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EXPERIMENTAL DETERMINATION OF THE CORROSION ENCRUSTATION VALUE IN STEEL GAS PIPELINES

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Statement of the problem. The operating experience of gas pipelines and gas distribution networks shows that despite the almost complete protection of gas pipelines from corrosion by passive and active methods, more than 55—60 % of the damage detected during the diagnostics process is caused by damage of various corrosive nature. Finding the residual resource of pipelines is a pressing issue in the context of limited funding. The aim of the study is to conduct a detailed analysis of statistical data on internal corrosion of gas pipelines and to assess the magnitude of corrosion overgrowth of used gas pipelines using the developed method of diagnostics and assessment of the condition of pipes using a probabilistic approach to risk assessment.

Results. The article presents the results of experimental measurement of the magnitude of corrosion overgrowth of steel gas pipelines, the regularities of changes in the diameter of the gas pipeline, the values of corrosion protrusions are obtained, the probability of their occurrence and their repeatability are numerically estimated. The processing of the measurement results of the overgrowth of steel gas pipelines was carried out using the methods of mathematical statistics, as a result, the probabilistic numerical characteristics of the investigated parameters of the gas pipeline were obtained.

Conclusions. The histograms of the distribution of amplitudes, built on the basis of experimental data, confirm that the modal values of the heights of corrosion protrusions are shifted to the region of small values. Analysis of the results obtained allows us to conclude that the corrosion parameters are consistent with the Charlier probability distribution. When inspecting gas pipelines, the coefficient of variation exceeding 75 % indicates a decrease in the flow area of the pipe, a decrease in the quality of operation and the condition of gas pipelines.

Keywords: steel gas pipeline, internal corrosion, experimental studies, corrosion fouling, corrosion protrusions, Charlier distributions.

Introduction. Corrosion is currently one of the major causes of damage and failure of gas pipelines. The International Standardization System (ISO) defines corrosion as follows: “Physico-chemical interaction between a metal and its environment causing the properties of

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the metal to change and as well as that of the functional characteristics of the metal, the environment or the technical system to deteriorate".

Losses caused by corrosion of metals can be conditionally divided into direct ones (the cost of steel gas pipelines and equipment that have become unusable) and indirect ones (cost of replacing gas pipelines, cost of corrosion prevention, forced downtime of the gas distribution system, etc.).

The major task of the organization operating hazardous production facilities (HPO) is to ensure the operability and reliability of the gas distribution and gas consumption system, to reduce and prevent accidents (including underground utilities) as the engineering structures being in operation are mostly exhausted, that is their service life exceeds the established depreciation period, and their replacement calls for considerable capital investments. In regards of optimizing the operating costs in the oil and gas industry, it is relevant to address the following: identifying the technical condition of the corrosion protection system as well as the major parameters of the anti-corrosion protection system, developing monitoring of the technical condition of underground steel gas pipelines, planning systems for routine and preventive anti-corrosion measures and assessing funding priorities [7—9, 16, 18, 21, etc.]. The objective of the work is to analyze the problem of corrosion of steel pipelines, to process statistical data on internal corrosion of pipes, to evaluate the condition of gas pipelines that were in operation using the developed diagnostic method for the risk of overgrowth of the gas pipeline over time and the actual life cycle.

1. Analysis of factors impacting the performance of the gas distribution system. According to Rostekhnadzor, state supervision in the field of industrial safety is currently performed in relation to 64.021 hazardous production facilities related to gas distribution systems. Comprehensive diagnostics of the technical condition of gas distribution and gas consumption network facilities to identify the major types of defects and industrial safety expertise are re-gulated by means of the current regulatory documentation of Rostekhnadzor and standards of STO GAZPROM.

