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FORECASTING NPP PIPELINES RESIDUAL LIFE BASED ON EROSION-CORROSION WEAR RATE MEASUREMENT

Abstract. *The article is devoted to solving issues related to the assessment and forecasting NPP pipelines residual life, taking into account the rate of erosion-corrosion wear. (ECW). The article investigates the theoretical issues that arise when carrying out probabilistic calculations when forecasting the residual life of pipelines of the supply network. The authors proposed the use of a probabilistic-physical approach to assess the real technical condition and forecast the residual life, in the absence of failures. As a probabilistic model, we use DM-distribution (diffusion monotonic) distribution. Its parameters have a physical interpretation – average rate of determining parameter change (validity criterion) and the variation coefficient of the generalized degradation process. The residual thickness of the pipeline wall is taken as the determining parameter, and it is assumed that when determining such a section of the pipeline, it is possible to measure it.*
Key words: probabilistic-physical approach, residual life, probabilistic-physical model of reliability.

Formulation of the problem. In view of recent events of recent events of our time, the nuclear industry is one of the priority areas for the development of the energy industry. And the reliability issues that are being addressed in this area certainly determine the future and must meet high standards of both safety and resource consumption. Since pipelines are one of the fundamental elements of nuclear power plants, the issues of assessing their residual life are certainly relevant.

Existing methods for studying the reliability of such structures under erosion-corrosion wear (ECW) are often deterministic (not taking into account the random nature of phenomena) or based on strictly probabilistic failure models, which leads to a low correlation of results with the object failures physics [1; 2]. Also, quite often, the calculations are approximate, since they are made without taking into account the variation coefficients of random degradation processes. This greatly affects the accuracy of forecasting the residual resource based on them.

Analysis of recent research and publications. The method of a priori calculation of reliability indicators is the most frequently mentioned in the literature [3,4] and used in determining the residual life. This method, in contrast to the experimental ones, makes it possible to take into account the entire spectrum of influences in the models. However, the existing calculation methods ignore the random nature of strength. Namely, these deviations occur during the production process, material defects and non-stationarity of loading processes.

Isolation of previously unsolved parts of the general problem. Thus, the problem of assessing the residual life of NPP feed water pipelines during their long-term operation under real conditions seems to be an urgent task. Within the framework of a probabilistic-physical approach to assessing the durability of pipelines under ECW conditions used a probabilistic model (diffusion monotonic *DM*-distribution). The parameters of this model have a physical interpretation, average rate of change of the determining parameter (validity criterion) and the variation coefficient of the generalized degradation process. The model also assumes that the ongoing degradation processes are irreversible and monotonous.

Purpose of the article. The purpose of the article is to apply a probabilistic-physical method for estimating the residual life of NPP feed water pipelines using the DM-distribution of time to failure.

Presentation of the main material. It is necessary to calculate the residual life of a straight pipeline section after 23 years of operation using two methods. 60 similar pipeline sections were subjected to the study. All pipelines were operated for the same time and under equal conditions [3]. The measurements were carried out for pipes with a diameter $D = 530$ mm with wall thickness $S_{nom} = 28$ mm. For a period of operation of 23 years, the measured wall thickness of the studied area was $S_1 = 24$ mm at the minimum allowable standard value $S_a = 19{,}5$ мм.

1. Calculation and experimental deterministic method with and without technological tolerances for the thickness of pipelines

The equation takes into account technological tolerances for the thickness of pipelines during their manufacture. As well as the presence of corrosion products deposits, the thickness of which is compared with the thickness of the intact metal. The equation for calculating the pipeline wear rate is as follows [3]:

$$W_{ECW} = (S_{nom} \cdot K_{11} \cdot K_{12} \cdot S_{\min} \cdot K_2) / \Delta\tau_0), \quad (1)$$

where W_{ECW} – pipeline emission-corrosion wear rate;

$\Delta\tau_0$ – time interval from the date of object commissioning to the date of control (years);

S_{nom} – initial wall thickness;

$S_{\min}$ – minimum allowable wall thickness;

K_{11} – coefficient, tolerance for wall thickness in the manufacture of the pipeline;

K_{12} – coefficient, the contribution of deposits of corrosion products to the initial design wall thickness;

K_2 – coefficient taking into account the contribution of deposits of corrosion products to the value of the minimum wall thickness.

Note 1. For the example below [3] and pipelines with an outer diameter of more than 108 mm, the coefficient K_{11} can be taken equal to 1,075. For pipelines with an outer diameter of up to 108 mm, it can be taken equal to 1,025. As the minimum value of the coefficient K_{12} can be taken equal to 1,05, and the value of the coefficient K_{21} – 0,95.

