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ASSESSMENT OF POWER EQUIPMENT OPERATIONAL SAFETY IN THE SUSTAINABLE MANAGEMENT OF RESIDUAL LIFESPAN

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Introduction. Ensuring the safe operation of energy facilities is a critical issue at all life cycle stages. It is associated with the adoption of management decisions when rescheduling and assessing the remaining resources, which are made based on a comprehensive assessment of the technical condition of the equipment, taking into account the economic efficiency and environmental requirements for further operation, which is the basis for technical and economic assessments.

Aim and tasks. This study aims to develop a technical and economic assessment of the safe operation of power equipment to ensure sustainable management of the remaining service lifespan.

Results. An algorithm for assessing pipeline system elements by the coolant environment is proposed, which allows for the pipeline load and changes in erosion and corrosion caused by coolant movement. It was proposed that the equipment be systematised by safety class and coolant. When conducting a technical and economic assessment, these parameters and the costs of extending the service life and upgrading the existing equipment were considered in the standard calculations of a certain type of equipment. For this purpose, mathematical models for calculating the residual life for each type, obtained and confirmed based on empirical studies, are proposed. Research findings into ensuring the reliability and safety of operation with various heat carriers have shown that it is necessary to consider low-cycle and high-cycle loads and erosion processes. It was found that the erosive wear rate is 0.3-0.4 mm/year for bending sections of the main circulation pipeline, where maximum loads occur relative to low-cycle and vibration loads, and the stress is 212.5 MPa when assessing the residual life of 7 years.

Conclusions. The cost-effectiveness of reassigning the service life is reasonable, as it does not require additional investment in upgrading or replacing equipment subject to annual technical diagnostics. The systematisation of pipelines, improved codifiers, lifespan assessment models, and algorithms for evaluating the remaining life under various loadings enhance the regulatory framework for safe nuclear power plant operations and support technical and economic evaluations for extending their lifespan.

Keywords: techno-economic assessment, nuclear energy, residual lifespan, safety, pipeline systems.

1. Introduction.

The current environmental situation determines the need to reduce greenhouse gas emissions in the electricity generation sector, leading to renewed interest in the nuclear power industry. Currently, there are two areas of sustainable development in the energy sector: construction of new power units and support for the sustainable operation of existing nuclear power plants. The sustainable development of the nuclear economy in terms of ensuring safe operation is supported by most generating companies, which plan to operate their existing nuclear power plants for as long as possible (Haas et al., 2019; Thomas, 2005).

At the same time, generating companies refrain from building new nuclear power plants due to significant costs and lack of guarantees and support from the state, such as the sales market and subsidies.

When extending the service lifespan of nuclear power units or justifying the remaining service life, safety, sustainable operation, and technical and economic indicators must be considered (Khamis & El-Emam, 2016). While the design of new power units is based on developing a feasibility study for the construction project, a different approach is required at the equipment operation stage, especially when making management decisions on the remaining life or lifetime extension. The economics of existing plants and future forecasts of sustainable operations require a comprehensive analysis that considers safety, operational efficiency, and current costs.

To achieve the goals of comprehensive analysis, it is necessary to use scientific and technical resources to the maximum extent possible to implement certain measures to implement a sustainable operation strategy in the context of extending/assessing the residual lifetime of operating power units, as determined by the IAEA guidelines (International Atomic Energy Agency, 2013). Measures within the energy strategy for sustainable development should meet the requirements for the safety improvement of nuclear power units and, at the same time, have an economic justification for their feasibility, taking into account the current technical conditions of power equipment (Danish, & Gábor, 2022).

2. Literature review.

The conducted studies offer different ways to justify both technical and economic efficiency of decision-making on the extension of NPP unit's operation, taking into account changes that occurred during their service life (Hrinchenko et al., 2023). In terms of technical effectiveness, research is being conducted in several directions and is based on approaches that allow taking into account factors that are crucial for safety, i.e., an assessment is made by dominant indicators that may have consequences for both performance and the environment.

One of the areas of ensuring safety is the comprehensiveness of research to assess the technical condition of energy infrastructure, which is aimed at forming a regulatory framework for assessing the ageing of various types of equipment and developing strategic management decisions to control these processes (Hrinchenko et al., 2024). Thus, scientific studies propose methods of comprehensive research that take into account the relative assessment of the condition of power equipment, i.e., the factors that have the most significant degradation impact are selected.

According to the recommendations (International Atomic Energy Agency, 2013), the periodic safety review is performed individually for a specific NPP unit and includes structural elements, structures, facilities and equipment that make up the unit, and the assessment considers all aspects and criteria related to safety. The analysis of the state of a power unit as a production complex (system) covers the following issues: technical condition of systems and elements; safety analysis; management; emergency preparedness and planning; and environmental impact.