A considerable part of the gas distribution and gas consumption networks has run the course of its life cycle to date. Due to the processes of aging, wear and corrosion, further operation of system elements that do not comply with the safety and reliability requirements can cause an increase in the number of failures and emergencies with varying consequences. Therefore the adoption of appropriate decisions on the operational life of the gas distribution system is possible only following a thorough assessment of the technical condition, performance and analysis of the economic efficiency of further modernization and reconstruction.

Violations that reduce reliability and directly impact the possibility of further functioning of the gas distribution system in satisfactory and safe operational condition as a whole include, among other things, poor organization of production control over timely and high-quality maintenance and scheduled repairs. Among other things, the quality of the HIF industrial safety review depends on the level of equipment of the non-destructive testing laboratory, the qualifications of specialists, and the use of specialized methods of non-destructive testing [8, 12, 13].

According to the results of technical diagnostics of gas distribution networks, it is possible to identify a considerable part of the damage related to the installation category due to violations of the technologies for laying gas pipelines and setting up gas-using equipment (e.g., undercuts and fistulas in welds, violation of the geometry of welded joints, fractures of gas pipeline axes, internal cracks, lack of penetration, uncompensated stresses in welds, etc.) and caused by operational defects - thinning of the walls of gas pipelines due to erosive and mechanical effects, dents, metal scuffs, loss of tightness of threaded and flanged joints, fatigue cracks, degradation of insulating coatings, etc. [2, 10, 11, 15].

The major mechanisms of damage to steel underground gas pipelines should also include local and heterogeneous corrosion (Fig. 1).

Fig. 1. Corrosion-damaged gas pipelines (photo by A. Yu. Chilikin)

The practice of operating gas pipelines of large diameters indicates that the most dangerous for them is stress corrosion occurring as a result of hydrogenation of the metal caused by the simultaneous influence of the current of the cathodic protection installation and mechanical stresses and leads to embrittlement, corrosion cracking and thereby the destruction of the gas pipeline and emergencies.

Another issue related to the operation of gas distribution networks is fouling (overgrowth) — the accumulation of unwanted material on the solid surface of pipelines, equipment and structures resulting in a decrease in the flow area and a decrease in gas supply. The greater the roughness of their inner surface, the faster the fouling of pipelines occurs, whereas as a result of overgrowth, the hydraulic resistance can rise by 8—9 times compared to the calculated value [6]. In order to improve the accuracy of hydraulic calculations, it is essential to predict the growth dynamics of roughness — a set of irregularities — of the inner surface of pipes. Due to the physical features of the formation methods, the actual (technical) roughness of the pipes is an irregular value based on the difference in the protrusions both in the height and in the order of location. Thus, in order to describe the roughness, probabilistic methods should be employed [1, 4, 5, 14].

During the operation, an increase in the roughness of the walls of the gas pipeline can be given by the formula of A. D. Altshul [1]:

$$k_t = k_0 + \alpha \cdot t, \qquad (1)$$

where k_0 is the absolute equivalent roughness, mm, for pipes at the start of operation (new pipes); k_t is the same after t years of operation; α is the coefficient depending on the pipe material, physical and chemical properties of the gas and characterizing the rate of increase in roughness, mm/year.

One of the issues of identifying dangerous defects is that the corrosion processes of underground gas pipelines are not visually detectable and call for special diagnostic measures [9, 15]. The task of detecting and identifying sections of gas pipelines affected by corrosion is thus extremely relevant at the moment as the timely detection of dangerous sections will enable measures for eliminating emergency situations to be taken immediately.

According to the studies by domestic and foreign scientists, the major causes of corrosion are the composition and mechanical stresses of the pipeline metal, the physicochemical properties of the pumped medium and the chemical compounds in it, the temperature regime, the aggressive properties of the surrounding soil, etc. [12, 17, 19, 20 , 22 etc.].

