: 1-3 Ωm; 2-7.5 Ωm; 3-15 Ωm; 4-60 Ωm; 5-300 Ωm

However, if we consider the distribution of corrosion rates over cavities and pits found in pits, we can say with confidence that the probability density continues to grow even at low corrosion rates. This makes it possible to extend the obtained regularities to lower values of the corrosion rate.

For saline soils, Equation (2) has the following form:

$$n_0 = \frac{1.2}{e^V \rho_g^{1.74} \left(L + 5\right)} \tag{3}$$

where, n_0 is the number of corrosion failures.

The total number of failures in the section can be found by integrating Equation (3) over three variables: corrosion rate, resistivity and distance from the compressor station (CS). If there are relatively homogeneous soils in the area, then the total number of failures N_0 in this area is equal to

$$N_0 = \frac{K_U}{e^V \rho_g^{1.74}} \iint \frac{d_V d_L}{e^V \left(L + 5\right)'} \tag{4}$$

The above error in calculations based on partial approximations turned out to be greater than the error in integral expressions, which give errors up to 10%. This error, of course, is quite sufficient for practical calculations, since only the soil resistivity is measured with an error of up to 20%. The coefficient K_U depends on the quality of the insulating coating, and the value K_U=0.9 corresponds to the average current density required to protect the pipeline and is equal to 3 mA/m^2 [3, 9]. It is natural to expect that with a higher current density or a larger exposed area of an insulated pipeline, the number of corrosion damage should increase, and vice versa.

3. ANALYSIS OF CORROSION FAILURES

As the processing of the statistical material shows, this dependence is logarithmic, i.e., the coefficient of increase in corrosion failures is directly proportional to the logarithm of the current density (Figure 5). Accounting for this dependence makes it possible to predict cases of failure of the structure in almost any state of insulation.

Comparison of the obtained expressions with the data on the change in the corrosion rate depending on the resistivity of the soil, obtained by foreign authors [4], shows that this change is approximated with a satisfactory error by the dependence $n_0 = \dfrac{K_U}{e^V \rho_g^B}$, which testifies to the general nature of the obtained expressions.

4. DETERMINING THE OPTIMAL DEGREE OF PROTECTION OF UNDERGROUND PIPELINES

Consider the issues of determining the optimal degree of protection of underground pipelines. Ensuring the trouble-free operation of pipelines depends on the correct choice of the degree of protection and on the system for maintaining it at a given level during the entire period of operation. The opinions of experts on the degree of protection, as a rule, are not based on a feasibility study, since no quantitative relationship has been found between the costs of electrochemical protection and possible losses from corrosion with a particular degree of protection [2, 8].

