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UDC 004.05

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EVALUATION OF THE RESIDUAL LIFE OF A PIPELINE UNDER CONDITIONS OF EROSION-CORROSION WEAR

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Анотація. *Стаття присвячена вирішенню проблеми визначення залишкового ресурсу трубопроводів. Основним негативним чинником, що досліджується та впливає на ресурс експлуатації, обрано ерозійні-корозійні пошкодження. Зокрема, ерозійно-корозійне пошкодження типу виразкової «піттингової корозії», що є одним із найбільш серйозних та поширених видів корозії. Це явище може призвести до суттєвого зниження ресурсу експлуатації технічних об'єктів та підвищення витрат на їх обслуговування, ремонт та заміну. За визначальний параметр обрано залишкову товщину стінки труби. Для виконання оцінки об’єктивного технічного стану та прогнозування залишкового ресурсу вказаних конструкцій, за відсутності значної статистики відмов, використовується ймовірнісно-фізичний підхід. В основі підходу щодо оцінки довговічності конструкцій лежить імовірнісна модель із застосуванням DM-розподілу відмов. Цей розподіл спеціально формалізований на основі марковського випадкового процесу дифузійного типу з постійною швидкістю. DM-розподіл найбільш точно вирівнює статистичні дані про відмови механічних об’єктів, якими є трубопроводи різного призначення. Дуже цінно, що параметри моделі, яка використовується, мають у своїй основі фізичну інтерпретацію, що дозволяє оцінювати параметри моделі в умовах відсутності статистики відмов. В основі аналізу лежать два ключові параметри: середня швидкість зміни визначального параметра – критерію працездатності та коефіцієнт варіації узагальненого процесу деградації. У роботі наведено приклад, у якому встановлено ймовірнісно-фізичним методом залишковий ресурс ділянки трубопроводу. Отримані при розрахунках результати порівнюються з результатами, які отримано іншим традиційним методом. Уточнення оцінки залишкового ресурсу ділянки трубопроводу дозволить оптимізувати експлуатаційні витрати за рахунок зменшення міжремонтних інтервалів.*

Ключові слова: *залишковий ресурс, модель надійності, трубопроводи.*

Abstract. *The article is devoted to solving the problem of determining the residual resource of pipelines. Erosion and corrosion damage was selected as the main negative factor that is being investigated and affects the service life. In particular, it is the erosion-corrosion damage of the “pitting corrosion” type which is one of the most serious and widespread types of corrosion that can cause a significant shortening of the service life of technical objects and an increase in the cost of their maintenance, repair, and replacement. The residual thickness of the pipeline wall was chosen as the defining parameter. In case there are no significant failure statistics, a probabilistic-physical approach is used to assess the objective technical condition and predict the residual resource of the specified structures. The approach to durability assessment is based on a probabilistic model and uses the DM failure distribution that is specially formalized on the basis of a Markov random process of the diffusion type with a constant rate. The DM distribution most accurately aligns statistical data on failures of mechanical objects, which are pipelines for various purposes. It is very valuable that the parameters of the used model are based on a physical interpretation, which allows for estimating the parameters of the model when there are no failure statistics. The analysis is based on two key parameters: the average rate of change of the defining parameter change (the performance criterion) and the coefficient of variation of the generalized degradation process. The paper provides an example in which the residual resource of a pipeline section is determined with the help of the probabilistic-physical method. The results obtained during the calculations are compared with* *the results obtained by another traditional method. Refining the assessment of the residual resource of the pipeline section will allow for optimizing the operating costs by reducing the intervals between repairs.*

Keywords: *residual resource, reliability model, pipelines.*

DOI: 10.34121/1028-9763-2023-2-88-93

1. Introduction

When assessing the residual life of pipelines with erosion-corrosion wear (ECW), various methods are used and each of which has its advantages and disadvantages. Some methods are oversimplified, others are intended mainly for assessing the service life of pipelines damaged by relatively uniform corrosion, and others are extremely difficult for practical use. For the widespread implementation, there is required a fairly simple, reliable and effective method for determining the resource of pipelines, which takes into account the most common and dangerous damages like superficial ulcerative defects. It can be developed on the basis of a calculation method for determining the residual strength of pipelines with local surface defects [1, 2].

