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**OPTIMIZATION
OF SYSTEMS
REPAIR PLANS
AND ASSESSMENT
OF THE USEFUL
LIFE OF NUCLEAR
POWER PLANT
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This paper presents a computer-aided method of planning the volumes of repairs of systems of nuclear power units and a method for calculating their gamma-percentile life. This planning is carried out on the basis of predicting the reliability indicator, the probability of no-failure operation for a certain time period, with the gamma-percentile life of the equipment being determined by solving the corresponding equations. The tasks considered are related to an important energy problem of extending the operation of nuclear power units. Its importance is determined mainly by economic feasibility: it is cheaper to assess the useful life of a nuclear power unit and, on this research basis, extend its operation, than create a new unit. It is also shown that the calculation of the probability of a radiation accident at a nuclear power unit is associated with the results of planning the repairs of its systems, with assessment of its useful life. An optimization problem is formulated: it is required to find such a plan for the volumes of repair of a system that, with limited repair costs, its reliability indicator for a given duration deviates least from the maximum permissible value. The solution to the problem is based on calculating the structural reliability of the system. A graphological image of the system is built in the form of a composition of graphological images of typical structures. After the reliability indicator of typical structures has been calculated, the structures are replaced with individual structural elements, which makes it possible to simplify the initial graphological image of the system in a computational scenario and calculate its reliability indicator. The determination of the repair volume is carried out by applying a version of the coordinate-wise optimization method. To assess the gamma-percentile life, a model is adopted, in which the recoverable equipment components have an unlimited life, although, of course, they "age", and the non-recoverable components spend their life up to the level when their replacement becomes conditioned by the violation of the requirement for the maximum permissible value of the system reliability indicator. Estimates of the gamma-percentile life of the equipment are calculated by planning system repairs on a sequence of intervals of annual energy production by a nuclear power unit.

Keywords: nuclear power plant, power unit, system, repair plan, useful life, optimization.

Introduction

The tasks of planning repairs and assessing the useful life of the equipment of nuclear power units (NPU) are mainly solved on the basis of regulatory instructions of equipment manufacturers. This article proposes an approach based on computing the reliability indicators of NPU systems, with account taken of their structural organization. As the reliability indicator, the reliability function (RF) over a particular time period is used. As the useful life indicator, the gamma-percentile life is used, which is the duration of the working state of a unit with the probability of gamma.

The main NPP quality indicator, that allows it to be operated, is safety. Safety assessment is a multifaceted problem. From the standpoint of systems analysis, one of the ways to obtain quantitative safety assessments is to mathematically model the risk from the operation of NPUs [1]. The magnitude of the risk is determined by the product of the probability of a radiation accident and the magnitude of the consequences of the accident: life loss, environmental pollution, material losses. Knowing the risk allows one to manage it, that is, to provide for compensatory measures.

One of the ways to reduce the risk is to provide high-quality maintenance and repair of NPUs. The paper considers part of this task, namely, the planning of rational volumes of system repairs, carried out during the periods of annual scheduled preventive maintenance overhauls ensuring that NPUs produce cost-effective energy and are safe. The solution to the repair planning problem is used to determine the gamma-percentile life of equipment.

The plans for repair and useful life assessment are related to the problem of extending the gamma-percentile life of NPUs [2]. The importance of the problem is mainly explained by economic feasibility: it is cheaper to assess the useful life of a NPU, and on this research basis, extend its operation, than create a new unit.

The useful life indicators depend not only on the physico-chemical, thermodynamic, vibrational, and other impacts on the equipment, but also on the requirements for the maximum permissible value of the probability of a radiation accident, on the quality of maintenance and repair.

Today, there is increasingly the problem of assessing the individual useful life of NPUs by accumulating reliable information, using diagnostics, witness samples, and accelerated tests as well as modelling the strength and useful life indicators of equipment. The need to carry out special useful life studies of an individual NPU is due to its individual characteristics and operating features. In NPP conditions, a complete study of the individual useful life of an NPU, its numerous equipment, measured in thousands of units, is practically impossible because there will be uncertainty in some of the results due to the reduced volume of measurements and engineering interpretations of incomplete information.