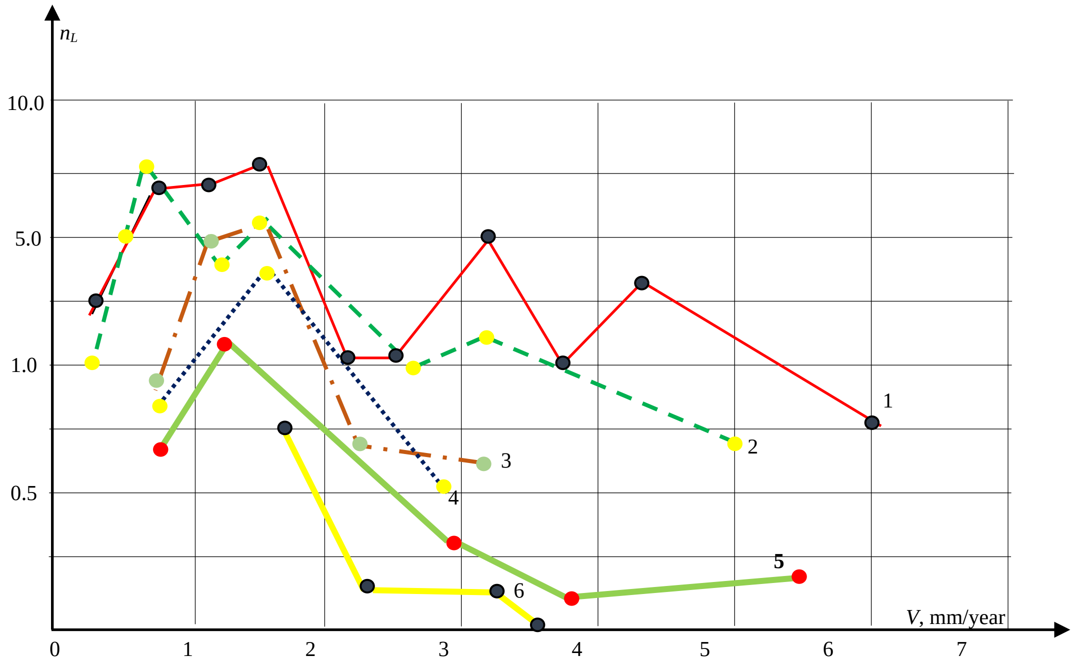

Figure 4. Distribution of the relative number of corrosion failures
n_L by corrosion rate V at different distances from the compressor station
L: 1. 0÷5 km; 2. 5÷10 km; 3. 10÷70 km; 4. 20÷40 km; 5. 40÷80 km; 6. more than 80 km

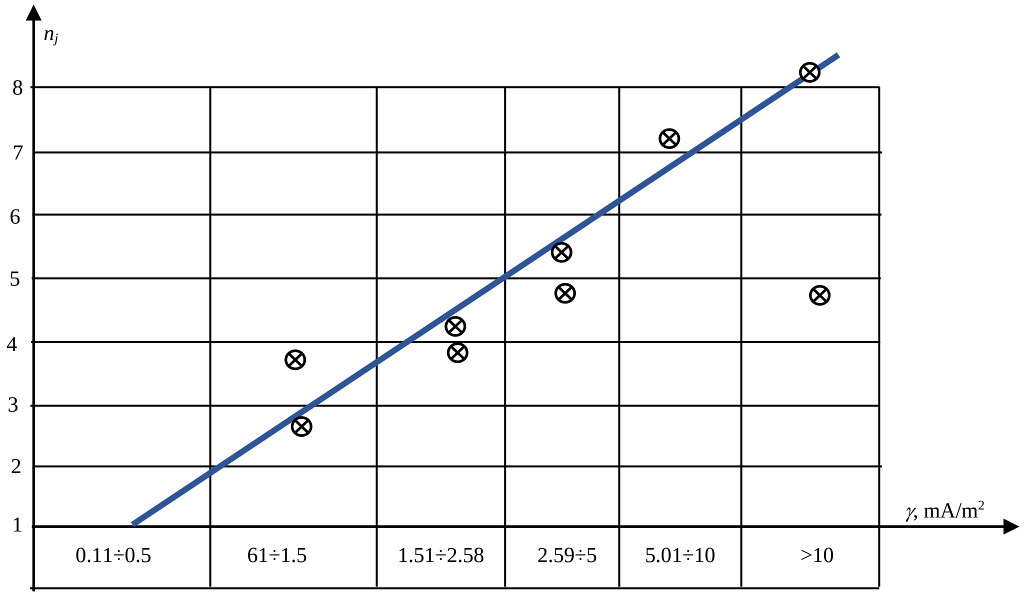

Figure 5. The increase in corrosion failures n_j with an increase in current density j required for cathodic protection on gas pipelines

In this regard, the most common opinion is that it is necessary to achieve a degree of protection close to 100%. As was convincingly shown theoretically and experimentally by academician Y.M. Kolotyrkin and his school, the degree of protection equal to 100% is impossible for steel, since even at very high values of negative potentials, the corrosion process proceeds on steel due to the pure chemical action of iron with the components of the environment.

The very choice of any single value of the degree of protection for all conditions is completely wrong. For some corrosive conditions, a protection level of 90% will be insufficient (for example, for a corrosion rate of 5 mm/g), while for others (corrosion rate less than 0.2 mm/g), this degree of protection is clearly overestimated.

Determining the average corrosion rate as $V = \frac{\delta_g}{t}(\delta_g)$ is allowable decrease in the pipe wall thickness, mm; t is time during which corrosion will penetrate into the metal by the value and substituting this rate into Equation (3), it is possible to calculate the corrosion failure rate over time.

