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Sustainable Energy Safety Management Utilizing an Industry-Relative Assessment of Enterprise Equipment Technical Condition

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Abstract: The study considers approaches to ensuring energy management for the safe operation of facilities and their equipment and ways to improve it. It has been established that to ensure effective safety management of industrial enterprises, one of the critical areas is the technical diagnostics of power equipment during operation. An assessment of the actual technical condition of power equipment of VVER-1000 power units is proposed based on establishing the aging mechanisms and determining the relative evaluation coefficients for the characteristics of individual equipment elements. The results of the calculations allowed us to conclude that the obtained results correspond to the coefficients of relative assessment Ki of the technical characteristics of the power equipment that determine its degradation. Studies indicates that when assessing the state of power equipment, it is necessary to consider the presence and impact of the following operational factors that are not considered in the design calculations: loads, high levels of mechanical stress, fatigue damage, and metal defects, which primarily indicate the presence of degradation changes. To assess the technical condition of the equipment, considering the degree of mechanical wear, 17 technical characteristics were selected to determine the aging mechanisms by signs of degradation. A mathematical model of the dependence of the relative evaluation coefficient K on changes in the operating parameters is presented, and it is noted that the most significant influence on the value of the coefficient is the temperature of the coolant at the inlet ($K = 0.56$). The developed approach makes it possible to improve the safety management system of power facilities by introducing the proposed model to assess the technical conditions of power equipment by defining the parameters in the overall safety management system.

Keywords: energy management; safety; power equipment; relative assessment; technical condition

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1. Introduction

Ensuring the safe operation of energy facilities is a priority for the sustainable development of any country. Energy complexes are complicated socio-technical systems, the management of which includes risks associated with both human and technical components. The technical component includes an assessment of the condition of individual equipment and processes. It aims to ensure reliable and safe operation, considering economic and environmental requirements. In the nuclear power industry, assessing the condition of nuclear power plant (NPP) equipment and determining its individual residual life is of particular importance because premature failure can lead to unacceptable environmental consequences and substantial material losses. Power plants have several units on their sites that share common infrastructure, and today, in the current environment, there is a need to manage the service life of multiunit NPPs. Decommissioning facilities that have formally reached the end of their designated service life but have not exhausted their actual service life leads to unjustified additional economic costs. According to experts, the cost of extending the life of the first Ukrainian power units was approximately USD 50 per kilowatt of capacity. The cost per kilowatt for the construction of a new power unit exceeds 500 USD/kW [1]. NPPs are deeply integrated into the regional economy and energy sector, and decommissioning of individual power units or the entire site will require solving not only technical and economic problems of creating replacement capacities but also related socio-economic problems, including in the satellite cities of NPPs.

According to regulatory documents and international requirements [2,3], operating NPP units have a service life of 30 years, which in the early 1970s was calculated using maximum conservatism and was based primarily on the insufficient level of knowledge available at the time of project approval. Nowadays, the accumulated practical experience of operation and international experience indicates that it is possible to extend the operation of such power units by up to 50–60 years. This level is achieved by developing and implementing systems and methods at NPPs to monitor and record the thermal–hydraulic and neutron–physical parameters affecting the performance of primary circuit elements, such as automatic and automated diagnostic systems, modeling maintenance facilities, and repair and inspection strategies. However, to develop and implement an effective mechanism for managing safety, it is also necessary to know the technical characteristics of the leading equipment of nuclear power units, scientific justification, and development of regulatory documents to extend the life of each unit separately based on the principles of economic feasibility and environmental sustainability [4].

The objective of this study is to develop a universal approach to energy management to ensure the safety of the operation of energy facilities by applying relative assessment to determine the defining characteristics and parameters of equipment.

In this regard, this study analyzed the latest research on safety assessment and effective approaches to management and safety at energy facilities. The literature review made it possible to propose a mathematical model for determining technical conditions as a direction for effective management. The relative assessment of the technical condition of power equipment proposed in this article based on the mathematical model makes it possible to develop a mechanism for energy management of the sustainable operation of equipment. It will be useful for industry experts in developing regulatory support and quality management policies and other stakeholders. Thus, Section 2 is titled “Analysis of Approaches to the Sustainable Energy Safety Management”, followed by Section 3 discussing substantiation of the choice of technical parameters for monitoring and assessing the technical condition of power equipment for the purpose of safety management, ending thus with Section 4 “Results”, Section 5 “Discussion” and Section 6 “Conclusions”.

2. Analysis of Approaches to Sustainable Energy Safety Management

Sustainable development of the economy’s energy sector plays a vital role in the development of each country. Special attention is required to ensure the quality of implementation of all stages of the energy life cycle and, most importantly, to ensure the safety of operation throughout the entire life cycle [5]. The safety management of energy facilities is critical. It is considered a component of the sustainability assessment of energy, regardless of whether it is a power plant, substation, gas pipeline, oil pipeline, or any other energy infrastructure.

The energy safety management system has several areas and tasks that should be addressed in a comprehensive manner, namely, a risk-based approach, development and implementation of measures to prevent threats and minimize risks (technical, organizational, and procedural), development of plans and a system of procedures for effective response in case of accidents, protection against cyber-threats and cyber-attacks on energy facility management systems, compliance with laws and regulations, training and education of personnel on safety issues, and continuous monitoring of the safety status, which may be adjusted depending on the specific type of energy facility and its characteristics. However, the overall goal of safety management remains the same: to ensure reliable and safe operation of energy infrastructure for society and the environment.