In this article, the determination of the equipment repair plan is based on the analysis of the structural reliability of NPU systems. It is assumed that the values of equipment reliability indicators can be obtained from the registration data of their failures, from expert assessments, or taken from the data of its manufacturers. Repair planning is transferred to the mathematical plane, that is, the problem of optimizing system repairs is formulated based on the calculation of its structural reliability. In this case, a functional relationship is used between the cost of repairing a piece of equipment and the increase in the value of its reliability indicator.

Due to the variety and range of technical systems, there is no and, apparently, will be no universal method for calculating their structural reliability [2]. To date, the main methods for assessing the structural reliability of systems include the logical-probabilistic method, the discrete-state Markov processes method, and the simulation modelling method. They are difficult to apply to systems with a large number of elements [3]. In this regard, other methods that facilitate the solutions of computational problems are of interest too.

One of the approaches used in engineering hand calculations is shown in [4]. It consists in compressing a structural diagram, that is, a graphological image of a system. When there are many elements in the system, the calculations become time-consuming. This process becomes even more labor-intensive if the calculations have to be performed repeatedly with changing data, for example, when optimization problems are being solved.

In order to automate the calculations of the structural reliability of complex systems with a large number of elements, an approach has been developed [5] based on the recognition and compression of structural schemes that change during the calculation on a computer.

The search for a rational plan is carried out step by step by assigning repairs to the equipment, the increase in the reliability of which ensures the greatest increase in the system reliability indicator at each step. The calculated repair plan determines the change in the system reliability indicator over time, which allows one, by solving the corresponding equations, to find the duration of the operative condition of a piece of equipment with the probability of gamma, thereby determining the estimate of its useful life.

Main Part

In this article, the method for planning the repair of a system and the assessment of the equipment useful life are presented according to the following scheme: a brief description of the method for calculating the structural reliability of the system is given; the task of optimizing the system repair plan is formulated; a method for solving the optimization problem is described; the connection of repair plans with the assessment of NPU safety and with the estimates of the equipment gamma-percentile life is shown.

Calculation of Structural System Reliability

The structural diagram of a system is composed of the images of its elements (hereinafter referred to as elements) with the known laws of their reliability indicator. To calculate the system reliability indicator on a computer, simple elements; generalized elements; typical basic graphological images, for example, redundant systems; virtual connectors are introduced into the information image of the system. The following theorem is used: if the graphological image of the system is composed either of typical basic graphological images with simple elements or from generalized graphological images with computable indicators of reliability, then the system reliability indicator can be calculated [5]. Based on this theorem, the process of calculating the structural system reliability is monitored on a computer.

The calculation method developed in [5] is based on the representation of the graphological image of a system in the form of a composition of typical graphological images. Automatic recognition of their images is carried out and the values of their reliability indicators are calculated. The calculation results are assigned to typical graphological images, turning them into elements of a structural scheme, which creates a new structural diagram of the system with new typical structures. Such replacements sequentially compress the initial graphological image of the system to one element with the calculated value of the reliability indicator, which determines the value of the reliability indicator of the initial graphological image of the system.

Statement of the Repair Planning Problem

For the mathematical formulation of the problem, the following is accepted: S is a system formed from systems $S_0, S_1, S_2, \dots, S_M$, each of which consists of elements $a_i^m, i^m=0, 1, 2, \dots, I^m, m=0, 1, 2, \dots, M$, (further $a_i, i=0, 1, 2, \dots, I$); t_0 is the repair start time; $\Delta t=t-t_0$ is the duration of the annual operation of the system; $Q(S_0), Q(S_1), Q(S_2), \dots, Q(S_M)$ are the probabilities of failures of the systems $S_0, S_1, S_2, \dots, S_M$ over time period Δt ; V is the repair volume of the system S ; Q_S^* is the maximum permissible value of the probability of failure of the system S over time period Δt ; Z_S^* is the maximum allowable value of the cost of repairing the system S .

