Research of Risks of Depressurization of Steel Oil Pipelines

Olena Stepova, Elena Hanoshenko, Gulnar Feyziyeva, and Yuliia Chukhlib

Abstract Modern development of safety theory justifies the introduction into practice of providing the necessary parameters of the state of technical facilities, namely pipelines and the environment, including operational conditions, climatic features of areas, standardized parameters of risk and safety, based on reliability, strength, resource, survivability. Based on mathematical model of electrochemical corrosion of oil pipeline in the coating cavity under the aggressive affect of electrolyte environment on the metal of the oil pipelines, the correlation has been found and studied, which enables counting of the remaining depth pit of the corrosive oil pipeline wall of macrogalvanic corrosive couples on the condition of aggressive liquid being in the affected area. The advantage of the given model is an opportunity to predict the development of corrosion progression over time irrespective of aggressive electrolyte chemical composition, opportunity of the necessary design parameters for the constructions that are operated. Correlation of section the assessment of the remaining corrosion cavity of an oil pipeline has been developed which gives an opportunity to rationally plan the repairs, predict the real terms of construction operating, reconsider the operation conditions etc. The given results enable valid assessment of the loadbearing capacity of the construction that operate in the aggressive environment with the defects.

Keywords Ecological safety · Oil pipeline · Corrosion · Pipe depressurization · Risk

1 Introduction

Ukraine has an extensive network of steel pipelines with a total length of almost 5,000 km, which are objects of increased danger in terms of modern environmental

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requirements. In case of their depressurization there are ecological risks of environmental pollution due to leakage of oil products, possible fires, explosions, etc. One of the negative factors that increase the environmental risks of emergencies related to soil, water and air pollution is the corrosion of steel oil pipelines. Understanding the patterns of such processes and taking them into account is a scientific basis for determining the residual life of steel oil pipelines, as well as developing measures to prevent increased risks of environmental pollution during their operation.

Modern development of safety theory justifies the introduction into practice of providing the necessary parameters of the state of technical facilities, namely oil pipelines and the environment, including taking into account operating conditions, climatic features of areas, normalized risk and safety parameters, based on reliability, strength, resource, survivability. A key factor in solving this problem should be the use of the concept of risk monitoring, based on continuous or periodic information on the diagnosis of conditions and basic parameters of hazards in the operation of these facilities. One of the conditions for safe operation, is the interconnected development and use of a comprehensive system for diagnosing and monitoring the condition of materials and structural elements in normal and emergencies, monitoring the risks of their operation at all stages of the life cycle, and operation of protection systems for accidents and disasters, as the risks go beyond acceptable approach them to the limit [1–5].

Risks as an interdisciplinary scientific basis for assessing integrated safety, including environmental, are based on laws, methods, equations and criteria obtained in fundamental fields of knowledge—mathematics, physics, chemistry, mechanics, computer science, mechanical engineering, biology, physiology, geology, geophysics. atmospheric and ocean physics, geography, philosophy, sociology, psychology, economics, law [3–5].

Generalized for the analysis of integrated risks are the developed theories of systems analysis, control theories, theories of catastrophes and protection constructions, methods of mathematical and simulation modeling, forecasting, mathematical statistics, methods and systems of diagnostics and monitoring.

Therefore, the development of scientific bases for environmental safety of existing steel oil pipelines, which take into account the features and patterns of their electrochemical corrosion as a source of environmental pollution is an urgent problem, the solution of which creates preconditions for reducing the risk of environmental pollution during operation.

2 Aim and Objectives of the Research

The aim of the work is to develop a methodology for assessing the residual life of steel pipelines and the risks of their depressurization under the influence of a corrosive environment in compliance with the requirements of safe operation on the basis of real characteristics. The following tasks are set to solve the goal:

based on a mathematical model of local electrochemical corrosion of oil pipeline steel and dependence, which allows to calculate the residual life of the pipeline in the crack of the insulating coating during macro galvanic corrosion pairs to develop a method for assessing the risks of depressurization of the pipeline;

to carry out verification calculations of strength characteristics and residual resource of the section of the operated oil pipeline.