Approaches to the implementation of certain areas of sustainable energy safety management have been considered in many studies because energy safety issues are relevant for all countries at all stages of economic and technological development. For example, papers [6–9] propose a risk-based approach for assessing the safety of nuclear power facilities. The authors of [6] proposed a new view of using the integrated safety and security management system (IMSS) as a means of preventing and preparing for accidents and showed the IAEA's structural support, as well as organizational and cultural aspects of security [9]. It is assumed that organizational culture automatically integrates safety and security and provides a better understanding of systemic risks. However, to counter convergent and systemic risks, energy management systems require more attention to the technical aspects of security. In [7,8], a risk-based approach was used to develop a methodology for assessing risks in the event of an accident at a nuclear power plant and, as a result, improve the relevant radiation monitoring network. The authors propose using Java-based Real-time Decision Support (JRODOS), a system for the emergency management of radioactive materials in an off-site environment, as a tool for implementing this approach. This approach allows modernizing the existing environmental radioactivity monitoring network to ensure environmental safety.

Papers [10–12] propose the use of causal models, such as dynamic Bayesian networks (DBNs), which contain structural logic and provide a graphical representation of cause-and-effect relationships in engineering systems to make informed decisions on maintenance and risk management at energy facilities.

Ensuring the security of control systems in energy facilities is essential for applying controls and assessing security against cyber-attacks, which can lead to financial losses and human casualties [13–15]. Cyber-security controls are necessary to reduce security threats, particularly NPPs, based on quantifying the impact of potential cyber-attacks on a facility and its associated security controls. Safety management based on technical diagnostics of the functioning of individual elements of power complexes was presented in [4,16–22]. The authors proposed a comprehensive diagnosis of power equipment and forecasting of the service life based on a study of the stress–strain state of elements and calculation of the residual life by analyzing the degree of metal degradation. Based on the proposed methodology for determining the number of permissible load cycles under different operating conditions, the authors of [4,17,20] proposed a model for managing the safety of nuclear power units using international regulatory and legislative requirements, as described in [18,23–25], and an algorithm for predicting further operations within the design and beyond the design life.

Understanding the factors that affect the overall result is crucial for sustainable security management of any facility and implementation of effective management strategies [26,27]. Papers [28–30] present a comprehensive assessment of various facilities using relative assessment by applying a relative importance index (RII), relative frequency index (RFI), relative severity index (RSI), and standard rank-to-rank factors. In addition, fuzzy logic was used to analyze the impact of these factors in different scenarios. Special attention has been paid to approaches for estimating measures of systemic risk [31,32]. Specifically, asymptotic forms of relative errors for widely used systemic risk indicators are presented.

A general framework for modeling systemic risk indicators is provided based on relative estimation. The numerical results show that the proposed modeling framework based on relative estimation performs well, is more user-friendly, is more suitable to extend, and is less time-consuming than resampling and significance sampling approaches.

The general issues of the facility performance management system and its assessment through the use of qualimetric approaches are disclosed in [33–37], which propose universal methods for assessing heterogeneous parameters, including those that affect safety, to prevent undesirable events, improve the management system, and respond promptly to deviations from the normal state of operation. At the same time, it should be noted that energy facilities, such as nuclear power plants, require special attention in the area of safety management based on the experience of previous operations and accidents that have occurred [38–41] and require the development of an appropriate strategy considering economic feasibility based on a science-based approach.

3. Assessing the Technical Condition of Power Equipment

When the design life of NPP equipment is coming to an end, there is a real need to develop unambiguous methods to formally determine its actual technical condition and degree of aging and identify potential mechanisms of power equipment aging to address safe operation. The main circulation pump (MCP) was selected as the object of the study as an element of critical power equipment that affects the overall safe operation of the power unit.

To solve the problem of identifying the technical criteria responsible for pump aging, considering more than the requirements of regulatory documents is needed. The methodology for monitoring the condition of the main circulating pump needs to be improved in this regard. Solving this problem requires the development of a unified approach to solving the problems of diagnostics, control, and assessment of operating modes and load cycles, which would provide the possibility of more complete and reliable detection of damage at an early stage of defects, as well as their subsequent effective elimination. The following types of work should be performed:

- to analyze the impact of operating modes and load cycles on changes in the pump's technical characteristics, to determine the typical sequence of the operating modes of the MCP with further assessment of changes in its technical parameters that characterize irreversible degradation processes;
- to identify the criteria for assessing the technical condition of the pump with the subsequent determination of a minimal but sufficient list of parameters characterizing the aging of the MCP;
- to improve the methodology of the evaluation of the technical characteristics of the pump through the determination of the relative evaluation coefficient;
- to analyze the dynamics of changes in the defining parameters of the pump for the entire period of operation before the study with the subsequent establishment of the mechanisms of aging of the MCP.