The task of planning is to find such a plan for the repair volume V of the system S that the probability of no-failure operation $R_S(\Delta t, V)$ over time period Δt deviates least from the maximum permissible value $R_S^* = 1 - Q_S^*$. At the same time, the costs Z_S of implementing the plan should not exceed the maximum permissible value Z_S^* . In a symbolic form, the problem can be written as follows: it is required, for given values $\Delta t, R_S^*$, to find V so that

$$\omega^* = \min_V [R_S[\Delta t, V] - R_S^*], \quad \omega^* \geq 0, \quad Z_S \leq Z_S^*. \tag{1}$$

For the mathematical formulation of the problem, it is necessary to determine the maximum permissible value R_S^* and the volume of repair V .

The value R_S^* can be obtained by calculating the reliability indicator of the system S , based on its structure and the reliability indicators $r(a_i)$ of the elements $a_i, i=0, 1, 2, \dots, I$, taken from the nominal data of equipment. Also, the value R_S^* can be determined by applying expert estimates.

To determine the repair volume V , the specific value of the reliability indicator δr_i of the element $a_i, i=0, 1, 2, \dots, I$ is introduced as the value of increase of the reliability indicator of the element a_i per one cost unit.

Let $r_i(t_0)$ be the RF of the element a_i over its operating time $\Delta^* t$ preceding time t_0 . As a result of repairs in the volume of costs c_i , the element can obtain the RF $r_i^*(t_0)$ over time period $\Delta^* t$. The difference between these RFs at time t_0 , divided by the value of incurred costs c_i , determines the value of the specific RF $\delta r_i(t_0)$ of the element a_i :

$$\delta r_i(t_0) = (r_i^*(t_0) - r_i(t_0)) / c_i = \Delta r_i(t_0) / c_i, \quad i=0, 1, 2, \dots, I. \tag{2}$$

In this formula, $r_i(t_0)$ and c_i are assumed to be known quantities and $r_i^*(t_0), i=0, 1, 2, \dots, I$ are unknown quantities. The specific value of the RF $\delta r_i(t_0)$ can be estimated as follows. Suppose that the element a_i is replaced with an identical new element that has not spent its reliability indicator over time period $\Delta^* t$. Therefore, it is assumed that its RF $r_i^*(t_0) = 1$ over time period $\Delta^* t$. Let the cost of installing a new element a_i equal z_i . Then the specific RF of the new element (the value of the increase in RF per unit cost) will be $\delta r_i(t_0) = 1 / z_i$.

Therefore, if the costs c_i of repairing the element will be z_i , it will mean replacing the element a_i with the RF $r_i(t_0)=0$ with an identical element a_i with the RF $r_i^*(t_0) = 1$. Then, according to expression (2), the value of the RF increase as a result of replacing the element a_i will be $\Delta r_i(t_0) = r_i^*(t_0) - r_i(t_0) = 1 - 0 = 1$. If the repair is carried out with costs c_i , then the value of the RF increase over time period $\Delta^* t$ is determined by the ratio: $\Delta r_i(t_0) = c_i \cdot \delta r_i(t_0) = c_i / z_i$, that is, it is assumed that the increase in the RF of the element during repair at

time t_0 is directly proportional to the costs of repair c_i , which determines the repair volume v_i of the element a_i . Then the performed repair volume V of the system S will be determined by the sum $V = \sum_{i=0}^I v_i = \sum_{i=0}^I c_i$. It is assumed that the costs of repairing the elements c_i , $i=0, 1, 2, \dots, I$ are known and can be measured in various units, for example, in monetary units or in labor costs.

The RF $R_S(t_0)$ over time period Δ^*t of the system S depends on the scheme of its structure and the RF $r_i(t_0)$ over time period Δ^*t depends on its elements a_i , $i=0, 1, 2, \dots, I$. Since the RF values over time period Δ^*t of the systems $S_0, S_1, S_2, \dots, S_M$ are computable, the FBG $R_S(t_0)$ over time period Δ^*t of the system S will be computable as well. To simplify the notation and emphasize that the RF of the system S is a function of the reliability indicators $r_i(t_0)$ of the elements a_i , the notation $R_S(t_0)=\varphi(r_i(t_0))$, $i=0, 1, 2, \dots, I$ is used.