Approaches to assessing the risks affecting the safety of pressurised water reactor equipment during the 360-day depletion cycle are proposed by Liu et al. (2024) and Shengzhe et al. (2019), which propose to study corrosion and erosion processes and analysis of this factor for different types of reactor equipment materials to establish a correlation between the metal composition and its effect on the wall thickness and, as a result, the risk of power deviation.

An equally important requirement is that the assessment of existing and new nuclear power plants should fully take into account long-term operation (LTO) conditions to mitigate the consequences of complex accidents involving multiple safety failures (Courtin et al., 2024; Havet et al., 2023; Harwood et al., 2017).

It proposes to standardise the sequence of identification of adverse events and quantify their risk by the indicator of representativeness to improve existing IAEA recommendations and develop its own national regulatory rules and requirements. The risk analysis uses probabilistic safety assessment (PSA) models, which include a four-step identification process to assess risks not considered in the design analysis (Havet et al., 2023), identify factors that influence the frequency of core damage, and identify events that compromise the integrity of the reactor core and containment (Harwood et al., 2017).

Risk management uses large-scale modelling and the approach of organising the emergency response to nuclear accidents at NPPs as their internal and external sources for timely and effective response (Sashi et al., 2020; Kasapoglu et al., 2024). Risk mitigation in this area is proposed by building an organisational network model based on four nodes assessed for vulnerability while linking technical and social risks (Chen et al., 2024).

The assessment of the economic efficiency of nuclear power plant operation is also often used in a risk-based manner, namely probabilistic risk assessment using error tree models, degradation models, reliability data and economic information (Miller et al., 2021; Badía et al., 2020; Verlinden et al., 2012).

The results of the technical and economic analysis of the conversion under four different modernisation scenarios for a steam turbine unit with a small reactor are presented by Łukowicz et al. (2024). It is proved that although all four retrofit options are technically feasible and may have an economic advantage over the complete replacement of individual equipment, it is economically feasible, from the point of view of safety and further operation, namely significant cost savings, to install new equipment compared to the construction of a new power unit and all other retrofit options (Ochmann et al., 2024).

Gehman et al. (2016) and Carrara (2020) examine changes in the economic and political sectors in the development of nuclear energy in OECD countries and the impact of such development on other countries, as it was in the last century, as a valuable option for decarbonising electricity production.

The economic feasibility of combining new technologies in traditional electricity production, such as new generation reactors, the construction of new nuclear power plants, and the use of small power units, is considered by Khamis and El-Emam (2016) and Shafiqul and Bhuiyan (2020). However, it is noted that it is economically feasible to use combined options, namely maintaining the existing energy system properly and gradually integrating additional sources into the energy sector.

The main goal of the feasibility study and energy policy development is to develop and implement an energy sector strategy aimed at transforming national energy systems into highly efficient ones, which is especially important for making informed decisions when nuclear power plants approach the end of their service life (Tola & Pettinau, 2014; Park et al., 2024). These decisions should be made taking into account the dynamics of changes and, on this basis, selecting the most appropriate energy scenario that will meet environmental, economic, and social sustainability (Martín-Gamboa et al., 2019; Danish & Gábor, 2022; Usman & Radulescu, 2022).

3. Methodology.

The study’s methodological approach is based on ensuring the national energy balance of Ukraine by expanding capacities and extending the service life of existing energy systems, which is especially important in the context of energy shortages in Ukraine, where nuclear energy plays a primary role. Regarding the extension of operational lifespans, Ukraine is guided by global experience, which shows that it is possible to extend the service life of NPP units beyond their design term, and, provided that nuclear and radiation safety standards are met, this may be one of the most effective ways to partially address the issue of replacing generating capacities.

It is necessary to develop a comprehensive program to study the current state of the equipment. The main goal of this program is to economically justify the safe operation of existing power units beyond their design life, in compliance with nuclear and radiation safety requirements, and consider IAEA recommendations and international experience.

The Comprehensive Programme consists of four blocks of cost-effective measures with the scope, order, and timing of implementation, as well as funding sources defined for each measure, which is performed using all available national scientific, technical, and production resources (Figure 1).