Analyzing the Impact of Operating Modes and Load Cycles on Changes in Equipment Specifications

When assessing the technical condition of the MCP, only those physical parameters should be taken as parameters for which a change can lead to an inoperable or limiting state of the equipment due to the accumulation of irreversible degradation changes associated with the aging process. Such physical parameters that characterize the state of an object are called determinants [42]. Therefore, to assess the condition of pumps for the purpose of their safe operation, in addition to the values of technical parameters, it is necessary to study the dynamics of changes in these parameters, analyze defects and damage to pumps, as well as determine the mechanisms of aging of the MCP, which are usually multifactorial and their patterns for this type of equipment are not yet sufficiently studied. Therefore, the aging nature of the MCP can be primarily determined by analyzing the operating modes of pumps, their load cycles, and changes in their technical parameters, which characterize irreversible degradation changes over the entire service life. The normal operation of the MCP system is based on the mode of long-term parallel operation in the circuit of four MCPs under normal parameters of the VVER-1000 reactor coolant. During operation of the MCPs, the following are allowed:

- long-term operation of one and parallel operation of two and three MCPs in a circuit at nominal coolant parameters;
- operation of one, two, three, and four MCPs in a circuit with changes in coolant parameters in transient modes (heating, cooling) at temperatures from 20 to 300 °C and pressures from 0.98 (10) to 17.6 (180) MPa (kgf/cm^2);
- operation of one, two, three, and four MCPs in a circuit with cold coolant and in decontamination mode at a temperature of 20–100 °C.

During the operation of the reactor unit, the actual number of modes is continuously recorded at the power unit. Taking into account the results of thermal–hydraulic calculations for normal operation (NO), abnormal operation (AO), and critical situation (CS) modes given in [4,17,20], the modes that lead to the greatest stresses in the elements of the first circuit were determined. Based on the results of the assessment of the stress–strain state, these modes were taken as curves for each group of the analyzed modes of NO, AO, and CS, when assessing the strength of the elements of the first circuit.

The analysis of the documentation on accounting of operating time and load cycles of the reactor equipment showed that:

- for AO with a regulated number of modes of 300 cycles, the actual number of modes for the entire power unit lifetime is 104 cycles;
- for CS with a regulated number of modes of 30 cycles, the actual number of modes for the entire power unit lifetime is 1 cycle.

When assessing the number of load cycles, a conservative approach was implemented, which is always used in the nuclear power industry, i.e., the calculations take into account the maximum possible number of load cycles.

A typical sequence of MCP operation modes is shown in Figure 1.

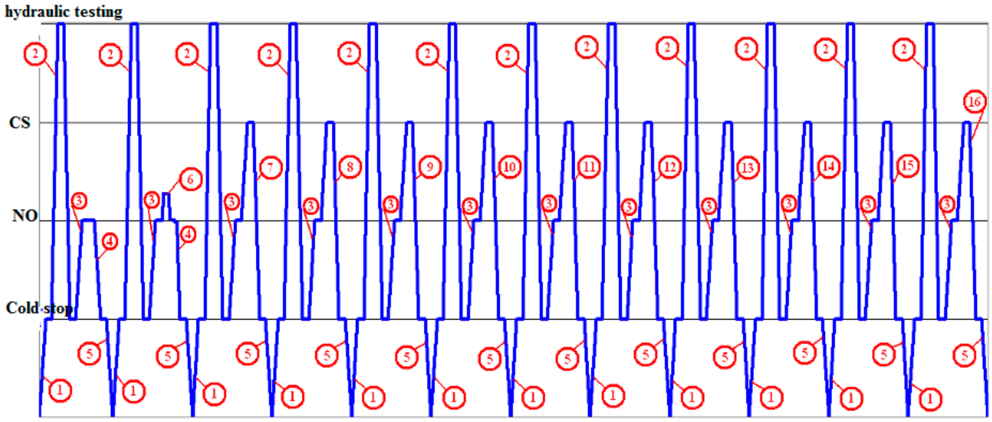
A detailed consideration of the model of the sequence of MCP operation modes shows that the operation of the equipment under consideration is actually possible in two cycles:

(1) Cycle 1. (Non-accidental) "Filling the equipment, sealing" (e.g., after scheduled preventive maintenance) → "Cold shutdown" → "Hydraulic testing" → "Scheduled heating" → "NO (stationary mode)" → "Scheduled cooling" → "Cold shutdown" → "Emptying the equipment, depressurization" (e.g., shutdown for scheduled preventive maintenance).
(2) Cycle 2. (Critical situation) "Filling the equipment, sealing" (e.g., after scheduled maintenance) → "Cold stop" → "Hydraulic test" → "Scheduled warm-up" → "NO (stationary mode)" → "AO or CS" → "Cold stop" → "Empty the equipment, depressurization".

With a detailed analysis of the modes, as well as the analysis accounting for the actual number of modes and load cycles for all pump performance characteristics, it becomes possible to develop an oriented process graph of the G-MCP, taking into account the physical parameters that characterize the technical condition of the pump (Figure 2). The graph nodes are the load modes and cycles, and the orientation of the graph arcs coincides with the direction of movement of the working fluids and coolants and the transfer of mechanical and thermal energy in the technological links of the MCP operation. The process graph allows the development of a mathematical model of the MCP, which is represented as follows:

$$\{N(\chi)/\phi_\iota(\chi) = 0, \chi \in M, \iota = 1, \bar{s}\} \quad (1)$$

where N(χ) and $\varphi_i(\chi)$—functional relations describing the performance of the pump as a technical system (N(χ)) and the technological processes taking place in it ($\varphi_i(\chi)$); *i*—number of the functional relation; *S*—number of relations in the simulation model; $\chi = (X, Y, Z, G^{MCP}, \Lambda)$—structure of the model, in which *X*—a vector of independent pump parameters, *Y*—a vector of dependent pump parameters, *G-MCP*—a technological graph, Λ=(λ_1. . ...λ_r)—a vector of parameters describing the influence of external conditions on the operation of the MCP, *Z*—a vector of parameters describing the level of aging of the pump during operation, *M*—the area of all possible functional states of the MCP that can be described using a mathematical model.