2. Study of the amount of overgrowth (corrosion) of gas pipelines by means of the risk theory. An analysis of the current state of gas distribution networks allows us to obtain some numerically expressed in time operational characteristics of gas pipelines. According to the collected and processed statistical data on the internal corrosion of gas pipelines, patterns of changes in the diameter of the pipeline can be obtained depending on the period of operation, the amount of overgrowth as well as to numerically estimate the probability of corrosion protrusions and their frequency over time [3, 9].

Considering the amplitude of its values, the thickness of the overgrowth is taken as the key parameter of the overgrowth of the gas pipeline. The amount of corrosion (the thickness of the corroded walls of steel gas pipelines) can be measured using an ultrasonic thickness gauge. In order to process the results of measurements of overgrowing of gas pipelines, methods of mathematical statistics are employed making it possible to obtain probabilistic numerical characteristics of the quantities being studied. Statistical materials are processed by means of plotting the distribution function of a random variable, in our case, the value of corrosion protrusions of the gas pipeline h.

Studies include theoretical — using the methods of probability theory and mathematical statistics, equations of mathematical physics — and full-scale measurements and calculations in compliance with existing methods. In order to improve the accuracy, the results of field measurements are processed by means of two methods — the multiplicative method and the summation method.

Based on the multiplicative method, the average value of the overgrowing heights of the inner wall of the gas pipeline is given by the formula:

$$\overline{X} = X_a + \frac{d}{n} \cdot B, \tag{2}$$

where X_a is the minimum of the selection option; d is the width of the interval; n is the total amount of the measurements; B is the sum of the product of the middle of a conditional interval by the frequency.

The dispersion of the measured characteristics of the gas pipeline is

$$\sigma^2 = \frac{d}{n-1} \cdot \left(A - \frac{B^2}{n} \right), \tag{3}$$

where A is the sum of the product of the square of the middle of the conditional interval and the frequency.

The mean square deviation of overgrowth heights is

$$\sigma = \sqrt{\sigma^2}\,. \tag{4}$$

According to the summation method, the average value, variance and standard deviation of the fouling heights are given by formulas (5), (6).

The average fouling heights are

$$\overline{X} = U_k - d \cdot \left(\frac{M}{n} - 1 \right), \tag{5}$$

where U_k is the lower of the selection option; M is the sum of the values of the partial sum.

The dispersion of the measured characteristics of the gas pipeline is

$$h^2 = \frac{d}{n-1} \cdot \left(2\sum T - M - \frac{M^2}{n} \right), \tag{6}$$

where T is the accumulated frequency.

3. Experimental studies of the magnitude of corrosion overgrowth of pipes. In order to investigate the law of distribution of the size of corrosion protrusions of gas pipelines, a series of field measurements of the protrusions of the roughness of the inner surface of gas pipelines of various diameters and service life was conducted.

As an example, the article provides the results of an experimental measurement of the overgrowth of a gas pipeline with a diameter of 60 mm after 16 years of operation (Fig. 2).

Fig. 2. A pipe with the diameter of 60 mm after 16 years of operation

The measurement results are shown in Table 1.

Table 1

Probability of protrusions of the roughness of the gas pipeline after 16 years of operation

Interval ranks, cm	Frequency m_i	Frequency $p_i = \frac{m_i}{n}$	Accumulated frequency of failures
0.0—0.1	49	0.245	0.245
0.1—0.2	64	0.32	0.565
0.2—0.3	39	0.195	0.76
0.3—0.4	27	0.135	0.895

End of Table 1

Interval ranks, cm	Frequency m_i	Frequency $p_i = \frac{m_i}{n}$	Accumulated frequency of failures
0.4—0.5	8	0.04	0.935
0.5—0.6	5	0.025	0.96
0.6—0.7	3	0.015	0.975
0.7—0.8	2	0.01	0.985
0.8—0.9	2	0.01	0.995
0.9—1.0	1	0.005	1.00
	$n = 200$		

In order to identify the correspondence between natural values and their frequencies, statistical (empirical) distribution functions were designed based on statistical series (Fig. 3).