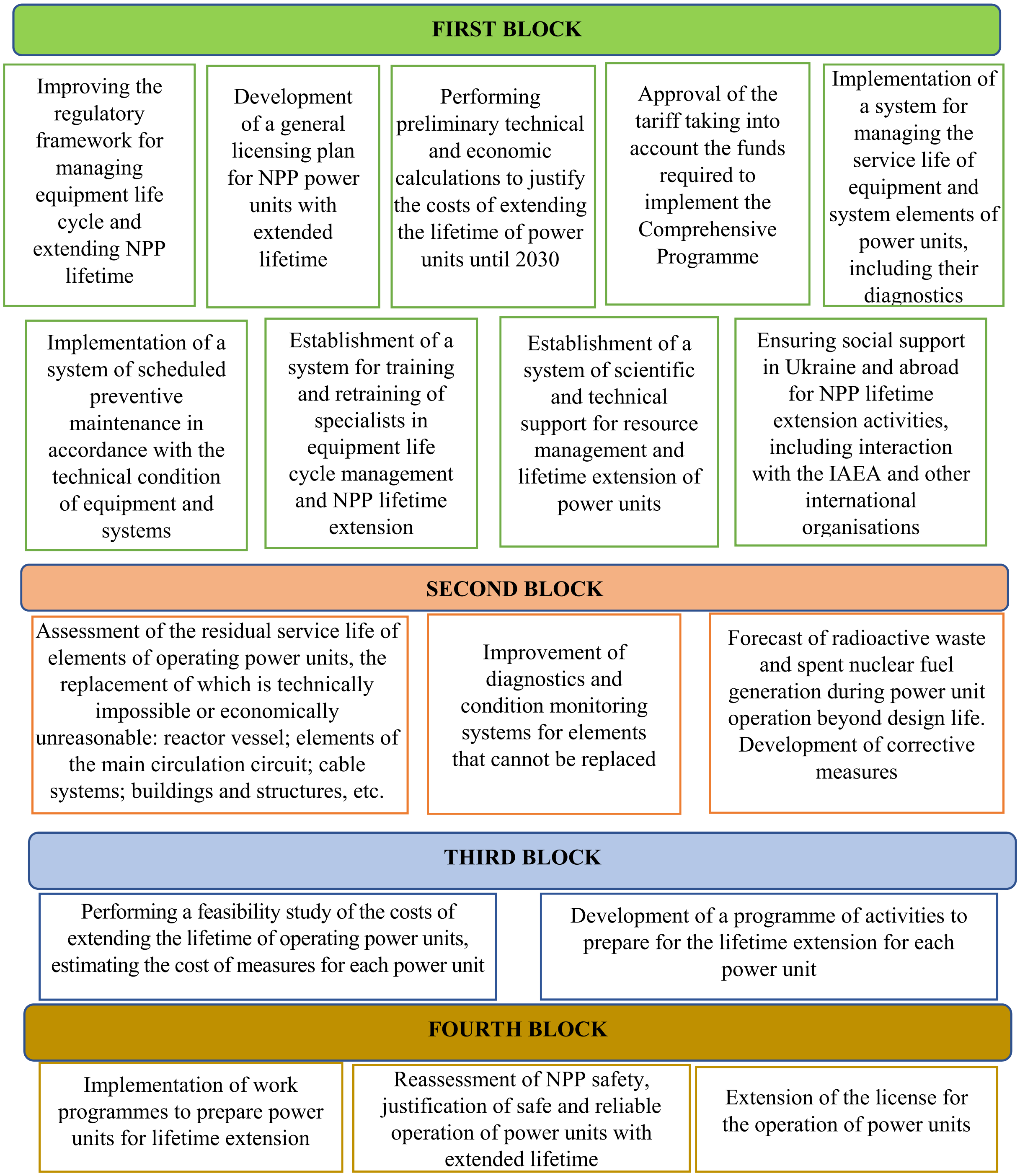

Fig. 1. Measures to implement the Comprehensive Programme for Technical and Economic Assessment and Reassignment of NPPs' Lifetimes.

One of the key points in the Comprehensive Programme is to assess the technical condition of the equipment and develop an appropriate regulatory framework to ensure operational safety and calculate residual life (Bauerbach et al., 2009; Weber et al., 2024). Using the primary circulation pipeline elements example, options were considered to solve this problem.

Ukraine's nuclear power plants operate at 440 MW and 1000 MW. The piping systems of power units have complex configurations and carry two-phase (water and steam) and single-phase (water and steam) media at different temperatures. A number of pipeline systems of nuclear power plants are subject to significant mechanical fluctuations; depending on the medium of the coolant and its temperature in the pipeline, there is polyharmonic or high-frequency loading (Bauerbach et al., 2010), as well as erosion-corrosion wear, destroying the support and suspension system (Aho-Mantila et al., 2012), thermal insulation, and contributing to the occurrence of cracks, which leads to emergencies. To prevent and eliminate emergencies, it is necessary to monitor and assess the vibration state of pipeline systems and calculate the vibration strength to predict the residual life (Cancemi & Lo Frano, 2021).

For this purpose, a proposed classifier will unify the methods of vibration strength calculation of pipeline systems, considering all loading parameters (polyharmonic, high-frequency loading, and erosion-corrosion wear). To study the vibration state, vibration resistance, and residual life determination, pipeline systems should be systematised and unified by classes of influence on operational safety as well as belonging to the equipment and performed functions and technical conditions (pressure, temperature, working medium, weight load, vibration load, fatigue strength, and wear during operation) (Yuzevych et al., 2017).