3 Materials and Methods of the Research

Risks (R) in safety theory are understood as such combinations of probabilities P (t) of occurrence of adverse events in time (dangerous and crisis phenomena, catastrophic and emergency situations), on the one hand, and mathematical expectation of the losses caused by it U (t)—on the other hand, which determine the change in the level of safety and the state of human protection systems, infrastructure and the environment from threats and dangers of internal and external nature—man-made, natural, anthropogenic.

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

As is known [4, 5], during the operation of the pipeline there is an accumulation of damage along with a certain trajectory D (N, t, σ), which is determined by the load parameters—the number of cycles N, the intensity σ, the defect l (Fig. 1).

To ensure safe operation of the structure instead of critical damages Dc, corresponding to the achievement of limit states, using a system of reserve ratios in the calculation can be introduced allowable damage [D]. Levels D_c and [D] divide the

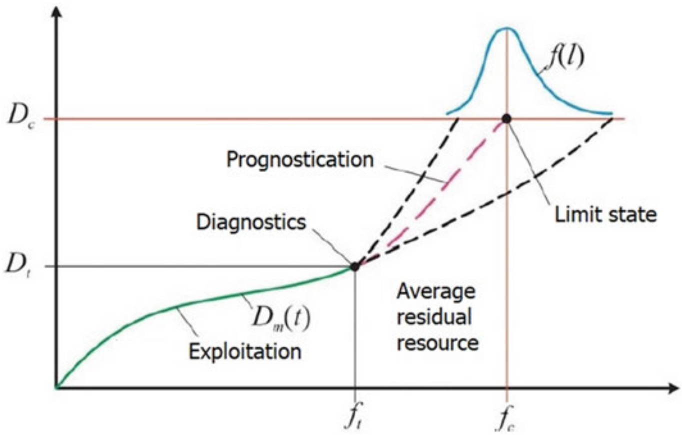

Fig. 1 Trajectories of accumulation of damages in the course of operation of the oil pipeline

area of safe operation and the area of limited safety and danger (risk). Monitoring the parameters of the state of the object in these areas and is the basis for analyzing the risks of the object in a particular state and the conditions of its transition between them. The results of assessing the state of the object as shown in Fig. 1 scheme has the form of a statistical function f and is not the final solution of the problem, which also includes determining the time interval Δt before the next examination of the state of the object.

In the probabilistic estimation of the interval Δt, the risk R_f of the possibility of reaching the limit state should be accepted as a safety criterion. The assigned interval Δt must ensure the probability of possible destruction not higher than the specified level [Rf] of risk. The magnitude of this risk should be determined taking into account the nature (class) of the potential danger of the object. If we use recurrent relations for the probability of transition of the object to the limit state $R_f(t)$, we can obtain an expression to estimate the optimal time until the next moment of the control inspection of the object.

In the general case, there are two main types of risk change scenarios R(t) in time t (Fig. 2). The first includes scenarios for managing the safety of the analyzed facilities in the normal operation of the oil pipeline section as a whole with a monotonous increase in risks R(t) to acceptable levels [R(t)] at time [t] at point A on line 1. The critical risks $R_i(t)$ are not achieved. At this time, special measures are required to reduce the current risks R(t) along with line 1 "to point C and further along line 1", when the risks for this system remain acceptable levels.

The second type includes scenarios in which there may be points of instability A and B with a dangerous increase in risks on lines 2 and 3 to the critical point K at time $t = t_i$, and the value of R (t) in this case is equal to R_i (t). Points of instability in the system may be the appearance of areas of local damage in the area of the pipe,

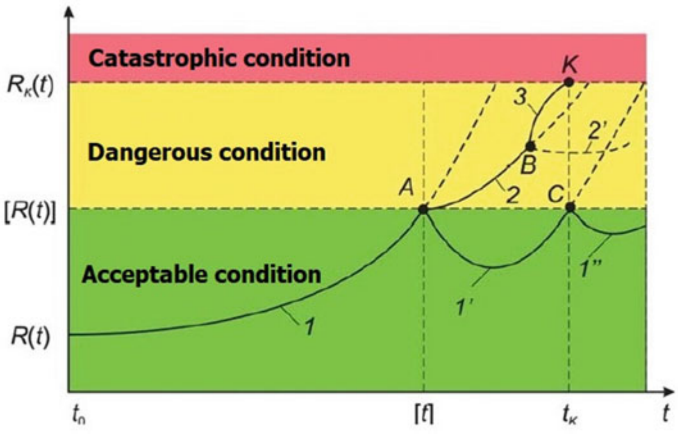

Fig. 2 Scenarios of change of risks R(t) in time t

the emergence of external threats to its normal operation, unauthorized impact on the object, etc.