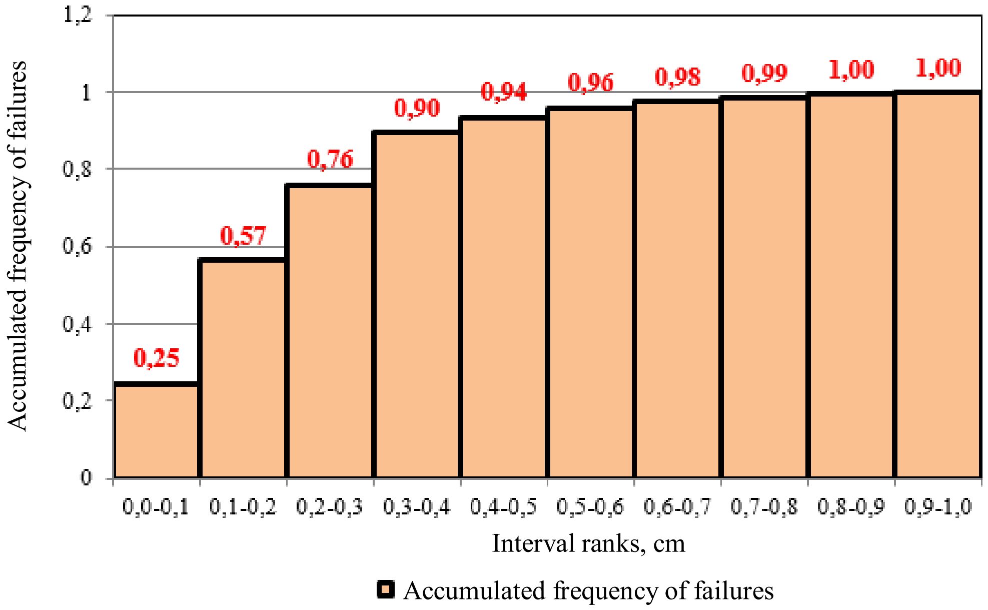

Fig 3. Statistical distribution function (16 years of operation)

Table 2 shows the statistical processing of the intervals of corrosion values of the gas pipeline as well as the average values and square deviations of the overgrowth amplitudes.

Applying the summation method to the data presented in Table 2, we obtain the following values of the required parameters:

1. average height of overgrowth:

$$\bar{X} = h_{cp} = U_k - d \cdot \left(\frac{M}{n} - 1 \right) = 0.95 - 0.3 \cdot \left(\frac{1663}{200} - 1 \right) = 0.23 \text{ cm};$$

2. average square deviation of the magnitude of the overgrowth:

$$\sigma_h = \sqrt{\frac{d^2}{n-1} \left(2 \cdot \sum T - M - \frac{M^2}{n} \right)} = \sqrt{\frac{0.1^2}{200-1} \left(2 \cdot 8027 - 1663 - \frac{1663^2}{200} \right)} = 0.17 \text{ cm}.$$

Table 2

Control of statistical processing of pipe overgrowth value intervals

Interval ranks, cm	Middle of the rank, cm	Absolute frequency m_i	Partial sum S_m	Accumulated frequency T	Middle of a conditional interval l_m	Products		
						$l_m \cdot m_i$	l^2_m	$l^2_m \cdot m_i$
0.0—0.1	0.05	49	49	49	–4	–196	16	784
0.1—0.2	0.15	64	113	162	–3	–192	9	576
0.2—0.3	0.25	39	152	314	–2	–78	4	156
0.3—0.4	0.35	27	179	493	–1	–27	1	27
0.4—0.5	$0.45 = x_a$	8	187	680	0	0	0	0
0.5—0.6	0.55	5	192	872	1	5	1	5
0.6—0.7	0.65	3	195	1067	2	6	4	12
0.7—0.8	0.75	2	197	1264	3	6	9	18
0.8—0.9	0.85	2	199	1463	4	8	16	32
0.9—1.0	$0.95 = U_к$	1	200	1663	5	5	25	25
$d = 0.1$		$n = 200$	$M = 1663$	$\Sigma T = 8027$		$B = –463$		$A = 1635$