1—Filling of equipment, sealing
2—Conducting hydraulic tests
3—Scheduled heating
4—Scheduled cooling
5—Emptying the equipment, depressurization
6—NO: "Shutdown of two MCP"
7—AO: "De-energizing of the gas compressor station"
8—NO: "Closing the turbine stop valves"
9—AO: "Erroneous injection from the regular feeding unit with a water temperature of 60 °C ÷ 70 °C"
10—CS: "LOCA 2.11. Rupture of the make-up water line"
11—CS: "LOCA 2.7. Rupture of the purge pipeline"
12—CS: "LOCA 2.8. Double-sided rupture of the main circulation pipework"
13—CS: "PRISE 3.7. Detachment of the steam generator manifold cover"
14—CS: "OTHER 2.3. Unintentional opening"
15—CS: "MSLB 4.6. Main steam header rupture"
16—CS: "OTHER 8. Complete loss of steam generator feed water with the implementation of the "feed reset" mode

Figure 1. Model of the sequence of MCP operation modes.

The system of functional relations (1) contains the equations of thermodynamics, hydraulics, and kinematic and thermophysical properties of working fluids and heat carriers, design dependencies of the MCP, and their composition, number, and order depending on the load cycles, respectively. The number of relations S depends on the number of technical parameters that characterize the state of the pump.

The developed mathematical model of MCPs allows solving the following tasks:

(1) Analysis of the influence of technical parameters and external operating conditions on the MCP operation, i.e., the task of determining the operational characteristics of the type:

$$N(\chi) = f\left(X, Y, Z, G^{MCP}, \Lambda\right) \quad (2)$$

(2) Analysis of the parametric optimization of the performance indicators of all operating MCPs at the power unit:

$$\left[extrN\left\{\mathrm{N}(\chi)/\phi_i(\chi) = 0; t = \overline{1,s}\right\};\ X_{min} \le X \le X_{max};\ Y_{min} \le Y \le Y_{max};\right] \quad (3)$$

(3) The task of diagnostics of technical parameters with subsequent comprehensive assessment of the technical condition of MCPs:

$$\left(X, Y, Z, G^{MCP}, \Lambda\right) = \psi(\Omega(\chi)) \quad (4)$$

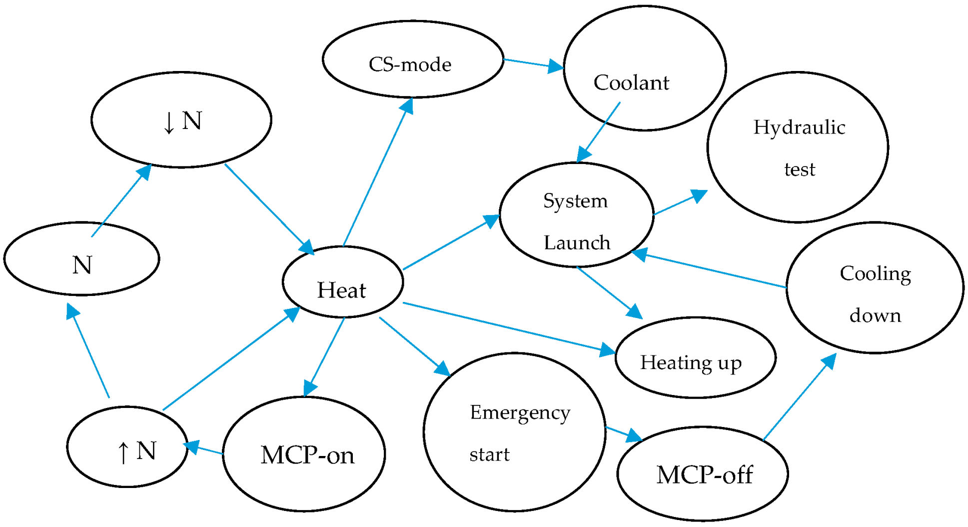


Figure 2. MCP process graph (orientated).

4. Results

Technological and financial considerations must be considered when developing new methods for improving the efficiency and dependability of machinery, owing to the dynamic nature of energy development and shifting production conditions. The necessity of adopting operational management decisions and analyzing the technical support for the safe functioning of power equipment subject to operational destruction accounts for the relevance of this [43–46]. Based on the study of design, engineering, operation, and repair documentation, the characteristics of the work performed to eliminate defects during the overhaul of the submersible pump, taking into account the impact of operating modes and load cycles on changes in the pump's technical characteristics, as well as the requirements of regulatory documents for the safe operation of pumps, the technical characteristics that determine the aging of the submersible pump were selected. The selection was also made considering the technological functions, physical properties of the equipment, and results of the analysis of failures and damage over the entire period of operation. Simultaneously, considering the functional purpose of the MCP at an NPP power unit and a conservative approach to solving the problem, the scope of the defining parameters should be sufficient to achieve the set goals.