The wall thickness of the pipeline is a determining parameter that characterizes its strength. Although each pipe has its own certificate, it must be calculated on strength, for which it is necessary to know the actual wall thickness, taking into account the working pressure and the maximum allowable wall thickness at which there is no depressurization of the pipeline with subsequent spillage of oil or oil products.

The allowable residual wall thickness of the oil pipeline corresponds to the complete depletion of the resource of the structure. Radial, longitudinal and annular strain act in the pipeline. Radial strain are much smaller in value than the ring and longitudinal tension, so the strength calculations are not taken into account in the test calculations.

Checking the strength of the pipeline is carried out by the known method of limit states. Considered so strain state of the pipeline is considered, at which its further operation is impossible. The first limit state is the bearing capacity (destruction of the pipeline under the influence of internal pressure), the second is the maximum allowable deformation. The characteristic of the bearing capacity of pipelines is the temporary resistance of the metal of the pipes or the tensile strength.

For failure of the steel oil pipeline on bearing capacity the condition is accepted when the strain from the design loads and influences on the investigated area in the crack, exceeds the yield strength of tubular steel

$$\sigma > R \tag{1}$$

where σ—longitudinal axial strain from design loads and influences, MPa;
R_s—the calculated resistance of the pipe material (yield strength).

The strength of the pipeline is ensured by calculating the strain arising in it during operation and comparing it with the resistance of the pipe material R.

When determining the stress state of the pipeline to check the first limit state, the strain that affect the destructive pressure are taken into account.

Check on the durability of underground pipelines for the purpose of an exception of inadmissible deformations carry out proceeding from conditions.

$$[\sigma_{npN}] \leq \phi_2 R_1, \tag{2}$$

$$\sigma_{ann} \leq \frac{m}{0{,}9k_n} R_2^n \tag{3}$$

where $[\sigma_{npN}]$—longitudinal axial strain from design loads and influences, MPa;
ϕ_2—coefficient taking into account the biaxial strain state of the metal of the pipe (at tensile strain is taken equal to 1);
R_1, R_2—calculated tensile strength (compression), MPa.

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

m—coefficient of working conditions of the pipeline;
k_1, k_2—reliability coefficients for the pipeline material;
k_n—reliability factor for the purpose of the pipeline.

The longitudinal axial stress measured at design load and impacts, taking into account of resilient metal. For rectilinear sections of underground pipelines in the absence of longitudinal and transverse displacements and subsidence of the soil, the longitudinal axial strain from the influence of internal pressure, temperature drop and elastic bending, MPa, are determined by the formula.

$$\sigma_{npN} = \frac{0{,}15 pD_{in}}{\delta} - \alpha E \Delta t \pm \frac{ED_{ext}}{2\rho}, \quad (5)$$

where p—working pressure, MPa;
$D_{вн}$—the inner diameter of the pipeline section, cm;

$$\sigma_{кц} = \frac{pD_{in}}{2\delta}. \quad (6)$$

де δ—the nominal wall thickness of the pipeline section, cm;
α—coefficient of linear expansion of metal pipes, deg^{-1};
E—variable modulus of elasticity of the pipe material, MPa;
Δt—calculated temperature difference, °C;
ρ—the minimum radius of elastic bending of the axis of the pipeline, cm.

The difference between the ultimate bearing capacity at the time of inspection and the design force acting on the structure during operation creates a margin for bearing capacity, which can be taken into account when calculating the residual life of the structure, with the affected corrosion of the pipeline section, in cracks in the insulation coating.