Substituting the values of the coefficients K_{11}, K_{12}, K_{21}, the equation for calculating the wear rate will be written as:

$$W_{ECW} = [(S_{nom} \cdot 1{,}075 \cdot 1{,}05 - S_{\min} \cdot 0{,}95)] / \Delta\tau_0. \quad (2)$$

The remaining service life of the pipeline until the minimum allowable thickness is reached, taking into account dependence (2), is calculated by the equation

$$\Delta\tau = \left(S_{nom} \cdot K_{21} - S_a\right) / \left(W_{ESW} \cdot K_{saf}\right), \quad (3)$$

where $\Delta\tau$ – residual life of the pipeline;

K_{saf} – safety factor;

K_{21} – coefficient taking into account the contribution of deposits of corrosion products to the durability of the pipeline.

Estimates of the ECW indicators of straight feed water pipelines sections, according to the algorithm given in [3], are given in Table 1, where $\Delta\tau_1$ – residual service life without taking into account technological tolerances for the thickness of pipelines; $\Delta\tau_2$ – residual service life, taking into account technological tolerances for the thickness of pipelines.

The total resource (R) of the investigated section of the pipeline, taking into account the time of preliminary operation, is:

$$R_1 = \Delta\tau_0 + \Delta\tau_1 = 23 + 27{,}2 = 50{,}2 \text{ year};$$

$$R_{21} = \Delta\tau_0 + \Delta\tau_2 = 23 + 10{,}8 = 33{,}8 \text{ year}.$$

2. Probabilistic-physical method for calculating the average resource without taking into account technological tolerances for the thickness of pipelines

The procedure for predicting the residual life of products is considered for the case when there are no failures (critical failures). And in the process of operation, the values of the resource (determining) parameter П can be measured. Achieving the parameter $\Pi_{\lim}$ of its limit value leads to the limit state or failure of the product.

Table 1

Item type	S_{nom}	S_1	S_a	W_{ECW1}	$\Delta\tau_1$	W_{ECW2}	$\Delta\tau_2$
Sraight section	28	24	19.5	0,169	27,2	0,416	10,8

Suppose there is an opportunity to periodically measure the resource defining parameter $\phi(t)$. It is assumed that the limiting value of the defining parameter is known or specified $\phi(t) = \Pi_{\lim}$.

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

Note 2. The time period Δt is taken equal to the value providing uncorrelated gains, the increment correlation interval $\Delta\phi(\Delta t)$ is determined in advance during testing or operation.

As a result of measurements, a number of non-decreasing values of the resource parameter $\phi(t)$ are obtained for certain moments of operating time (which grow):

$$\phi(t_1);$$
$$\phi(t_1) = \phi(t_1 + \Delta t);$$
$$\phi(t_n) = \phi(t_{n-1} + \Delta t);$$
$$\phi(t_{n+1}) = \phi(t_n + \Delta t).$$

Note 3. To ensure sufficient accuracy in estimating the rate of change of the determining parameter, it is desirable to have at least ten increments (measurements) n(values). Further reasoning assumes that the values of the determining parameter increase with time.

In the general case, according to the measurement data, the average determining parameter rate changeis calculated by the formula:

$$a = \frac{1}{\Delta t \cdot n} \cdot \sum_{i=1}^{n} \left[\phi(t_{i+1}) - \phi(t_i)\right] = \frac{1}{\Delta t \cdot n} \cdot \sum_{i=1}^{n} \Delta\phi_i\,. \quad (4)$$

Approximately the rate of change of the determining parameter can also be determined by two measurement points – from the beginning of operation $t_0 = 0$ and the moment of the first measurement of the determining parameter t_1, wherein $\Delta t_0 = t_1 - t_0$, $\Delta\phi_1 = \phi(t_1) - \phi(t_0)$ and $n = 1$.

As a theoretical model of reliability, we accept the DM-distribution of time to failure [2], since the destruction of this type of product is irreversible.

The parametric form of the *DM*-distribution entry is as follows:

$$F(t) = DM(t; a; \nu) = \Phi\left(\frac{at + \Pi_1 - \Pi_0}{\nu\sqrt{at\left(\Pi_0 - \Pi_1\right)}}\right), \quad (5)$$

where a – the average rate of change of the determining parameter (increase in the depth of corrosion, thinning of the pipe wall);

Π_0 – initial measured value of the determining parameter (corrosion depth);

Π_1 – the maximum measured value of the determining parameter;

ν – coefficient of variation of the corrosion depth growth process.

The variation coefficient value of the change in the determining parameter can be chosen taking into account the recommendations [1] Table 2.

Table 2. Values of coefficients of variation for various types of corrosion processes

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

If the defining parameter of the product changes monotonously and irreversible changes are observed, that is, all $\Delta\phi(t_i)$ have a plus sign, then the average residual life is calculated by the formula:

$$\tilde{\pi} = \frac{(\Pi_{\lim} - \Pi_1)}{a}\left(1 + \frac{\nu^2}{2}\right), \quad (6)$$

where $\Pi_{\lim}$ – limit value of the determining parameter (validity criterion.) Gamma percentage residual resource is calculated by the formula:

$$\tilde{\pi}_\gamma = \frac{(\Pi_{\lim} - \Pi_1)}{a}\left(1 + \nu^2 U_\gamma^2 / 2 - \nu U_\gamma \sqrt{1 + \frac{\nu^2 U_\gamma^2}{4}}\right), \quad (7)$$

where U_γ – quantile of the normalized normal distribution of the level γ.