All parameters that characterize the aging of individual elements and the pump as a whole can be divided into:

- MCP operating parameters;
- load cycles over the entire service life of the MCP;
- condition of the base metal and welded joints;
- actual values of the metal's physical and mechanical characteristics;
- the degree of erosion and corrosion wear (wall thinning).

The aging of a pump that has reached the end of its design life [47,48] primarily depends on the condition of the metal of the pump's structures and elements and the degree of its mechanical and erosion–corrosion wear. The safety margins incorporated in the MCP design allow for further safe operation of the pump [49].

The pump structure's strength characteristics primarily characterize the properties of the MCP metal. The actual strength characteristics of metal structures can be determined by measuring their hardness. The relationship between metal strength and hardness is well known, and the correlation between these steel parameters is specified in regulatory documents. The measurements were carried out using the dynamic method, which considers the structure's complexity, protruding parts, and various types of connections (threaded, keyed, and spline) in the pump design [50,51]. The metal hardness was measured in the area of the welded joints on both sides of the weld in the following zones: weld, near-weld zone, at a distance of up to 20 mm from the weld edge, and base metal at a distance of 20 to 50 mm from the weld edge.

The measurements also revealed that:

- the proximity of the measuring area to the weld has a significant impact on the measurement error;
- the increased hardness in the weld zone is maintained over an area approximately equal to three weld widths.

The metal hardness was determined as the arithmetic mean of five measurements at the same location. The relative error of each measurement did not exceed 4%. The metal hardness of the tested elements and structures of the pump was determined in order to check the compliance of the mechanical characteristics with the values established by the regulatory documents and technical documentation for the pump and to identify individual areas with unsatisfactory values.

The characteristics of the mechanical properties of the metal of MCP elements in accordance with the measured Brinell hardness values were determined by a correlation in accordance with the provisions of modern methods.

The advantage of the proposed methodology for controlling the main properties of MCP metal when considering the issues of assessing the technical condition of equipment is primarily in the clarity and unambiguity of the selected areas of work. Based on the results of measuring the hardness of MCP metal, a direct assessment of the strength characteristics is given:

tensile strength R_m^T = 0.38 HB, MPa;

yield strength $R_{p0.2}^T = -4.28 + 0.238$ HB + 0.00022 HB2, MPa;

relative elongation $A^T = [3\text{k}/(2R_m^T + R_{p0.2}^T)] \times 100\%$, where k = 28 for austenitic steels.

As part of the task at hand, it is advisable to measure the thickness of the base metal using the ultrasonic method in accordance with the inspection of the metal condition of MCP elements.

At the moment, there are no regulatory documents approved for use in the industry that allow calculating the thinning rate and the duration of equipment operation based on operational control data. The need for the measurements was caused by the lack of data to confirm the technical condition parameters and determine the causes of MCP degradation in general. The choice of MCP control elements for thickness measurements was determined by the presence of: welded joints of MCP structural elements; welded joints of MCP with other power unit elements; areas with stress concentration in the MCP structure; defects, including thinning, introduced during operation; the most loaded areas; areas subject to vibration loads.

The diagram of the pump metal thickness control zones is shown in Figure 3. The wall thickness was measured in the area of welded joints No. 1 and No. 2 of the adapters to the suction and discharge pipes. The nominal thickness of the welded parts in the welded area is 100 mm (in the control zones). The minimum design wall thickness of the adapters is 43 mm.

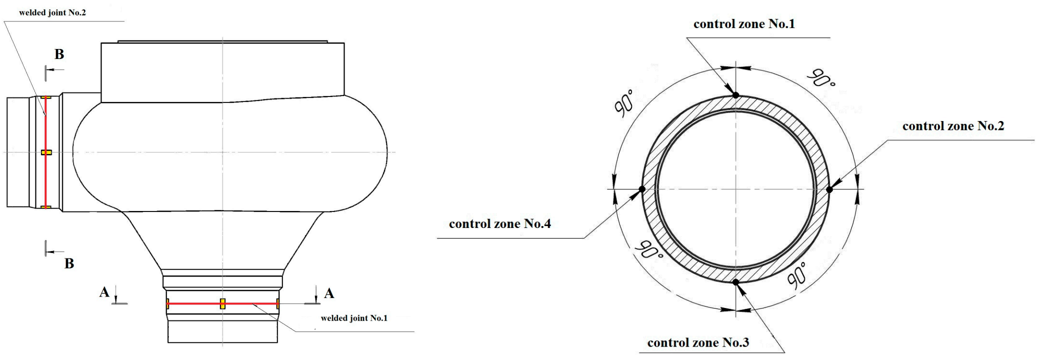


Figure 3. Diagram of MCP metal thickness control zones.

Numerical results of MCP metal wall thickness control are shown in Table 1.

Table 1. Results of MCP metal wall thickness control.

