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Simulation of the risks of the safe operation of oil pipelines

Stepova Olena^{1*}, Adamski Mariusz², Stepovy Yevhen³

¹ National University «Yuri Kondratyuk Poltava Polytechnic» <https://orcid.org/0000-0002-6346-5484>

² Technical University of Bialystok, Bialystok, Poland <https://orcid.org/0000-0002-1686-8301>

³ National University «Yuri Kondratyuk Poltava Polytechnic» <https://orcid.org/0009-0001-4783-3929>

*Corresponding author E-mail: alenastepovaja@gmail.com

The development of practical aspects of environmental safety requires taking into account the necessary parameters of the technical condition of equipment, namely oil pipelines, including their operating conditions, climatic features of the regions, standardized risk and safety parameters, and residual resource based on reliability and durability indicators.

On the basis of the electrochemical corrosion mathematical pipeline model in the insulating coating crack under the action of an aggressive electrolytic medium towards the pipeline metal, the dependence was obtained that allows to calculate the corrosion depth of the pipeline wall during the work of macro-galvanic corrosion couples in the conditions of stable and periodic stay of the aggressive solution in the damaged zone. The advantage of this model is the ability to predict the development of corrosion over time regardless of the corrosive electrolyte chemical composition, the possibility of obtaining necessary design parameters for operated structures. The developed dependencies of the pipeline section corrosion depth make it possible to plan rationally the repair work, to predict the real terms of the structure work, to review the operation mode, etc. The obtained results allow us to more reliably evaluate the bearing capacity of structures that operate in conditions of aggressive medium with cracks

Keywords: environmental safety, oil pipeline, corrosion, pipe depressurization, risk

Моделювання ризиків безпечної експлуатації нафтопроводів

Степова О.В.^{1*}, Адамський М.², Степовий Є.Б.³

¹ Національний університет «Полтавська політехніка імені Юрія Кондратюка»

² Білостоцький технологічний університет (Польща)

³ Національний університет «Полтавська політехніка імені Юрія Кондратюка»

*Адреса для листування E-mail: alenastepovaja@gmail.com

Розвиток практичних аспектів екологічної безпечної експлуатації об'єктів критичної інфраструктури, в тому числі нафтопроводів вимагає розуміння та врахування необхідних параметрів технічного стану обладнання, а саме сталевих нафтопроводів, включаючи фактичні умови їх експлуатації, кліматичні особливості регіонів, стандартизовані параметри ризиків та екологічної безпеки, а також залишковий ресурс їх експлуатації з врахуванням показників надійності та довговічності. Метою дослідження є розроблення та теоретична апробація методики розрахунку залишкового ресурсу ділянки нафтопроводу за умов наявних корозійних пошкоджень сталевих труби та її розрахункова перевірка. На основі математичної моделі електрохімічної корозії сталевих нафтопроводів в тріщині ізоляційного покриття за умов агресивного впливу електролітичного середовища на метал нафтопроводу запропоновано та досліджено залежність, яка дозволяє розрахувати залишкову товщину стінки на ділянці нафтопроводу. Перевагою даної моделі є можливість прогнозування розвитку процесу електрохімічної корозії в часі незалежно від хімічного складу агресивного електроліту, також можливість визначення необхідних конструктивних параметрів конструкцій, що експлуатуються. Отримані результати дозволяють науково обгрунтовано оцінити фактичну несучу здатність нафтопроводу з врахуванням реальних умов експлуатації конструкції. Запропонована залежність встановлення залишкової товщини стінки нафтопроводу дає змогу прогнозувати фактичний ресурс конструкції, раціонально планувати ремонтні роботи, переглядати умови експлуатації тощо задля запобігання можливої розгерметизації ділянок нафтопроводу внаслідок електрохімічної корозії

Ключові слова: екологічна безпека, нафтопровід, корозія, розгерметизація труби, ризик

Introduction

Ukraine has an extensive network of steel oil pipelines with a total length of about 5,000 km, which are classified as high-risk facilities in terms of environmental safety. In the event of a breakdown, they pose anthropogenic and environmental risks of environmental pollution due to oil and oil products and possible fires. Corrosion damage to steel oil pipelines is one of the factors that increase the anthropogenic and environmental risks of environmental pollution. Understanding and taking into account the regularities of corrosion processes is the scientific basis for preventing increased risks of environmental pollution during the operation of existing oil pipelines and determining their residual service life of steel oil pipelines.