The existing methods for studying the reliability of structures subject to ECW are often deterministic, that is, they do not take into account the random nature of the degradation process, or are based on strictly probabilistic failure models. As a result, there is a small correlation with the results and real estimates of the residual life of structures. Such methods can only be used as approximate calculations since they do not take into account the random nature and variability of random degradation processes occurring in an object, which determines their low reliability in predicting the residual resource. In our opinion, the problem of estimating the residual life of pipelines during their long-term operation seems to be relevant within the framework of a probabilistic-physical approach to estimating the durability of pipelines using a probabilistic model (diffusion monotonic DM distribution of failures), the parameters of which have a physical interpretation in the form of an average rate of change of the determining parameter (the validity criterion) and the coefficient of variation of the generalized degradation process. The model assumes that the ongoing degradation processes are stochastic, irreversible, and have monotonic realizations and a constant rate.

The aim of the article is to develop a method for assessing the residual resource of a pipeline section based on the results of studying the change over time of the defining (resource) parameter and establishing a relationship with the limit value.

2. Physics of failures in ECW conditions

The simplest scheme of corrosion damage (ulcers, cavities) is shown in Fig. 1 [2], where A is the cross-sectional area of the corrosion damage, L is the length of the corrosion area, d is the depth of corrosion, and t is the wall thickness.

Thus, the calculation of the residual life of a pipe with a surface defect (ulcers, cavities) is based on two parameters of the defect and the mechanical characteristic of the material – the minimum yield strength. Based on these parameters, the critical combination of the length and depth of the defect, which can lead to failure, is calculated. A similar method is used to determine the residual life of the pipeline [4]. In this case, the product of the depth and length of the corrosion defect is taken as the criterion for the limiting state of the pipe (the boundary curve in Fig. 2).

To determine the resource, it is necessary to predict the behavior of a controlled defect in time at a certain average speed, that is, it is necessary to predict the development of a defect both in depth and in length (according to the plan). The average corrosion rate should be understood as the average value at a point (pit) obtained in the case of performing several measurements.

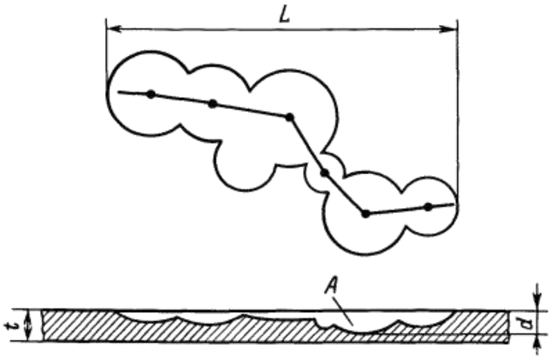

Figure 1 – Corrosion damage scheme used in strength analysis

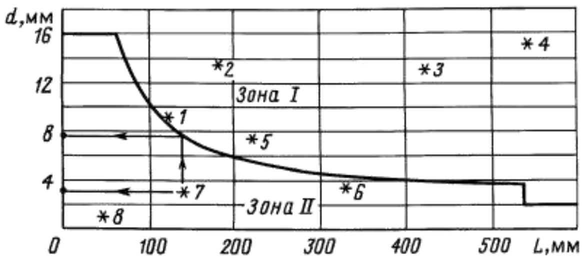

Figure 2 – Classification of defects of the “pitting corrosion” type and sections of a pipeline affected by pitting corrosion (Zone 1 – repair needed, zone 2 – no repair needed, 1–8 – the numbers of ulcerative defects)

Note 1. The practice of corrosion research [3] shows that the development of a corrosion defect in width after formation and reaching certain dimensions is often significantly slowed down (or it stops altogether) and is not as significant as development in depth.