Controlled Element Name	Control Zone	Smallest Measured Thickness Value, mm	
		Nozzle	Adapter
Welded joint No. 1	No.1	99.0	100.8
	No.2	100.5	99.0
	No.3	100.7	98.8
	No.4	100.9	98.7
Welded joint No. 2	No.1	99.4	100.8
	No.2	100.3	100.7
	No.3	100.5	100.9
	No.4	99.5	100.8

When processing the results of the control of mechanical properties by metal hardness, the compliance of the values of the mechanical properties of the MCP metal with the requirements of regulatory documents, as well as the presence and patterns of their change during operation, should be established. At the same time, a change (decrease and/or increase) in the obtained mechanical properties (2)–(4) compared to the passport or previously obtained ones by a value greater than the error of their determination is assessed as a need to take this fact into account when reassigning the service life of the MCP.

Thus, based on the above studies, analysis, and scientific substantiation of their results, a list of technical characteristics that determine the aging of MCP was formed (Table 2).

Selected characteristics that determine the aging of MCP are necessary for:

- analyzing the further dynamics of their change and statistics of these changes over time in order to identify specific processes that gradually change the material characteristics of MCP elements as a result of operation;
- establishment of probable aging mechanisms;
- formalization of the criteria for assessing the technical condition of MCPs with the subsequent solution of the issue of safe operation of the equipment.

Table 2. List of characteristics that determine MCP aging.

Name of Characteristics That Determine MCP Aging
1. Operating characteristics of MCP (nominal flow, m^3, suction pressure, MPa, head, MPa, bearing temperature, °C, inlet coolant temperature, °C, vibration characteristics, μm)
2. The number of MCP load cycles at NO
3. The number of MCP load cycles in case of violation of the NO
4. Number of MCP load cycles in critical situations
5. Condition of base metal and welded joints (condition of base metal and welded joints and MCP snail adapters)
6. Actual values of mechanical properties of the metal
The body of the snail. Material¯high-chrome steel : yield strength $R^T_{p0.2}$, MPa, tensile strength R^T_m, MPa
The body pipes of the snail. Material¯pearlite alloy steel : yield strength $R^T_{p0.2}$, MPa, tensile strength R^T_m, MPa, relative elongation A^T, %.
7. Wall thickness of the MCP snail, wall thickness of the MCP snail adapters

The Results of Applying the Relative Assessment Coefficient as an Indicator of Assessing the Technical Condition of the Pump

To assess the current technical condition of an MCP and subsequently determine its safety, a special methodology is required which, first of all, involves the use of the information obtained from the results of special surveys during the period of scheduled preventive maintenance. Such a methodology should be optimal regarding the costs of conducting equipment inspections, not contradict the current regulatory documents, and allow obtaining the final results in a convenient and accessible form for a wide range of specialists. The actual technical condition of the equipment in operation determines its further safe operation, the need for its replacement, unscheduled repairs, or extension of its service life. The quality of the condition, and therefore the quality of the pump's operation, is assessed not by a single criterion or quality indicator but by a set of such criteria—technical characteristics and equally significant. It is noted that in developing a method for assessing the technical condition of specific equipment, the coefficient of relative assessment (K_i) is used, which is calculated for each defining characteristic by comparing the value of this parameter measured at a given time with the initial (plant) and limit (normalized) values.

$$K_i = 1 - \frac{P_{0i} - P_{Mi}}{P_{0i} - P_{Li}} \quad (5)$$

where: P_{0i} is the initial value of the i-th defining technical characteristic according to the plant passport or test; P_{Mi} is a measured value of the i-th defining characteristic during the inspection; P_{Li} is the limit value of the i-th defining characteristic at which the operation of this equipment is not allowed (according to the requirements of regulatory documents).

At the beginning of the equipment operation, when the value of the defining parameter is equal to the passport value ($P_{0i} = P_{Mi}$), $K_i = 1$.

As the equipment ages, the measured value of the determining parameter decreases (increases) and at $P_{Mi} = P_{Li}$ the coefficient $K_i = 0$.

Thus, the technical condition of the equipment according to this defining parameter is assessed by the coefficient K_i, which varies from 1 to 0. The disadvantage of this method was the assumption of simplifying the process of calculating the value of the overall assessment of the technical condition of the equipment. The overall real technical condition was determined by the "weakest link" method and corresponded to the value of the minimum K_i coefficient.

In this regard, it is proposed to improve this method to assess the technical condition of the pump as a whole. First of all, the parameters characterizing the degradation of the pump during operation were determined. In addition, such determining load parameters as the rate of change in the values of operational characteristics—temperature and pressure, vibration, number of cycles of the corresponding modes—are the main criteria for assessing the technical condition during its safe operation.

Thus, the probability of obtaining the results of an observation with the exception of a particular parameter is expressed by a distribution function (6), and it is necessary to obtain statistical estimates $\overline{\theta}$ of these parameters. Considering the sample values $x_1\,,\ x_2,\ \ldots,\ x_n$ as realizations of random variables $X_1\,,\ X_2,\ \ldots,\ X_n$, it is possible to transform the estimate $\overline{\theta}$ as a function of these random variables:

$$\overline{\theta} = \phi(X_1,\ X_2,\ \ldots, X_n) \tag{6}$$

If several samples n are used for estimation, we obtain the same number of random estimates. In our case, the random variable $\overline{\theta}_1, \overline{\theta}_2 \ldots, \overline{\theta}_n$ based on the sample data is the relative valuation coefficient K_i.