The calculation of the actual stresses occurring in the pipeline at the time of the survey is performed by taking into account the reduction of the wall thickness of the pipeline, which is entered into the calculation

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

where $\Delta\delta$—the residual wall thickness of the oil pipeline on the site affected by corrosion, mm;

h—depth of corrosion, mm;

The level of annular strain in the pipeline having corrosion lesions (Fig. 2) must meet the condition [9]:

$$\frac{p(D_{in}+2h)}{2(\delta-h)} \le [\sigma_{ann}] \tag{8}$$

$D_{вн}$—the inner diameter of the pipe, mm;
$[\sigma_{кц}]$—allowable ring tension.
The allowable depth of corrosion of the pipe wall [h] is calculated by the formula

$$[h] = \delta - \frac{pD_з}{2([\sigma_{ann}]+p)} \tag{9}$$

where $D_з$—outer diameter of the pipeline, mm.

Since for pipes $\delta \ll D$, formula (9) can be applied to cases of internal and external corrosion. Formula (9) can be written as:

$$[\varepsilon] = (1 - \frac{p \times D_з}{2\delta([\sigma_{ann}]+p)}100\% \tag{10}$$

where $[\varepsilon] = \frac{[h]}{\delta}$—permissible relative thinning of the pipeline wall.

The actual absolute h (or relative ε) thinning of the wall must be less than the allowable: $h \le [h]$ (or $\varepsilon \le [\varepsilon]$).

Similarly, the test is performed on the longitudinal strain and the allowable depth of corrosion is calculated.

According to the requirements for sections of oil pipelines having corrosive thinning of pipe walls within certain limits, the calculation of operating pressure is carried out according to the formula:

$$[p] = \frac{2[\sigma_{ann} \times (\delta-h)]}{D_{ext} - 2(\delta-h)} \tag{11}$$

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

In addition, having the value of the allowable depth of pipeline corrosion section of the oil pipeline and knowing the speed of the corrosion process, it is possible to determine the residual life of the oil pipeline [6–8]

$$T = \frac{[h]}{i} - t_1 \tag{12}$$

where $[h]$—allowable depth of corrosion of the pipeline section, mm, i—corrosion rate on the investigated section of the pipeline, mm/year, $t_в$—time of the pipeline in these conditions, years.

Main oil pipelines are used in natural conditions, mainly, below the ground. For protection of steel oil pipelines from aggressive attack of the environment, different coatings are used as a rule. But in the process of operating wholeness of coatings is broken and the aggressive environment affects the steel of an oil pipeline. In such a case the question of the remaining lifetime of the oil pipeline is very urgent. In the below ground with the sectors, where the coating is broken, anode and cathode polar characteristics of steel essentially change, and as a result, the potentials are steady in these places. Taking into account that operating of an oil pipeline with sectors where broken coating is connected with electrochemical corrosion of the metal of a pipeline, when examining an oil pipeline, attention should be paid to determining of characteristics of corrosive process. Electric potential of the given galvanic couples is a universal indicator for calculating the expenses for metal damage in the cavity.

Coating, as capillary-porous material, is a conductor of 2-d type, that's why the process of steel corrosion in it is possible to consider from ordinary electrochemical corrosion of metals in the electrolytes. The authors [10–15] consider the electrical field near the heterogeneous electrode, model of which consists of 2 sectors of arbitrary width, which differ in steady potentials. Local corrosive element is in the sector of oil pipeline under the coating (cathode) and sector of the pipeline in the cavity under the electrolyte.

Electrical boundary of the electrical field potential is determined in this case on the basis of the two-dimensional solution of Laplace's equation.

$$\begin{aligned}\phi(x,y) &= \frac{a(E_a - E_K) + E_K}{c} + \sum_{K=1}^{\infty} \frac{2(E_a - E_K)}{\pi k\left(1 + \frac{\pi k}{c}L\right)} \sin\frac{\pi k}{c}a \cos\frac{\pi k}{c}xe^{-\frac{\pi k}{c}y} \\ &= \frac{a(E_a - E_K) + E_K}{c} + \frac{2(E_a - E_K)}{\pi} \sum_{K=1}^{\infty} \frac{\sin\frac{\pi k}{c}a}{\left(1 + \frac{\pi k}{c}L\right)k} \cos\frac{\pi k}{c}xe^{-\frac{\pi k}{c}y},\end{aligned} \tag{13}$$

where φ—potential; a—width of anode selector, м; E_a, $E_к$—currentless potentials of anode and cathode, мВ; c—width of cathode selector, м; x, y—flow coordinates; $k = 1, 2, 3$;L— coefficient that depends on electroproductivity of electrolyte and coefficient of polarization, L—coefficient depending on the specific electrical conductivity of the electrolyte and the polarization coefficient, $L = \gamma \cdot b$; γ—electric conductivity of electrolyte; b—polarization efficiency.