Review of the research sources and publications

The development of the theory of technogenic and environmental safety justifies the practical consideration of the parameters of the actual state of technical facilities, namely oil pipelines and environmental conditions, including operating conditions, climatic characteristics of the regions, regulatory parameters of risks and safety, which are justified by the criteria of survivability, strength, reliability, and service life. One of the main factors in solving this problem is to consider the concept of risk monitoring, which is based on periodic data on the diagnostic state and standardised hazard parameters in the operation of such facilities. One of the conditions for safe operation is the use of a comprehensive system for monitoring the condition of materials and structural elements in normal and emergency situations and analysing the risks of their operation at all stages of the life cycle [1-3].

Risk analysis is the scientific basis for assessing integrated technogenic and environmental safety, which is based on methods, equations, patterns and criteria obtained in fundamental fields of knowledge [3, 4].

For the analysis of integrated risks, there are developed management theories, system analysis theories, disaster theories, methods of simulation and mathematical modelling, forecasting, mathematical statistics, methods and systems of monitoring and diagnostics.

Thus, the development of scientific foundations for ensuring anthropogenic and environmental safety of steel oil pipelines in operation, which would consider the features and patterns of their electrochemical corrosion processes, is an urgent problem, the solution of which will reduce the risks of environmental pollution during the operation of steel oil pipelines.

Analysis of recent research sources and publications. Corrosion of steel oil pipelines is one of the negative factors that increase the anthropogenic and environmental risks of creating emergencies related to environmental pollution. Domestic scientists have studied the anthropogenic and environmental risks of operating hazardous facilities [1-7].

The general issues of ensuring the safety of operation, including the environmental safety of steel oil pipelines, were dealt with by such scientists as Kryzhanivskyi E., Gerasymenko Y., Andreikiv O., Poberezhnyi L., Grabovsky R., Zhdek A., Dmtrakh I.,

Ivanitskyi Y., Klymenko A., Lobanov L., Niki-forchyn G., Skalskyi V., Fedirko V. and others, but their works pay insignificant attention to the prevention of technogenic and environmental risks of environmental pollution due to corrosion processes of steel oil pipelines.

A few foreign scientists have carried out their research.

Definition of unsolved aspects of the problem

Understanding and taking into account the regularities of corrosion processes is the scientific basis for preventing an increase in the anthropogenic and environmental risks of pollution of environmental components during the operation of oil pipelines by establishing the residual life of steel oil pipelines.

Problem statement

The purpose of the study is to develop and theoretically test a methodology for calculating the residual life of an oil pipeline section under conditions of existing corrosion damage to a steel pipe and to verify it.

Basic material and results

Risks $R(t)$ in reliability theory are understood as the following combinations of probabilities $P(t)$ of occurrence of emergency events in time, on the one hand, and mathematical expectation of losses $U(t)$, on the other, which determine the change in the level of security of critical infrastructure facilities and the environment from internal and external threats and hazards.

$$P(t) = F_R \{P(t), U(t)\} \quad (1)$$

It is known [4; 5] that during operation, an oil pipeline accumulates damage along a certain trajectory $D(N, t, \sigma)$, which is determined by the load parameters: the number of cycles N , stress σ , and defectiveness.

To ensure the safe operation of the structure, instead of critical damage D_c , which ensures the achievement of limit states, permissible damage $[D]$ is introduced into the calculation, taking into account the system of safety factors. The levels D_c and $[D]$ divide the area of safe operation and the area of marginal safety and danger, i.e. risk. Monitoring of the object's condition parameters in these areas is the basis for analysing the risks of the object being in a particular state and the conditions of its transition between them. The results of the assessment of the object's state according to this scheme have the form of a statistical function f and are not the final solution to the problem, which also includes the determination of the time interval Δt until the next examination of the state of the object under study.