It is not known exactly how fast the defect will develop in depth since it depends on many factors, but for a rough estimate of the resource, one can proceed from the constancy of the average corrosion rate that contributed to the formation of a fixed ulcer [4, 5].

Knowing the depth of the ulcer, the process duration, and the maximum allowable thickness of the metal “eaten” by corrosion until the critical depth of the pit is reached, you can find the residual resource T_R (year) [2] using the formula

$$T_R = \frac{t_A}{\rho_A}, \tag{1}$$

where t_A is the permissible wall thickness for removal and ρ_A is the average corrosion rate.

Example. For an ulcerative defect N 7 (Fig. 2) with the depth of 3 mm, the nominal pipe wall thickness of 20 mm, the critical depth of the defect of 7,5 mm, and the average corrosion rate at the time of detection of the ulcer of 1 mm/year, the estimated residual resource is

$$T_R = \frac{7,5-3}{1} = 4,5 year.$$

The corrosion rate in the pit can change over time, so to control it, it is advisable to make additional measurements during the operation and correct it within the assigned resource. Such a deterministic approach in determining the residual life of a product with surface pits (caverns) is the simplest, but has a number of disadvantages described above. An alternative to this method is the prediction of the state of an object in time using physical parameters and random functions – a probabilistic-physical method.

3. Probabilistic-physical method of calculation

The authors propose to apply the method of predicting the residual life of products [4–7], which is based on a probabilistic calculation of the change in the determining parameter of the degradation process using the DM distribution of a random variable.

Let’s think it is possible to periodically measure the resource defining parameter $\varphi(t)$. It is assumed that the limiting value of the defining parameter is known or specified $\varphi(t) = \Pi_{\lim}$.

During the operation, measurements of the determining parameter are carried out after a certain period of time Δt.

As a result of the measurements, a series of non-decreasing values of the resource parameter $\varphi(t)$ is obtained for certain moments of operating time:

$$\varphi(t_1),$$

$$\varphi(t_2) = \varphi(t_1 + \Delta t),$$

$$\varphi(t_n) = \varphi(t_{n-1} + \Delta t),$$

$$\varphi(t_{n+1}) = \varphi(t_n + \Delta t).$$

Note 2. The following discussion assumes the growth of the values of the determining parameter during the operation time.

In the general case, according to the measurement data, the average rate of change of the determining parameter is calculated by one of the known methods, for example, by the formula

$$a = \frac{1}{\Delta t \cdot n} \cdot \sum_{i=1}^{n} \left[\varphi(t_{i+1}) - \varphi(t_i) \right] = \frac{1}{\Delta t \cdot n} \cdot \sum_{i=1}^{n} \Delta\varphi_i . \qquad (2)$$

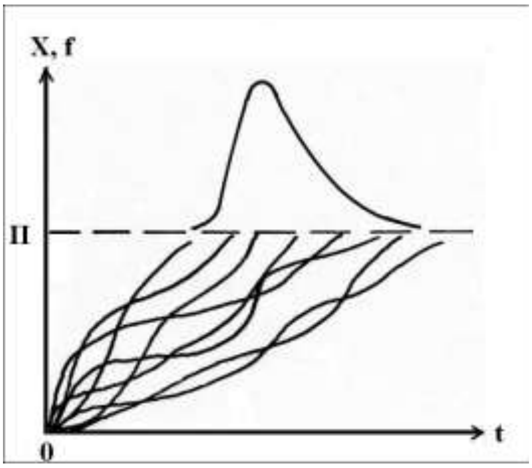

Figure 3 – Model of a random process of degradation (Markov monotonous process) and the scheme of time-to-failure distribution (DM distribution)

Note 3. Roughly, the rate of the determining parameter change can also be defined from two measurement points: from the beginning of the operation $t_0 = 0$ and the moment of the first measurement of the determining parameter t_1, where $\Delta t_0 = t_1 - t_0$, $\Delta\phi_1 = \phi(t_1) - \phi(t_0)$ and $n = 1$.