Introducing the concepts of the time of the first corrosion damage t_n and the time of corrosion damage at the end of the service life t_c, we obtain that, provided that no corrosion failures are excluded over the entire period of operation, the corrosion rate should be reduced by a factor t_c/t_n, i.e., ensure the degree of protection P_g in % [1, 2, 6]:

$$P_g = \frac{t_C - t_M}{t_C} \times 100 \tag{5}$$

This maximalist approach assumes that the cost of at least a corrosion failure is greater than the cost of electrochemical protection (ECP). The optimized degree of ECP can be found by minimizing the cost of operating the pipeline. The total cost of pipeline operation consists of the cost of restoring corrosion-damaged sections of the pipeline and comprehensive protection. Both items of expenditure are related to the degree of ECP.

The greater the degree of protection, the higher (in absolute value) the polarization potential, and therefore, its implementation will require more electrochemical protection installations and more power, i.e. As the degree of protection increases, so do the costs of its implementation. The cost of electrochemical protection should be minimized in terms of the area of pipe metal exposure in insulation defects, since the larger the total area of exposure, the more corrosion failures, the more electrochemical protection means and the cost of electrical energy are required.

Introducing into Equations (2) or (3) the corrosion rate (when protected with a degree of P_p), equal to $V_p=V(1–P_p)$, instead of V, we obtain an expression for estimating the specific number of corrosion failures at cathodic polarization, which will show that with an increase degree of protection, the number of corrosion failures will drop sharply. So, corrosion failures will decrease with an increase in the degree of protection and a decrease in the area of pipe exposure.

Modern construction technology cannot completely exclude defects in pipe insulation, and in the course of operation, insulating coatings age, this is expressed in an increase in the area of bareness and means that the degree of protection must be optimized taking into account this factor, and, consequently, taking into account the costs of restoring the destroyed isolation [11, 12].

Thus, if the cost of operating pipeline Z is equal to

$$Z = Z(P_p, \delta) \tag{6}$$

where, P_p is degree of protection; δ is the area of metal exposure in insulation defects, then the optimal degree of protection will be found by solving the system of equations.

$$\frac{\partial}{\partial P_p} Z\left(P_p, \partial\right) = 0 \tag{7}$$

$$\frac{\partial}{\partial S} Z\left(P_p, S\right) = 0 \tag{8}$$

which, also allows us to find the optimal degree of bareness.

Since the degree of bareness is characterized by the transition resistance of the pipeline R_{tp}, the system of Equations (7) and (8) can be written in the following form:

$$\begin{cases} \dfrac{d}{dP_p} Z\left(P_p, R_{tp}\right) = 0 \\ \dfrac{d}{dP_{tp}} Z\left(P_p, R_{tp}\right) = 0 \end{cases} \tag{9}$$

Given that the solution of the system of Equations (7-9) is a difficult task, since the isolation is extremely heterogeneous, then an approximate solution can be obtained by partial optimizations.

At the first stage, the number of defects allowed on the pipeline is determined by minimizing the costs of electrochemical protection and restoration of insulation in defective areas. At the second stage, the search for the optimal degree of protection is carried out by solving Equation (7) or (9).

5. CONCLUSION

1. The metal-insulation-soil system is a sharply heterogeneous system, which causes the use of probability theory methods to describe this stochastic system.
2. The regularities of the corrosion process on the pipeline have been established and the dependence of the corrosion failure flow on the resistivity of the soil, the distance from the compressor station, and the state of the insulation has been found.
3. The greater the degree of protection, the higher the polarization potential, i.e. As the degree of protection increases, so do the costs of its implementation. The more corrosion failures, the more electrochemical protection means and electrical energy costs are required. An expression is proposed for estimating the specific number of corrosion failures in cathodic polarization, which will show that with an increase in the degree of protection, the number of corrosion failures will sharply decrease.
4. A methodological basis for determining the optimal degree of protection based on technical and economic data and probabilistic relationships between the number of corrosion failures, environmental parameters, insulation and operating conditions is proposed.

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