To systematise pipelines according to the above criteria, it is necessary to introduce belonging to a certain type. Such systematisation (Fig. 2) makes it possible to develop a classifier according to the following three features: safety class, heat carrier medium, and criterion characterising the technical condition of the pipeline (Cancemi & Lo Frano, 2021). Considering the proposed systematisation of pipeline systems, the codifier will be constructed similarly to the existing one but considering additional variable criteria critical for assessing vibration resistance.

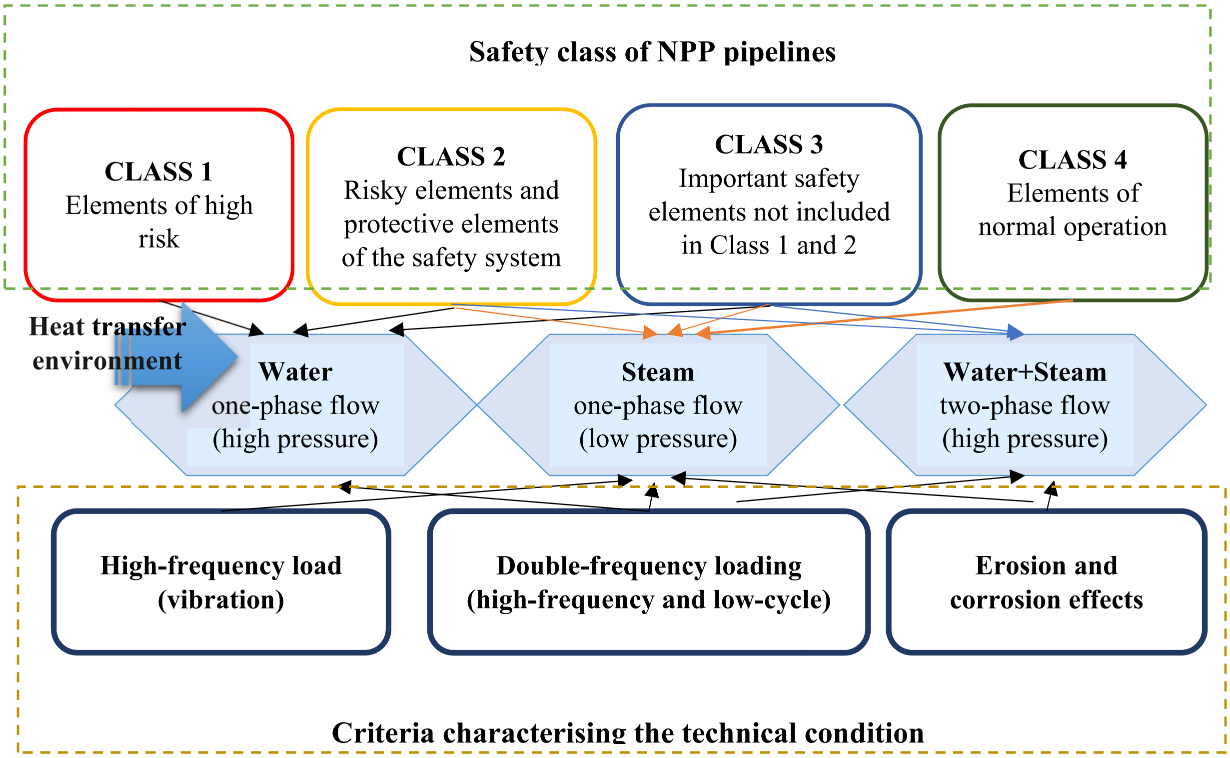

Fig. 2. Scheme of systematisation and unification of NPPs piping systems.

If steam is supplied through the system of main steam pipelines and water is supplied through the system of technical water supply, the systems of feed water deaeration and condensate paths require a solution to the problem of nonstationary vibration resistance.

It requires solving the problem of the nonstationary motion of a two-phase medium, which considerably complicates the analysis of the vibration state of pipeline systems, and it is advisable to consider the nature of loading and the presence of erosion-corrosion wear even before the vibration survey.

The conducted systematisation improves the codifier of pipelines and their elements and makes it possible to determine the algorithm of resource calculation and necessary initial parameters for vibration resistance assessment.

That is, in addition to the data reflected in the existing codifier, such as nuclear plant, power unit number, department, pipeline code and serial number, signs are added that define:

- Safety class: C1 (Class 1), C2 (Class 2), C3 (Class 3), C4 (Class 4).
- Heat transfer environment: W (water), S (steam), T (two-phase flow, water and steam).
- Criteria characterising the technical condition: 01 – high-frequency loading (vibration); 02 – double-frequency loading (high-frequency and low-cycle loads); 03 – erosion-corrosion impact; 13 – high-frequency loading and erosion-corrosion impact; 23 – double-frequency loading and erosion-corrosion impact.