In the probabilistic assessment of the interval Δt , it is advisable to accept the risk R_f of reaching the limit state as a safety criterion. The designated interval Δt should ensure that the probability of possible failure does not exceed the specified risk level $[R_f]$. The value of this risk should be set considering the potential hazard class of the facility. If we use recurrent relations for the probability of the object's transition to the limit state $R_f(t)$, we can obtain an expression for estimating the optimal time until the next moment of the object's inspection.

Thus, in the general case, it is possible to consider two main types of scenarios of risk change $R(t)$ in time t . The first includes scenarios for managing the safety of the analysed facilities under the conditions of normal operation of the oil pipeline section with a monotonic increase in risks $R(t)$ to acceptable levels $[R(t)]$ at time $[t]$. At the same time, critical risks $R_i(t)$ are not reached. Currently, appropriate measures are required to reduce the current risks $R(t)$ when the risks to the system in question remain at acceptable levels.

The second type includes scenarios in which instability points can be created when risks increase dangerously to a critical point at time $t = t_i$, and the value of $R(t)$ in this case is equal to $R_i(t)$. As a rule, instability points in the system are the appearance of zones of local damage in the pipe section and the emergence of external threats to its normal operation.

The thickness of the pipeline wall is a parameter that determines its strength. Although each pipe has a certificate, a verified strength calculation must be carried out, for which purpose it is necessary to establish the actual wall thickness, taking into account the operating pressure and the maximum permissible wall thickness at which depressurisation of the pipeline with subsequent oil or oil products spillage will not occur.

The permissible residual wall thickness of the pipeline corresponds to the full exhaustion of the structural life.

The pipeline is subject to longitudinal, annular, and radial stresses. Radial stresses are much smaller than longitudinal and annular stresses, so they can be ignored in the strength checks.

The strength of the pipeline is checked using the well-known limit state method. This means that the stress state of the pipeline is such that its further operation is impossible. The first limit state is the bearing capacity (destruction of the pipeline under the influence of internal pressure), and the second is the maximum permissible deformation. A characteristic of the bearing capacity of pipelines is the temporary resistance of the metal, or tensile strength.

Failure of a steel oil pipeline in terms of bearing capacity is a condition when the stress from the design loads and impacts in the area under study exceeds the yield strength of the pipe steel:

$$\sigma > R \quad (1)$$

where σ – longitudinal axial stress from design loads and impacts, MPa;

R – calculated resistance of the pipe material (yield strength).

Pipeline strength is ensured by considering the stresses that occur in the pipeline during operation and comparing them with the pipe material resistance R .

When determining the stress state of the pipeline to check the first limit state, the stresses that affect the destructive pressure are considered.

Strength testing of underground pipelines to exclude unacceptable deformations is performed based on the following conditions:

$$[\sigma_{longN}] \leq \varphi_2 R_1, \quad (2)$$

$$\sigma_{an} \leq \frac{m}{0.9k_n} R_2^n, \quad (3)$$

where $[\sigma_{longN}]$ – longitudinal axial stress from design loads and impacts, MPa;

φ_2 – a coefficient that takes into account the biaxial stress state of the pipe metal (at tensile stresses it is taken equal to 1);

R_1, R_2 – calculated tensile (compressive) strength, MPa.

$$R_1 = \frac{R_1^n m}{k_1 k_n}, \quad R_2 = \frac{R_2^n m}{k_2 k_n} \quad (4)$$

m – pipeline operating conditions factor;

k_1, k_2 – reliability factors by pipeline material;

k_n – reliability factor for the purpose of the pipeline.