As a result of repairs, within the allotted time, the RF increment $\Delta R_S(t_0)$ over time period Δ^*t of the system S with the RF increments of its elements a_i , $i=0, 1, 2, \dots, I$, $\Delta r_i(t_0)$ over time period Δ^*t , can be written as follows:

$$\Delta R_S(t_0) = \varphi(r_0(t_0) + \Delta r_0(t_0), r_1(t_0) + \Delta r_1(t_0), \dots, r_I(t_0) + \Delta r_I(t_0)) - \varphi(r_0(t_0), r_1(t_0), \dots, r_I(t_0)).$$

Due to the fact that the RF $R_S(t_0)$ over time period Δ^*t of the system S without the application of repair costs will be $R_S(t_0)=\varphi(r_0(t_0), r_1(t_0), \dots, r_I(t_0))$, as a result of the application of the costs for the repair of the elements a_i , $i=0, 1, 2, \dots, I$, we will receive the RF $\hat{R}_S(t_0)$ over time period Δ^*t of the system S in the form

$$\hat{R}_S(t_0) = R_S(t_0) + \Delta R_S(t_0) = \varphi(r_0(t_0) + c_0 \delta r_0, r_1(t_0) + c_1 \delta r_1, \dots, r_I(t_0) + c_I \delta r_I), \tag{3}$$

since the RF increment of the elements a_i , $i=0, 1, 2, \dots, I$, over time period Δ^*t will be $\Delta r_i(t_0) = c_i \cdot \delta r_i(t_0)$.

In formula (3), the values $\delta r_i(t_0)$, $i=0, 1, 2, \dots, I$ determine the specific RF over time period Δ^*t of the elements, which are calculated by the formula $\delta r_i(t_0) = 1/z_i$, and the unknown repair costs c_i , $i=0, 1, 2, \dots, I$ can take any real non-negative values.

The result of the repair carried out at time t_0 will affect the RF $r_i(\Delta t)$ over time period $\Delta t = t - t_0$ of the elements a_i , $i=0, 1, 2, \dots, I$, and the RF $\hat{R}_S(\Delta t)$, over time Δt of the system S . Denoting $\hat{R}_S(\Delta t) = R_S(\Delta t)$, we get

$$R_S(\Delta t) = \varphi[(r_0(t_0) + c_0 \delta r_0) \cdot r_0(\Delta t), (r_1(t_0) + c_1 \delta r_1) \cdot r_1(\Delta t), \dots, (r_I(t_0) + c_I \delta r_I) \cdot r_I(\Delta t)]. \tag{4}$$

In expression (4), the RF $R_S(\Delta t)$ of the system S over time period Δt depends on the RF values $r_i(t_0)$ over time Δ^*t of the elements a_i at time t_0 , on the laws of the RF $r_i(\Delta t)$ over time period Δt of the elements a_i ; on the costs c_i incurred during the repair of the elements a_i ; on the specific RF $\delta r_i(t_0) = 1/z_i$, $i=0, 1, 2, \dots, I$, that is, $R_S(\Delta t)$ is a function of many variables $R_S(t_0, t) = \varphi(c_i, \delta r_i, r_i(\Delta t))$, $i=0, 1, 2, \dots, I$.

Using (4), problem (1) can be formulated as follows: it is required to find such a distribution of costs c_i , $i=0, 1, 2, \dots, I$ that

$$\omega^* = \min_{c_i} [\varphi[(r_0 + c_0 \delta r_0) \cdot r_0(\Delta t), \dots, (r_I + c_I \delta r_I) \cdot r_I(\Delta t)] - R_S^*], \quad \omega^* \geq 0, \quad \sum_{i=0}^I c_i \leq Z_S^*. \tag{5}$$

Thus, in problem (5), the uncertainty of problem (1) is eliminated: the values R_S^* and V are determined. The desired repair plan, as follows from (5), will consist of the values $c_i = C_i$, $i=0, 1, 2, \dots, I$.

If one supposes that the events of failures of the systems $S_0, S_1, S_2, \dots, S_M$ are independent, problem (5) can be solved for each of the systems $S_0, S_1, S_2, \dots, S_M$ separately, and then the results can be combined, or the problem can be solved immediately for the entire system S . Such solutions may be different [4].