Based on the codifier, the classification of pipelines is developed according to the following characteristics: safety class, heat carrier medium and operating loads (Table 1).

Table 1. Classification of pipelines according to safety class, heat transfer environment and operating loads.

Safety class	Heat transfer environment	Type of loading	Code
Class 1	Water	Double-frequency	C1W02
Class 2	Water	High-frequency	C2W01
		Double-frequency	C2W02
		Erosion and corrosion effects	C2W03
		High-frequency Erosion and corrosion effects	C2W13
		Double-frequency Erosion and corrosion effects	C2W23
	Steam	High-frequency	C2S01
	Water + Steam (two-phase flow)	High-frequency	C2T01
		Double-frequency	C2T02
		Erosion and corrosion effects	C2T03
		High-frequency Erosion and corrosion effects	C2T13
		Double-frequency Erosion and corrosion effects	C2T23
Class 3	Water	High-frequency	C3W01
		Double-frequency	C3W02
		Erosion and corrosion effects	C3W03
		High-frequency Erosion and corrosion effects	C3W13
		Double-frequency Erosion and corrosion effects	C3W23
	Steam	High-frequency	C3S01
	Water + Steam (two-phase flow)	High-frequency	C3T01
		Double-frequency	C3T02
		Erosion and corrosion effects	C3T03
		High-frequency	C3T13
		Erosion and corrosion effects	C3T23
Class 4	Steam	High-frequency	C4S01
		Double-frequency	C4S02

The improved codifier makes it possible to determine the parameters based on which it is necessary to calculate the resource assessment of pipeline systems.

To improve the regulatory support of the safe operation of pipeline systems, an algorithm for predicting the resources of pipeline systems, taking into account the loading parameters, is proposed (Fig. 3).

According to the given algorithm, it is proposed to carry out diagnostics of vibration condition and calculation of amplitude-frequency characteristics of pipelines. The obtained calculated data are compared with the results obtained experimentally and with the permissible values (Bond, 2010).

The error between the experimental and calculated results should be no more than 20%, if δ>20% the calculation is carried out again taking into account the correction of the initial data. In the case when the calculated data exceed the permissible values, it is necessary to apply methods of pipelines vibration reduction and to carry out again calculation-experimental research. If the calculated data do not exceed the permissible values, or there is no possibility of reducing the pipeline vibration, the residual lifespan calculation is carried out. Such an algorithm makes it possible to assess the pipeline resource and predict the resource of pipeline systems, taking into account the loading parameters.