The experimental design includes all the factors (17 characteristics) that determine the aging of MCPs, the impact of which is assessed using a multivariate two-level design. When selecting variables, the problem of determining the factors and their number that influence the objective function often arises. Under these conditions of uncertainty, possible variables that may have such an impact are assumed. In this case, if a full factor plan is used, a large number of experiments need to be performed. Such experiments are time-consuming and costly. The Plackett–Burman plan offers an experimental design that allows effectively "sifting" a large number of factors using a minimum number of observations.

The coefficients are calculated by calculating the difference between the sums of the objective function values for the factor at levels +1 and −1, and the plan matrix shows that the effect estimates can be calculated independently of each other (Table 3).

Table 3. Plan matrix for identifying factors affecting degradation processes.

N	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
1	+	+	+	+	−	+	−	+	+	−	−	+	−	−	−	−	−
2	+	+	+	−	+	−	+	+	−	−	+	−	−	−	+	−	−
3	+	+	−	+	−	+	+	−	−	+	−	−	−	+	+	−	−
4	+	−	+	−	+	+	−	−	+	−	−	−	+	+	+	−	+
5	−	+	−	+	+	−	−	+	−	−	−	+	+	+	+	−	+
6	+	−	+	+	−	−	+	−	−	−	+	+	+	+	−	−	−
7	−	+	+	−	−	+	−	−	−	+	+	+	+	−	+	+	+
8	+	+	−	−	+	−	−	−	+	+	+	+	−	+	−	+	−
9	+	−	−	+	−	−	−	+	+	+	+	−	+	−	+	+	−
10	−	−	+	−	−	−	+	+	+	+	−	+	−	+	+	−	−
11	−	+	−	−	−	+	+	+	+	−	+	−	+	+	−	−	+
12	+	−	−	−	+	+	+	+	−	+	−	+	+	−	−	−	+
13	−	−	−	+	+	+	+	−	+	−	+	+	−	−	+	−	−
14	−	−	+	+	+	+	−	+	−	+	+	−	−	+	−	+	−
15	−	+	+	+	+	−	+	−	+	+	−	−	+	−	−	−	−
16	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−

The variance of the observation errors is estimated by duplicating the observations, and the variance of the parameter estimates is equal to:

$$\delta_i^2 = \frac{\delta_i^2}{4\kappa}, \tag{7}$$

After comparing the results, the dispersion of the influence of critical factors on the objective function is assessed (Table 4).

Table 4. Estimation of the dispersion of the influence of critical factors on the objective function.

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Value	No	No	No	No	No	Yes	No	Yes	No	No	No	Yes	No	No	Yes	No	No

The results of the experiment show that out of all 17 variables, only 4 critical factors were significant for influencing the objective function: the temperature of the coolant at the MCP inlet, the pressure at the MCP suction, the temperature of the bearings, and the pressure at the MCP outlet, which have the most significant impact on the degradation processes of pump elements and structures. The mathematical model of the integral characteristic of the technical condition assessment of the pump $\overline{\mathrm{K}}$—the dependence of the relative assessment coefficient on changes in the aging parameters in the form of MCP performance characteristics (t_1'—temperature of the coolant at the inlet to the MCP, p_1—pressure at the suction of the MCP, t_{PV}—bearing temperature, p_2—pressure at the outlet of the MCP)—was obtained by statistical analysis in the form of a regression equation. This dependence with coded values of the above factors is as follows:

$$\begin{aligned} \hat{y} = 0.902924 + 0.0505074x_1 + 0.0110797x_2 - 0.0287184x_3 - 0.00139962x_4 + \\ 0.00062025x_1x_2 - 0.0003435x_2x_3 + 0.000212437x_1x_3, \end{aligned} \tag{8}$$

where ŷ is the predicted value of the response function:

$$x_1 = (t_1' - {t_1'}^0)/\Delta t_1',\ x_2 = (t_{PV} - t_{PV}^0)/\Delta t_{PV}, x_3 = (p_2 - p_2^0)/\Delta p_2, x_4 = (p_1 - p_1^0)/\Delta p_1 \tag{9}$$

The dependence of the relative valuation coefficient $\overline{\mathrm{K}}$ on operational parameters is explicitly as follows:

$$\begin{aligned} \overline{E}\left(t_1', t_{pv}, p_2, p_1\right) = 0.393 - 0.009\ t_1' - 0.00931t_{pv} - 0.2209p_2 - 0.1518p_1 + 0.00006t_1't_{pv} \\ +0.0008t_{pv} - 0.0005\ t_1' - 0.2209p_2 \end{aligned} \tag{10}$$

Since MCP is estimated by a set of parameters and all of them are equivalent to each other, forming a complex structure, it is difficult to identify them and adequately determine the correct single aging parameter. For the operational parameters of the pump, models (7) and (8) are more meaningful because they allow taking into account the influence of the interaction of factors on the response function $\overline{E}\left(t_1', t_{pv}, p_2, p_1\right)$. The statistical analysis of dependence (7) made it possible to establish that the greatest influence on the value of the relative evaluation coefficient among the operational characteristics is the temperature of the heat carrier at the inlet to the MCP, followed by the suction pressure, outlet pressure, and bearing temperature in order of hierarchical importance. The results of the statistical analysis of the dependence $\overline{\mathrm{K}}$ on operational parameters are summarized in Table 5.