The longitudinal axial stresses are determined from the design loads and impacts, taking into account the elastic-plastic behaviour of the metal. For straight sections of underground pipelines in the absence of transverse and longitudinal movements and ground subsidence, longitudinal axial stresses due to internal pressure, temperature difference and elastic bending are determined by the following relationship:

$$\sigma_{npN} = \frac{0.15 p D_{int}}{\delta} - \alpha E \Delta t \pm \frac{E D_{inv}}{2 \rho}, \quad (5)$$

where p – operating pressure, MPa;

D_{inv} – internal diameter of the pipeline section, cm;

$$\sigma_{an} = \frac{p D_{int}}{2 \delta}, \quad (6)$$

where δ – nominal wall thickness of the pipeline section, cm;

α – coefficient of linear expansion of pipe metal, deg^{-1} ;

E – variable modulus of elasticity of the pipe material, MPa;

Δt – calculated temperature drop, $^{\circ}\text{C}$;

ρ – minimum radius of elastic bending of the pipeline axis, cm.

The difference between the ultimate load-bearing capacity at the time of inspection and the calculated force acting on the structure during operation creates a certain margin of safety, which can be considered when calculating the remaining service life of a structure with corrosion damage.

It is advisable to calculate the actual stresses occurring in the pipeline at the time of inspection by taking into account the reduction in the thickness of the pipeline wall, which is introduced into the calculation:

$$\Delta \delta = \delta - h, \quad (7)$$

where $\Delta \delta$ – is the residual thickness of the pipeline wall in the corroded area, mm;

h – corrosion depth, mm;

The level of annular stress in the pipeline with corrosion damage should meet the condition:

$$\frac{p(D_{\text{int}} + 2h)}{2(\delta - h)} \leq [\sigma_{\text{an}}], \quad (8)$$

D_{int} – inner diameter of the pipe, mm;

σ_p – permissible ring stress.

The permissible corrosion depth of the pipe wall $[h]$ is calculated by the formula:

$$[h] = \delta - \frac{pD_o}{2([\delta_p] + p)}, \quad (9)$$

where D_o – outer diameter of the pipeline, mm.

As with pipes, formula (7-9) can be applied to both internal and external corrosion. Formula (7-9) can be written as follows:

$$[\varepsilon] = (1 - \frac{pD_o}{2\delta([\sigma_{\text{an}}] + p)})100\%, \quad (10)$$

where $[\varepsilon] = [h]/\delta$ – permissible relative thinning of the pipeline wall.

The actual absolute h (or relative) wall thinning must be less than the permissible: $h \leq [h]$ (or $\varepsilon \leq [\varepsilon]$).

Similarly, the inspection is performed by longitudinal stresses and the permissible corrosion depth is calculated.

According to the requirements of [8], for sections of oil pipelines that have corrosion thinning of the pipe walls within certain limits, the working pressure is calculated using the formula:

$$[p] = \frac{2[\sigma_{\text{an}}] \cdot (\delta - h)}{D_{\text{int}} - 2(\delta - h)}, \quad (11)$$

where h – corrosion depth of the oil pipeline wall, mm.

In addition, having the value of the permissible corrosion depth of the oil pipeline section and knowing the rate of the corrosion process, it is possible to determine the remaining life of the oil pipeline section [6, 7]

$$T = \frac{[h]}{i} - t_b, \quad (12)$$

where $[h]$ – is the permissible corrosion depth of the oil pipeline section, mm

i – corrosion rate on the investigated section of the oil pipeline, mm/year.

t_b – time spent by the pipeline in these conditions, years.

It is recommended to determine the corrosion rate on the investigated section of the oil pipeline by the developed mathematical model [7]

$$i(x) = \frac{2(E_a - E_k)\gamma}{c} \sum_{k=1}^{\infty} \frac{\sin \frac{\pi k a}{c} \cos \frac{\pi k x}{c}}{k(1 + \frac{\pi k L}{c})}, \quad (13)$$

K – is the electrochemical coefficient of the metal determined by the formula $K = A/(F \cdot U)$ as follows $K = 55.845/(2 \cdot 26.80139) = 1.04183$ g/A·h. According to reference material $K = 1.0424$ g/A·h;

A – atomic weight of metal, for iron $A = 55,845$ g/mol [10, 11];

U – metal valency, for iron $n = 2$;

F – Faraday constant,

$F = 96485.33$ A·s/mol = 26.80148 A·hour/mol;

t – time duration, hours;

E_a, E_k – are the potentials of the anode and cathode sites, respectively, V;

γ – the specific electrical conductivity of the electrolyte, is the inverse of the resistivity of the electrolyte, i.e. $\gamma = 1/\rho$;

L – a coefficient that depends on the specific electrical conductivity of the electrolyte and the polarisation coefficient;

a – width of anode selector, m;

c – width of cathode selector, m;

x, y – flow coordinates;

$k = 1, 2, 3$.