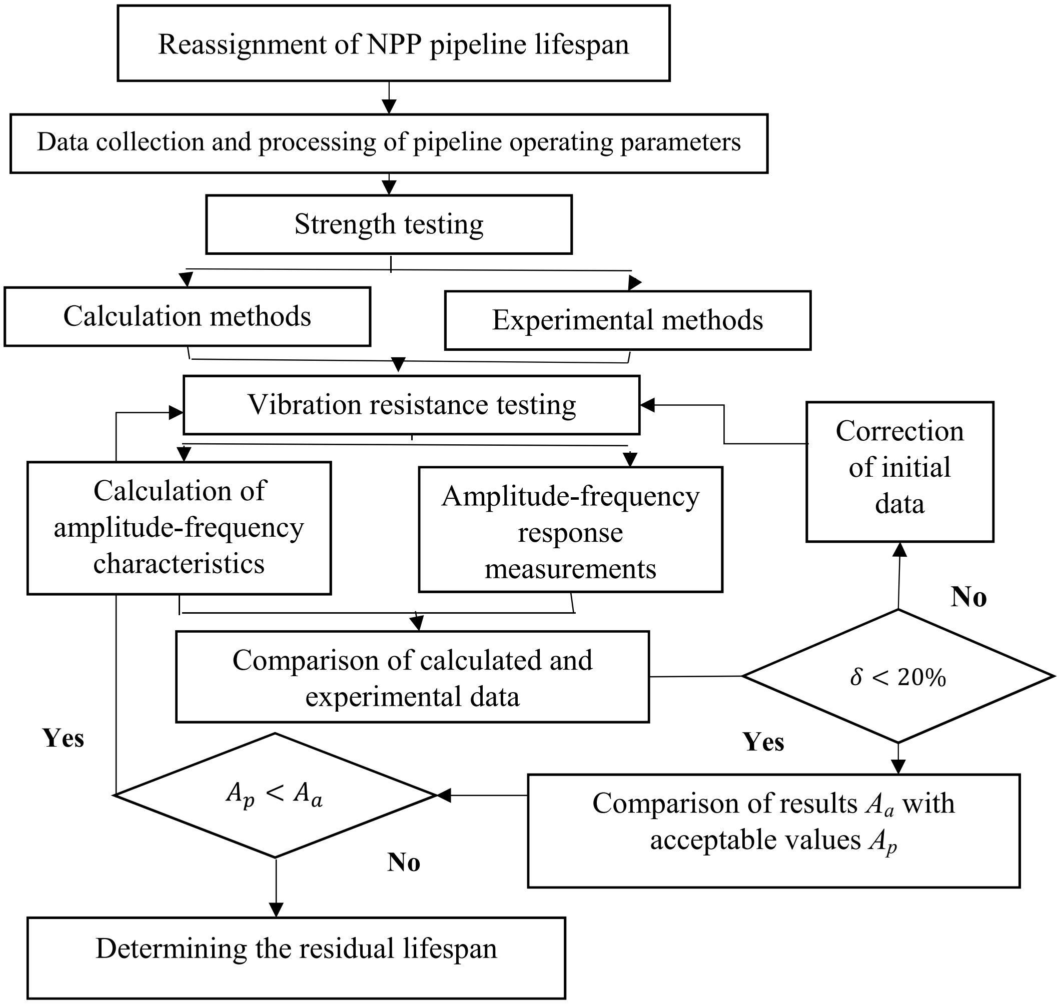

Fig. 3. Algorithm for assessment of residual life of pipelines taking into account loading parameters.

4. Results.

To create a normative provision for the operational safety of NPP pipelines, it is necessary to build a mathematical model to calculate their service life. By systematising pipeline systems by safety class, it is possible to single out the pipelines representing the most critical place in the safety system of NPPs due to their exposure to high loads. Consider one of the most loaded pipeline systems, the primary circulation circuit (MCC). The pipeline system under consideration belongs to the second class of safety. It is subject to vibration loading, which occurs during the transportation of two-phase coolant (water, steam) and low-cycle loads due to thermal expansion during pipeline start-up and erosion-corrosion wear. Subsequently, the section of the primary circulation circuit from the steam generator to the main circulation pump is considered, which is affected by all the above load parameters.

To assess the operational safety of the MCC, it is necessary to solve the joint problem of double-frequency loading under erosion-corrosion wear to determine the residual life. For this purpose, it is necessary to determine the following parameters: amplitude and frequency of vibration, frequency of low-cycle loading, pipeline wall thickness, rate, and geometry of erosion-corrosion wear. In this regard, by analysing the initial parameters of the main circulation pipeline (MCP), according to the algorithm (Fig. 3), experimental and calculated studies of natural frequencies for the MCP pipeline of the South-Ukrainian NPP were carried out (Hrinchenko et al., 2023), and the results are presented in Table 2. As can be seen from Table 2, when comparing the experimental data with the calculated data high convergence of the result from 95% to 98%, which indicates the correctness of the selected model for calculation.

Table 2. Eigen frequencies of the MCP pipeline.

Eigen frequencies	**P1, (Hz)**	**P2, (Hz)**	**P3, (Hz)**	**P4, (Hz)**	**P5, (Hz)**	**P6, (Hz)**	**P7, (Hz)**	**P8, (Hz)**
Estimated data	8.85	13.70	24.67	50.00	56.27	65.54	72.61	81.11
Experimental data	8.70	13.65	24.65	50.00	56.25	65.50	73.12	81.20

The stress–strain state of the pipeline under low-cycle loads was determined based on the obtained data on the pipeline vibration frequencies. Low-cycle loads in the framework of this study are defined as loads on the pipeline metal arising from temperature expansion and pressure changes during the start-up of the power unit after scheduled preventive maintenance (SPM). The temperature and pressure changes in different operating modes during the start-up of the power unit after the SPM are presented in Table 3. This process is not stationary, and it is necessary to determine the measure of fatigue damage introduced by the stresses in different operating modes.

Table 3. Pressure and temperature changes at unit start-up after SPM.

Operating modes during power unit start-up	**P, MPa**	**T, °C**
Checking the equipment performance. Testing of the 1st circuit. ‘Cold water’ test of the head circulation pump.	3.5	20
Tightness test	3.5	30
Warming up to temperature	3.5	60
Strength test	20	120
Adjustment test with pneumatic device	12	120
Power change	3.5	125
1 circuit test	16	180
Emergency boron injection system test	11	220
Real pressure test	19.2-19.7	250
MCC ‘hot water’ test	12	270
Testing of protections and interlocks	17	290
Vibration evaluation	16	290

Determine the stress intensity under low-cycle loads for different operating modes depending on pressure changes (Chen et al., 2018). The corresponding pressure value is set for each mode in the calculation, and the stress intensity at the set value is determined.

Table 4 shows the pressure change and stress intensity results in the MCP pipeline after preventive maintenance at different operating modes. As can be seen from the table, there is a linear dependence on pressure and stress intensity change.