Table 5. Statistical analysis results of dependence $\overline{K}$.

Parameter		Year of Measurement			
		2016	**2018**	**2020**	**2021**
1	Suction pressure of MCP, MPa	15.6	15.3	15.3	15.5
	Relative evaluation coefficient	0.61	0.63	0.63	0.603
2	Outlet pressure of MCP, MPa	15.88	15.7	15.35	15.7
	Relative evaluation coefficient	0.68	0.7	0.718	0.7
3	Coolant temperature at the inlet to MCP, °C	290	294	287	288
	Coefficient of relative evaluation	0.58	0.56	0.6	0.601
4	Bearing temperature, °C	70	78	70	69
	Coefficient of relative evaluation	0.77	0.73	0.76	0.77

The relative assessment coefficient K_i in assessing the technical condition of the MCP makes it possible to: confirm the qualitative selection of physical parameters that characterize the technical condition of pumping equipment, taking into account its degradation; improve the methodological support for a reliable assessment of the technical condition of the equipment using the methods of mathematical statistics; systematize the results of the surveys and calculations for further determination of the forecast value of the residual life of the MCP.

5. Discussion

The study discussed the service life of nuclear power plant units and how it can be extended up to 50–60 years by implementing monitoring systems and repair strategies. Safety issues and effective energy safety management mechanisms are crucial in ensuring sustainable development. An analysis of factors affecting power equipment's safety, functionality, and durability is required to justify new safety management mechanisms. The research proposes a method for determining the technical condition of the main circulation pump (MCP) for safe operation, which helps assess the actual technical condition of equipment, track the dependence of the relative assessment coefficient on changes in aging parameters, and systematize the results of surveys and calculations for further safe operation of MCPs and overall safety management. The proposed method of relative assessment can be similarly applied to any equipment of the energy complex. Further research will be aimed at developing a method for predicting the residual life of electrical equipment based on a preliminary assessment of its technical conditions. The main points of discussion are the assessment of extending the service life of nuclear power plants, which can create a safety hazard and increase maintenance costs.

In addition, there are limitations on the potential environmental consequences of extending the operation of nuclear power units, including the disposal of nuclear waste and the risk of accidents [52]. Therefore, taking into account the potential risks of extending the service life of nuclear power units beyond the originally established period, as well as the potential consequences for the environment, requires the development of tools for formalized assessment and selection of reengineering projects for implementation at the enterprise [53,54].

6. Conclusions

Equipment aging and the corresponding analysis of service life characteristics are essential issues in any power equipment operation. Experience in the operation of nuclear power plants has shown that particular focus should be given to safety issues and effective energy safety management mechanisms integral to sustainable development. However, a thorough analysis of the factors affecting the power equipment's safety, functionality, and durability is required to justify the introduction of new safety management mechanisms.

In particular, it is essential to study the factors that affect degradation changes during long-term operation at specific facilities and to identify the critical parameters and characteristics that contribute significantly to these processes. The proposed approach for determining the technical condition of the pump for safe operation allows the assessment of the actual technical condition of a particular type of equipment in a numerical form, convenient operation, establishment of aging mechanisms, and assessment of the technical condition and safe operation of the main circulation pump. The research was conducted in several zones where degradation processes occurred, with the following parameters: nominal thickness of welded parts in the welding area of 100 mm (in control zones) with a minimum design wall thickness of 43 mm for adapters.

The obtained results of the relative assessment coefficients K_i correspond to the technical characteristics of the pump that determine its degradation. The use of the relative assessment coefficient when assessing the technical condition of MCPs makes it possible to track the dependence of the relative assessment coefficient on changes in aging parameters in the form of MCP performance characteristics, improve the methodological support for a reliable assessment of the technical condition of equipment using mathematical–statistical methods, and systematize the results of surveys and calculations for further safe operation of MCPs and overall safety management. It was determined that out of seventeen technical characteristics that determine the aging mechanisms based on the signs of pump degradation, four are the determining parameters that have the most significant impact on the degradation processes and changes in the operational parameters of the pump. The temperature of the heat carrier at the pump inlet has the most significant influence on the coefficient value (K = 0.56). MCP studies also showed that when performing work aimed at assessing the condition of the pump, the existence and influence of operational factors must be considered, such as loads that are not considered in the design calculations, high levels of mechanical stress, fatigue damage, metal defects, welds, and surfacing during manufacture and installation, which primarily indicate the presence of degradation changes and aging of the pump.

The identification of the factors that have the most significant impact and the application of the proposed method of relative assessment for further safety management can be similarly applied to any equipment of the energy complex, which makes it possible to set the frequency of monitoring individual defining parameters and adjust the defining characteristics. Further research will be aimed at developing a method for predicting the residual life of electrical equipment based on a preliminary assessment of its technical conditions, which will allow for making scientifically grounded predictive conclusions about the possibility of extending the sustainable operation of NPP equipment. The proposed model of energy safety management and prediction algorithm will become the basis for the development of regulatory support, which will include normative indicators of relative assessment for specific equipment, methods of technical diagnostics, and assessment of the term for further sustainable operation of the relevant power equipment.

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