Applying the multiplicative method to the data presented in Table 2, we obtain

1. average height of the overgrowth:

$$h_{cp} = x_a + \frac{d}{n} \cdot B = 0,45 + \frac{0.1}{200} \cdot (-463) = 0.23 \text{ cm};$$

2. average square deviation of the overgrowth:

$$\sigma_h = \sqrt{\frac{d^2}{n-1} \cdot \left(A - \frac{B^2}{n} \right)} = \sqrt{\frac{0.1^2}{200-1} \left(1635 - \frac{(-463)^2}{200} \right)} = 0.17 \text{ cm}.$$

The standard measure of dispersion of the probability distribution for the investigated case is 74 %, which indicates the highest degree of destruction and degradation of the gas pipeline. The results of the sequence of calculating the ordinates of the statistical density and the empirical distribution function of the corrosion indicators of the investigated gas pipeline are summarized in Table 3.

Table 3

Sample distribution function of gas pipeline overgrowth

Interval boundaries, mm	Interval in the rank d_i	Middle of the rank h_i	Frequency m_i	Frequency $p_i = m_i / n$	Ordinates of the empirical density $f^*(h_i) = m_i / nd_i$	Empirical distribution function $F^*(h_i) = \Sigma p_i$
0.0—0.1	0.1	0.05	49	0.245	2.45	0.245
0.1—0.2	0.1	0.15	64	0.32	3.2	0.565
0.2—0.3	0.1	0.25	39	0.195	1.95	0.76
0.3—0.4	0.1	0.35	27	0.135	1.35	0.895
0.4—0.5	0.1	0.45	8	0.04	0.4	0.935
0.5—0.6	0.1	0.55	5	0.025	0.25	0.96
0.6—0.7	0.1	0.65	3	0.015	0.15	0.975
0.7—0.8	0.1	0.75	2	0.01	0.1	0.985
0.8—0.9	0.1	0.85	2	0.01	0.1	0.995
0.9—1.0	0.1	0.95	1	0.005	0.05	1.00
			$n = 200$			

According to the experimental data, amplitude distribution histograms were designed whose analysis confirms the correctness of the conclusion regarding the shift of the modal values of corrosion heights (protrusions) to the region of small values (Fig. 4). Therefore it was decided to check the empirical curves of the distribution of height values for compliance with the Charlier distribution [2], as the most adequate for the investigated case (Table 4). The resulting sample is representative and its volume is sufficient to evaluate the parameters and check the consistency of the chosen distribution law.