As mentioned above, for the considered example, the corrosion depth is taken as the determining parameter.

We calculate the average corrosion depth growth rate depth from the results of one measurement

$$a_{ECW} = \frac{1}{\Delta t_0 \cdot n} \cdot \sum_{i=1}^{n} \Delta\phi_1\,,$$

where $\Delta t_0 = t_1 = 23$ year;

$\phi(t_0) = 0$ mm;

$\phi(t_1) = S_{ном} - S_1 = 28-24 = 4$ mm;

$n = 1$;

$\nu = 0{,}25;$

$\Delta\phi(t_1) = \phi(t_1) + \phi(t_0) = 4 - 0 = 4$ mm,

$$a_{ECW} = \frac{\Delta\phi_1}{\Delta t_0 n} = \frac{4}{23\cdot 1} = 0{,}173 \text{ mm/year};$$

We calculate the value of the residual resource of the pipeline section:

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

$$= \frac{8{,}5 - 4}{0{,}173}\cdot\left(1 + \frac{0{,}25^2}{2}\right) = 23{,}7 \text{ year},$$

where $\Pi_{\lim} = S_{nom} - S_a = 28 - 19{,}5 = 8{,}5$ mm;

$\Pi_1 = S_{nom} - S_1 = 28 - 24 = 4$ mm.

Full resource of the pipeline section, taking into account the time of preliminary operation

$$R_3 = \Delta t + \tilde{\pi} = 23 + 23{,}7 = 49{,}7 \text{ year}$$

Conclusions.

Calculation-experimental method

$\Delta\tau_1$ – residual service life without taking into account technological tolerances for the thickness of pipelines; $\Delta\tau_1 = 27{,}2$ year;

$\Delta\tau_2$ – residual service life, taking into account technological tolerances for the thickness of pipelines; $\Delta\tau_2 = 10{,}8$ year;

Probabilistic-physical method

$\tilde{\pi}$ – residual service life without taking into account technological tolerances for the thickness of pipelines; $\tilde{\pi} = 23{,}7$ year.

The excess of $\Delta\tau$ $\Delta\tau_2$ has a natural justification and does not require additional explanations. The remaining resource $\tilde{\pi}$ is less than $\Delta\tau_1$ due to the random probabilistic nature of the degradation process with the coefficient of variation 0,25. Pessimistic assessment $\tilde{\pi}$ indicator for nuclear power plants is more preferable in terms of the overall safety of the facility.

As a development of the probabilistic-physical method, one should consider a rather complicated problem statement – the study corrosion products mosaic deposits effect (thickening of the pipe walls in a number of places) on the value of the residual life of the pipeline as a whole.

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ПРОГНОЗУВАННЯ ЗАЛИШКОВОГО РЕСУРСУ ТРУБОПРОВОДІВ АЕС НА ОСНОВІ ВИМІРЮВАННЯ ЕРОЗІЙНО-КОРОЗІЙНОГО ЗНОШУВАННЯ

Анотація. *Стаття присвячена вирішенню питань, пов'язаних із проведенням оцінки та прогнозуванням залишкового ресурсу трубопроводів АЕС з урахуванням швидкості ерозійно-корозійного зношування (ЕКЗ). У статті досліджено теоретичні питання, що виникають під час проведення ймовірнісних розрахунків при прогнозуванні залишкового ресурсу трубопроводів живильної мережі. В роботі приймається допущення, що прогнозування залишкового* *ресурсу базується на визначенні розрахунковим шляхом його мінімальної оцінки. Проводиться порівняння мінімальної оцінки з встановленим допустимим рівнем зносу трубопроводів живлення. В роботі приймається допущення, що прогнозування залишкового ресурсу базується на визначенні розрахунковим шляхом його мінімальної оцінки. Авторами заборонено для виконання оцінки об'єктивного технічного стану та виконання прогнозування залишкового ресурсу вказаних конструкцій, за відсутності значної статистики відмов використовується ймовірнісно-фізичний підхід. В рамках цього підходу, що до оцінки довговічності, лежить ймовірнісна модель, що застосовує DM-розподіл відмов. Параметри моделі, що використовується мають в своїй основі фізичну інтерпретацію. Основними параметрами, які враховуються є середня швидкість зміни визначального параметра та коефіцієнт варіації узагальненого процесу деградації. Як визначальний параметр прийнята залишкова товщина стінки трубопроводу і передбачається, що при визначенні такої ділянки трубопроводу є можливість її вимірювання. У статті приведені критерії оцінки залишкового ресурсу досліджуваних зразків сталевих трубопроводів, використання яких дозволить знизити експлуатаційні витрати за рахунок збільшення міжремонтних інтервалів. Наведено порівняння двох прикладів розрахунків розрахунково-експериментальним та ймовірнісно-фізичним методами, встановлено залишковий та загальний ресурс служби.*

Ключові слова: ймовірнісно-фізичний підхід, залишковий ресурс трубопроводу, ймовірнісно-фізична модель надійності.

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