The Commission on Atomic Weights and Isotopic Abundances [10] has changed the recommended value for the standard atomic weight of iron to $A(Fe) = 55.845$ g/mol [11] based on recent calibrated positive thermal ionization mass-spectrometric measurements carried out on a metallic iron sample of high purity. The magnitude of the uncertainty on this value is mainly due to the variations of iron isotopic composition found in geological and biological samples. The previous value of $A(Fe) = 55.847$ was assigned in 1961, based on mass-spectrometric measurements and value $A(O) = 16$ g/mol. Values concordant with $A(O) = 15.99941$ g/mol include: 1894, 56.04; 1896, 56.02; 1900, 56.0; 1901, 55.9; 1909, 55.85; 1912, 55.84; 1940, 55.85; and 1961, 55.847 g/mol.

The proposed methodology for calculating the residual allowable thickness of the oil pipeline wall as a parameter that determines the pipe's service life and its safe operation has been tested in assessing the condition of a section of an existing oil pipeline under the conditions given in Table 1.

The results of calculations of the residual life of the oil pipeline according to the dependencies proposed by the author coincide with the calculations based on existing methods with a relative error of 17%.

The novelty of the research is to prevent pollution of environmental components due to depressurisation of the oil pipeline section by applying the developed methodology for determining the depth and permissible depth of corrosion of a steel oil pipeline during the operation of a macro galvanic corrosion couple under the influence of an aggressive electrolytic solution, as well as the methodology for determining the residual life of its technogenic and environmental safety of operation, which will allow predicting the development of corrosion processes on a steel oil pipeline and planning the necessary measures.

Table 1 – Nomenclature and values taken to calculations

Parameter	Designation	Units of measurement	Meaning
Initial data			
Outer diameter of the oil pipeline	D_3	mm	530
Pipeline wall thickness	δ	mm	9
Tensile strength of the pipe material	σ	MPa	
Operating pressure in oil pipelines	p	MPa	5.04
Potential difference between galvanic pairs	ΔE	mV	0.06
Lifetime of the pipeline	t_e	year	15
Area of the corroded area	a	cm ²	0.0024
Calculated values			
Permissible ring stress	σ	MPa	363
Corrosion current of the galvanic cell	I	A/cm ²	0.88×10^{-4}
Corrosion rate of the galvanic couple	i_e	mm/h	3.17×10^{-5}
Corrosion rate of the galvanic couple	i_e	mm/year	0.27
Estimated corrosion depth at the time of inspection	h	mm	4.05
Permissible pressure at the defect at the time of inspection	$[p]$	MPa	8.17
Permissible wall thicknesses	$[h]$	mm	5.37
Residual life-1	T	year	20.94-15=5.94 years
Residual life -2	T	year	19.88- 15=4.88 years
Permissible x value	$[x]$		

Conclusions.

In order to reduce the likelihood of emergencies with increased risks of their occurrence and minimise damage from their manifestation, a set of measures should be implemented for potentially hazardous critical infrastructure facilities, taking into account the nature of the hazard sources and the peculiarities of their manifestation, permissible operating modes and the possibility of using threat prevention measures based on the results of comprehensive diagnostics and monitoring of the facility.

To solve the problems of ensuring environmentally safe operation of main oil pipelines, it is advisable, first of all, to apply a set of modern methods and means of controlling the parameters of the state of critical infrastructure and the environment in real operating conditions, the use of monitoring systems and analysis of data on the environment and possible external influences on the system under study, the use of databases with sources of hazards and scenarios of emergency situations, criteria for their assessment and methods of.

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