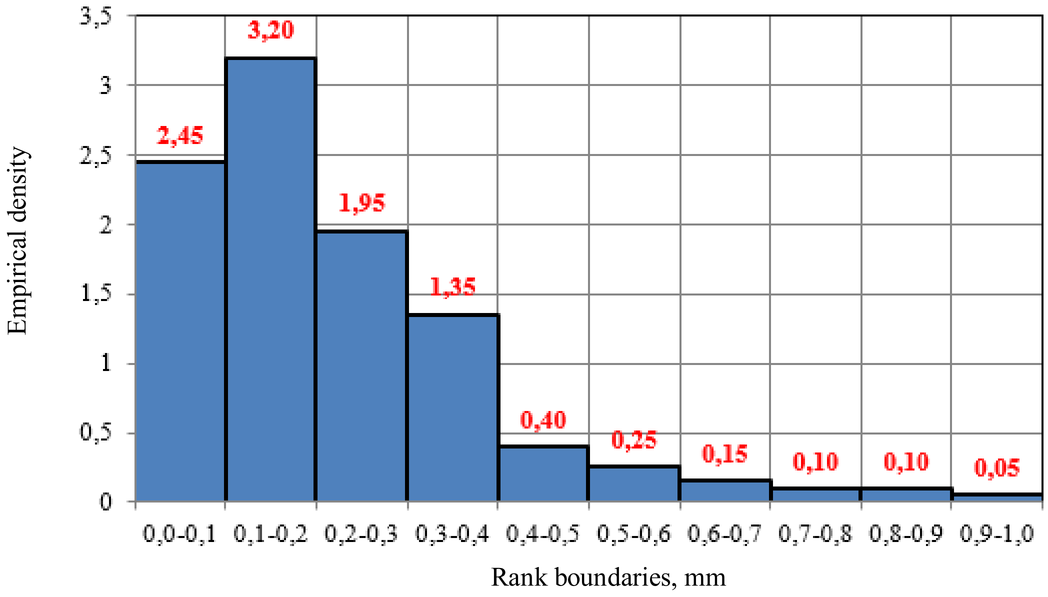

Fig. 4. Histogram of the distribution of corrosion slopes of the gas pipeline

Table 4

Results of comparing the empirical distribution of overgrowth in the gas pipeline with Charlier distribution

Ranks of the intervals of the overgrowth, mm	Absolute frequency m_i	Probability of the measurements being in the rank P_i	Theoretical number of the measurements in the rank $n_t = P_i \cdot n$	$\chi^2 = \frac{(m_i - n_t)^2}{n_t}$
0.0—0.1	49	0.233	46.6	0.12
0.1—0.2	64	0.293	58.6	0.50
0.2—0.3	39	0.206	40.6	0.06
0.3—0.4	27	0.141	28.6	0.05
0.4—0.5	8	0.048	9.6	0.27
0.5—0.6	5	0.032	6.4	0.34
0.6—0.7	3	0.019	3.8	0.17
0.7—0.8	2	0.016	3.2	0.45
0.8—0.9	2	0.014	2.8	0.23
0.9—1.0	1	0.007	1.4	0.11
> 1.0	0	0.003	—	—
				$\sum \chi^2 = 2{,}3$

The corrosion risk assessment of pipelines, which is a qualitative engineering characteristic and based on the Charlier distribution, is given by the following formula:

$$r = 0.5 - \Phi\left[\frac{h_{\text{кр}} - h_{\text{ср}}}{\sqrt{\sigma_{\text{кр}}^2 + \sigma_{\text{ср}}^2}}\right] - \frac{1}{6} C_s \times f^{(2)}\left[\frac{h_{\text{кр}} - h_{\text{ср}}}{\sqrt{\sigma_{\text{кр}}^2 + \sigma_{\text{ср}}^2}}\right] + \frac{1}{24} E_u f^{(3)}\left[\frac{h_{\text{ур}} - h_{\text{ср}}}{\sqrt{\sigma_{\text{кр}}^2 + \sigma_{\text{ср}}^2}}\right], \qquad (7)$$

where C_s, E_u are the asymmetry coefficient and excess of empirical distribution of intervals between the overgrowth values; $f^{(2)}, f^{(3)}$ are the second and third derivatives of normal distribution; U is the quintile of normal distribution:

$$U = \left[\frac{h_{\text{кр}} - h_{\text{ср}}}{\sqrt{\sigma_{\text{кр}}^2 + \sigma_{\text{ср}}^2}}\right];$$

$h_{\text{ср}}$, $h_{\text{кр}}$ are the average and critical overgrowth values; $\sigma_{\text{ср}}$, $\sigma_{\text{кр}}$ are the average square deviations of the overgrowth values.

A graphical interpretation of the results of a comparative analysis of the histogram of gas pipeline overgrowing values with the Charlier distribution density is shown in Fig. 5.