Table 4. Changes in pressure and stress intensity of the MCP.

Operating modes during power unit start-up	**P, MPa**	**σ, MPa**
1 circuit test	16	180
Emergency boron injection system test	11	220
Real pressure tests. Check of protections and interlocks	17	250
Stationary operation of the power unit at	12	270

The stress-strain state under vibration loading caused by pressure pulsations is determined by the MCP pipeline's vibration displacement (vibration). The initial data for calculating stresses under vibration loading were obtained for the pipeline section with maximum displacement. Then, the maximum value of vibration displacements was set.

It determined the stress intensity under vibration loads at different operating modes, that is, at the MCP pipeline's transient and stationary operating modes. The obtained numerical values of the stresses at different operating modes and the curve of the stress intensity variation in the MCP pipeline as a function of time t are presented in Figure 4.

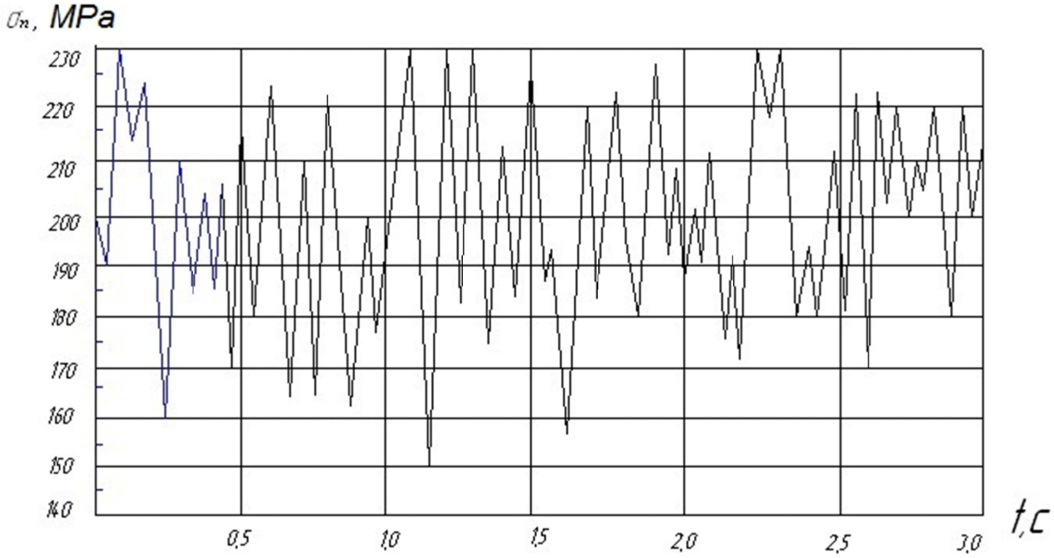

Fig.4. Stress intensity curve in the MCP pipeline.

The condition of the pipeline under erosion-corrosion wear during operation was monitored by measuring the wall thickness of the areas subjected to erosion-corrosion wear using an ultrasonic thickness gauge (UTG) to establish changes in geometry, with the aim of determining the minimum wall thickness. Monitoring was carried out in the cross sections of the middle part of the bend, the peripheral parts of the bend, tee connections, transitions, welded joints, and at the locations where the flow meters were installed. The measurement points were evenly distributed along the entire length of the stretched curve of the bend in the direction of the flow medium, with the distance between the wall thickness measurement cross sections being 45 mm.

The geometry of the wear was determined at the cross-section with the minimum wall thickness. South Ukrainian Nuclear Power Plant personnel have provided the necessary data for analysing the technical conditions of the pipeline: passport data, operating modes, water-chemical regimes, results of ultrasonic thickness measurements, and metallographic analysis. The results of the wall thickness measurements for the main circulation pipeline over nine cross sections for five years are presented in Table 5.

Table 5. Erosion wears of the MCP pipeline.

Cross-section	**Wall thickness measurement results δ, mm**				
	2018	**2019**	**2020**	**2021**	**2022**
1	32.7	32.2	32.0	31.5	31.2
2	32.0	31.7	31.4	30.9	30.6
3	31.0	30.7	30.2	30.0	29.6
4	30.3	30.1	29.8	29.4	29.2
5	29.4	29.1	28.8	28.6	28
6	30.3	30.1	29.8	29.4	29.2
7	31.0	30.7	30.2	30.0	29.6
8	32.0	31.7	31.4	30.9	30.6
9	32.7	32.2	32.0	31.5	31.2

Erosion wear rate: 0.3-0.4 mm/year. The analysis enabled the development of recommendations for the Comprehensive Program of Technical and Economic Assessment, considering various loading types according to the proposed codifier (Table 6).

Table 6. Calculation of the residual lifespan of NPP pipelines under various types of loading.