As a theoretical reliability model, we accept the distribution of time to failure since the destruction of this type of product is irreversible, and the degradation processes are monotonous (Fig. 3).

The parametric form of the distribution entry is as follows:

$$F(t) = DM(t; a; v) = \Phi\left(\frac{at + \Pi_1 - \Pi_0}{v\sqrt{at\left(\Pi_0 - \Pi_1\right)}} \right), \quad (3)$$

where a is the average rate of the determining parameter change (increase in the depth of corrosion and thinning of the pipe wall), Π_0 is the initial measured value of the determining parameter (the corrosion depth), Π_1 is the maximum measured value of the determining parameter, and v is the coefficient of variation of the corrosion depth growth process.

As a determining parameter, we take, for example, the depth of corrosion. The value of the coefficient of variation of the change in the determining parameter can be chosen taking into account the recommendations [5] (Table 1).

Table 1 – Values of coefficients of variation for various types of degradation processes

Type of degradation process	Coefficient variation of factor degradation
Corrosive wear:	
– with a small unevenness of destruction	0,1 – 0,20
– with a significant unevenness of destruction	0,3 – 0,6

If the defining parameter of the product changes monotonously at a constant average speed, then based on the accepted reliability model, the average residual life is calculated by the formula

$$\tilde{\pi} = \frac{(\Pi_{\lim} - \Pi_1)}{a}\left(1 + \frac{\nu^2}{2}\right), \qquad (4)$$

where $\Pi_{\lim}$ is the limit value of the determining parameter (the validity criterion.) Average residual life $\tilde{\pi}$ (4) is a mathematical expectation of the residual resource (operating time) after time τ (the moment of monitoring the technical condition of the object).

Gamma percent residual life is calculated by the formula

$$\tilde{\pi}_\gamma = \frac{(\Pi_{\lim} - \Pi_1)}{a}\left(1 + \nu^2 U_\gamma^2 / 2 - \nu U_\gamma \sqrt{1 + \frac{\nu^2 U_\gamma^2}{4}}\right), \qquad (5)$$

where U_γ is the quantile of the normalized level distribution γ.

Gamma percent residual life $\tilde{\pi}_\gamma$ (5) is the operating time, starting from a certain point in time τ (the moment of monitoring the technical condition of the object) during which the object that has worked without failure has the value of the conditional probability of failure-free operation equal to γ. The expression in square brackets of formula (5) is the quantile of the DM distribution of level γ.

Let's consider the previous example of a pipeline in ECW and calculate the average residual life of the pipeline using the formula (4) where ν =0,5.

$$\tilde{\pi} = \frac{(\Pi_{\lim} - \Pi_1)}{a}\left(1 + \frac{\nu^2}{2}\right) = \frac{(7{,}5 - 3)}{1}\left(1 + \frac{0{,}5^2}{2}\right) = 4{,}5(1+1{,}125) = 9{,}6 \text{ year.}$$

4. Conclusions

The developed method for calculating the remaining service life of pipelines with surface ulcer-type corrosion defects allows for a significant refinement of the residual service life estimate, resulting in substantial economic benefits through the optimization of preventive and capital maintenance cycles.

The method can be further developed by expanding the scope of factors considered, specifically by accounting for wall thickness variations in specific pipeline segments, which can affect the overall residual service life of the pipeline.

One of the limitations of the method is the lack of accounting for external factors such as pressure, temperature, and environment, which can intensify or weaken the impact of corrosion.

Overall, the use of a probabilistic-physical method enables a more accurate assessment of the remaining service life of a pipeline and facilitates the planning of necessary maintenance and replacement measures.

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Стаття надійшла до редакції 05.04.2023