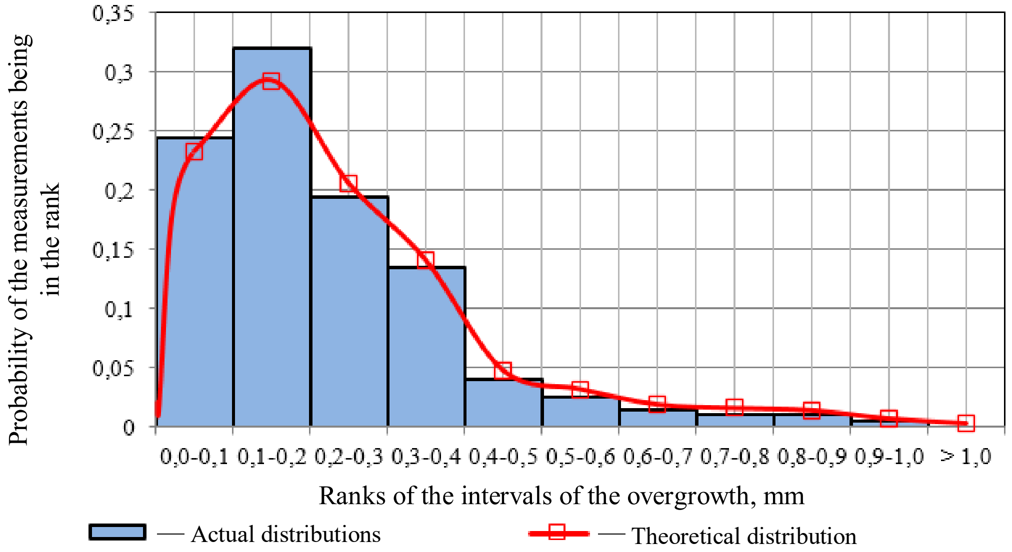

Fig. 5. Histogram of corrosion values and Charlier distribution density (gas pipeline after 16 years of operation)

The critical overgrowth of the gas pipeline can be given by the expression:

$$h_{\text{кр}} = 2 \cdot h_{\text{дон}} - \frac{\sqrt{h_{\text{дон}}^2 + \left[25 \cdot \left(C_v^{h_{rh}}\right)^2 - 1\right] \cdot \left(h_{\text{дон}}^2 - 25 \cdot \sigma_{\text{дон}}^2\right)} - h_{\text{дон}}}{25 \cdot \left(C_v^{h_{\text{кр}}}\right)^2 - 1}, \qquad (8)$$

where $C_v^{h_{rh}} = C_v + \left(h_{\text{дон}} + \alpha \cdot t\right) / d$ is the variation coefficient; t is a life cycle; d is the diameter of the gas pipeline; α is the coefficient characterizing the rate of unevenness growth; $h_{\text{дон}}$ is an absolute unevenness for welding steel pipes depending on the time of operation.

Conclusions. An analysis of the conclusions of the industrial safety review according to the results of technical diagnostics of the condition of underground steel gas pipelines of various diameters and operating conditions indicates the need for improving the methodology for assessing the parameters of overgrowth (corrosion) and developing appropriate planned and preventive measures to optimize costs, identifying the timing of repairs and the remaining life cycle of pipelines. Considering the factors affecting the performance and reliability, in order to address the problem of predicting the state of gas pipelines, for any period of time it is proposed to make use of the assessment method for the risk of overgrowth of the gas pipeline over time and the actual operational life of the gas pipeline.

An analysis of the research results enables us to conclude that the overgrowth parameters are sufficiently consistent with the Charlier distribution which can be used both for processing statistical data and for assessing the risk of corrosion. The relative standard deviation of 75.1 % obtained during the examination of a gas pipeline with the diameter of 60 mm after 16 years of operation indicates a drop in the flow area due to corrosion overgrowth, an increase in roughness and thereby a low quality of the operational and technical condition of the gas pipeline.

The suggested mathematical model additionally represents the possibility of solving the problem of rational distribution of allocated funds for the current and major repairs of gas distribution systems.

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