Code	**Residual lifespan of the pipeline under various types of loading**	
01 13	$N = \left[\dfrac{(\varepsilon_a - \sigma_{-1}/E)4}{\ln\left(\dfrac{1}{1-\varphi}\right)} \right]^m$.	ε_a is low-cycle fatigue under rigid loading; σ_{-1} is the fatigue limit; *E* is the modulus of elasticity; φ is the Poisson's ratio
02	$N_i = \left[\dfrac{(\varepsilon_{a_i} - \sigma_{-1}/E)4}{\ln\left(\dfrac{1}{1-\varphi}\right)} \right]^m$	ε_{ai} is low-cycle fatigue under block loading; σ_{-1} is the fatigue limit; *E* is the modulus of elasticity; φ is the Poisson's ratio.
03 23	$N = \dfrac{2}{(n-2)CY^n \pi^{n/2} \Delta\sigma^n} \times \left[\dfrac{1}{a_o^{\frac{n-2}{2}}} - \dfrac{1}{a_c^{\frac{n-2}{2}}} \right]$	*n* is the number of cycles to failure; *C* is a constant characterizing cyclic failure of different steels; *Y* is a constant for the stress intensity factor; a_o and a_c are crack parameters under cyclic loading.

The residual lifespan of the pipeline is determined through the damage reserve *z = 1 – a* and the average annual damage rate $a_d = (1/[N_0] + 1/[N_0]_k)/2$.

Knowing the endurance limit of the pipeline component, damage can be determined.

The number of loading cycles to failure is calculated from the following relation:

$$[N_0]_i = N_0 \sigma_{-1ki}^m / \sigma_{ai}^m , \qquad (1)$$

$$N_0 = 2 \cdot 10^6$$

Damage for the *i*-th time interval is given by the following formula:

$$a_i = N_i / [N_0]_i \tag{2}$$

For *k* start-ups, the total damage under the linear hypothesis is expressed by:

$$a_k = \sum_{i=1}^{k} a_i = \sum_{i=1}^{k} N_i / [N_0]_i \tag{3}$$

The residual lifespan of the pipeline will be:

$$r_{res} = z / a_d \ . \tag{4}$$

Considering a specific case with 10 start-ups per year and assuming a constant endurance limit over a 1-year period, the damage for the first time interval, according to formula (2) is $a_1 = 0.00117$. The total damage is determined from relation (3): $a = 0.63$. The damage reserve will be $z = 0,37$, and the average annual damage rate is $a_d = 0.05$. Therefore, the residual lifespan of the pipeline is $r_{res} \approx 7$ years.

It is recommended to conduct an annual assessment of the technical and economic conditions of the equipment and analyse the effectiveness of the work performed within the framework of the Comprehensive Assessment Program. Extending the operational lifespan of equipment is a viable solution, as it does not require additional investments for modernisation or replacement.

The economic efficiency of this approach indicates that, without considering further modernisation of the equipment in the year following the calculation, the specific costs per unit of installed capacity (kW) may range from 121.8 USD to 680 USD, depending on the specifics of the comprehensive program. This demonstrates that costs remain within the economically justified parameters, even with significant fluctuations.

This assessment confirms the feasibility of using the equipment without substantial capital expenditure, thereby maintaining the economic benefits and continuing the effectiveness of existing resources.

5. Conclusions.

Based on the analysis of regulatory documentation, a systematisation of pipelines and a classification according to three criteria were proposed: safety class, coolant environment, and operating load parameters. Based on this systematisation, a new, improved pipeline code for constructing a mathematical model to determine the lifespan is suggested.

An improvement in the calculation of the stress-strain state of pipelines and a mathematical model for assessing their lifespan were proposed, based on which a mathematical model for calculating the pipeline lifespan for different types of loading and various coolant environments was developed.

The impact of wall thickness reduction due to erosion-corrosion wear on pipeline damage and the changes in the stress-strain state of the pipeline metal were analysed, allowing for the prediction of metal damage over time. According to measurements taken on the central circulation pipeline of the South Ukrainian Nuclear Power Plant, the erosion wear rate was found to be 0.3-0.4 mm/year. Based on numerical studies of the impact of erosion-corrosion wear and dual-frequency loading on the pipeline metal, the locations of the maximum stresses in the pipeline walls were identified. The mathematical model for assessing the lifespan of pipelines allows the prediction of the operational lifespan of pipeline systems, thereby enhancing their operational safety.

Recommendations were made to extend the service life by seven years, taking into account the annual implementation of the Comprehensive Program of Technical and Economic Assessment, with specific costs without modernisation. The systematisation of pipelines, their improved classifier, the mathematical model for assessing their lifespan, and the proposed algorithm for evaluating the remaining lifespan under the combined action of different types of loading allows for the improvement of the regulatory framework for ensuring the safe operation of nuclear power plants and conducting a technical and economic assessment to extend their operational lifespan.

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