Taking into account Ohm's law in the differential form in the Eq. (1) expression for determining current density on the surface of one local element is found out.

$$i(x) = \frac{2(E_a - E_k)\gamma}{c} \sum_{k=1}^{\infty} \frac{\sin\frac{\pi ka}{c}\cos\frac{\pi kx}{c}}{k\left(1 + \frac{\pi kL}{c}\right)} \tag{14}$$

The proposed method of calculating the residual allowable wall thickness of the oil pipeline as a parameter that determines the life of the pipe and its safe operation is tested in assessing the condition of the section of the current state of pipeline under the conditions listed in Table 1.

Thus, the operating pressure on the investigated section of the oil pipeline should not exceed 8,17 MPa.The results of calculations of the residual life of the oil pipeline

Table 1 The results of the calculation of the residual resource

Parameter	Marking	Units of measurement	Value
Output data			
Outer diameter of the pipeline	$D_з$	mm	530
The wall thickness of the oil pipeline	δ	mm	9
The strength limit of the pipe material	σ	MPa	
Working pressure in the oil pipeline	p	MPa	5,04
The potential difference of electroplating	ΔE	мB	0,06
The service life of the oil pipeline	t_e	year	15
The area of the corroded section	a	cm^2	0,0024
Calculated values			
Permissible ring tension	σ	MPa	363
Corrosion current of electroplating	I	A/cm^2	$0{,}88 \times 10^{-4}$
The corrosion rate of electroplating	$i_в$	mm/hour	$3{,}17 \times 10^{-5}$
The corrosion rate of electroplating	$i_в$	mm/year	0,27
The estimated value of corrosion depth at the time of inspection	h	mm	4,05
The value of the allowable pressure at the defect at the time of inspection	*[p]*	MPa	8,17
The value of the allowable wall thickness	*[h]*	mm	5,37
Residual resource-1	T	year	20,94–15 = 5,94
Residual resource-2	T	year	19,88−15 = 4,88

according to the dependences proposed by the author coincide with the calculations according to existing methods with a relative error of 17%.

The novelty of the research is the development of a calculation method for determining the depth and allowable depth of corrosion of a steel oil pipeline during macro galvanic corrosion vapour under the influence of aggressive electrolytic solution, as well as a method for calculating the residual life of its environmentally safe operation, which will allow predicting the development of corrosion processes on the steel oil pipeline, to plan the necessary measures to prevent environmental pollution.

4 Conclusion

Based on mathematical model of electrochemical pipeline corrosion in the coating cavity correlation is found out and researched which enables counting the remaining lifetime of the oil pipeline of operating macrogalvanic corrosive couples in the conditions of aggressive liquid in the damaged coating. The developed correlation enables possibility of rational planning of the repairs, to predict the real terms of construction operation, to reconsider operating regime etc. The results enable valid assessment of the loadbearing capacity and the remaining lifetime of the constructions with the cavities in the coating that operate in the aggressive environment.

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

In order to reduce the likelihood of abnormal situations (with a corresponding increase in risks of their implementation) and reduce possible losses from their manifestation for potentially dangerous objects of the technosphere should be implemented a set of measures that take into account the nature of sources of danger and peculiarities of their manifestation, permissible modes of operation for each phase of risk increase, the possibility of using means of reflecting threats based on the results of comprehensive diagnostics and monitoring of the object.

To solve the problem of ensuring the safe operation of main oil pipelines, it is advisable first of all to use a set of modern methods and means of monitoring the parameters of these facilities and the environment in the considered conditions with the widest possible range of changes (including outside regular modes), application of monitoring systems and analysis of environmental data and possible external influences on the studied system, use of data banks with sources of danger and scenarios of emergency situations, criteria for their evaluation and methods of preventive action to reflect emergencies according to the programmed teams of the risk monitoring system.

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