Repair Planning Problem Solution

The RF function $R_S(\Delta t) = \varphi(c_i, \delta r_i, r_i(\Delta t))$ is continuous and differentiable in time t in the domain of its definition as it is continuous and differentiable by the parameters of c_i , $i=0, 1, 2, \dots, I$. It is assumed that the maximum permissible values R_S^* and Z_S^* are such that a solution to problem (5) exists. However, as is easy to see, considering the serial connection of two elements, it is not unique.

Problem (5) is solved using the coordinate descent method. The efficiency of descent depends on the ratio between the costs of repairing the elements and the magnitude of the increase in the system reliability indicator for these costs. The descent is carried out along that coordinate $c_j, j=0, 1, 2, \dots, I$, for which at the end of the interval $[t_0, t]$ the partial derivative of the RF $R_S(\Delta t) = \varphi(c_i, \delta r_i, r_i(\Delta t))$ with respect to the parameters of c_i gets the highest value at the end of the interval $[t_0, t]$: $\partial\varphi(\Delta t)/\partial c_j = \max_i |\partial\varphi(\Delta t)/\partial c_i|$.

Since for a complex system it is practically impossible to compose the RF $R_S(\Delta t) = \varphi(c_i, \delta r_i, r_i(\Delta t))$ in analytical form, the values of its partial coordinate derivatives $c_i, i=0, 1, 2, \dots, I$ are calculated by the approximate formula $\partial\varphi(\Delta t)/\partial c_i \approx \varphi(\dots, c_i + \Delta c_i, \dots) - \varphi(\dots, c_i, \dots) / \Delta c_i$, where Δc_i is the value of the applied costs for the repair of the element $a_i, i=0, 1, 2, \dots, I$.

The value of the partial derivative $\partial\varphi(\Delta t)/\partial c_j$ can be interpreted as the partial specific RF of the system S along the coordinate c_j . It is the value of the change in the RF over time period Δt of the system S per unit of applied costs. Naturally, the descent along the coordinate c_j having the greatest value of the partial specific RF $\partial\varphi(\Delta t)/\partial c_j$ of the system S will be most effective. With the same costs for the repair of the elements, the costs (volume of repair) c_j of the element are selected, the repair of which increases most the RF over time period Δt of the system S . The coordinate descent is carried out until a solution to problem (5) is obtained.

Since it was assumed that the repair costs c_j can be any real non-negative numbers, the solutions to problem (5) may require interpretation in terms of the traditional discipline of repairs – capital, average, current, maintenance. If there is information on the costs of these types of repairs, the solution to problem (5) in these terms can be interpreted automatically.

Connection of Repair Plans with the Safety Assessment of a NPU with the Estimates of the Gamma-percentile Equipment Life

The system repair plan is connected with the safety assessments of a NPU. One of the ways to calculate the probability of a radiation accident is to construct a set of chains of events consisting of the occurrences of the initial events and failures of the systems that handle them. Let $H_0, H_1, H_2, \dots, H_M$ be independent events determined by the failures of the systems $S_0, S_1, S_2, \dots, S_M$, which are a chain of events consisting of the occurrence of the initial event H_0 (failure of the system S_0) and the way of development of an accident (failures of the systems S_1, S_2, \dots, S_M). The probabilities of system failures over time period Δt can be computed, for example, using nominal data of system elements. Then the probability of a radiation accident $P(A)$ of this chain of events will be defined as the product of the probabilities of system failures $P(A) = Q(S_0) \cdot Q(S_1) \cdot \dots \cdot Q(S_M)$.

The repair plan $c_i=C_i, i=0, 1, 2, \dots, I$, obtained as a result of solving problem (5), will change the probabilities of system failures $Q(S_0), Q(S_1), Q(S_2), \dots, Q(S_M)$ over time period Δt for new probabilities of system failures $Q_1(S_0), Q_1(S_1), \dots, Q_1(S_M)$ over time period Δt . Then the probability of an accident $P(A)$ associated with a chain of events will acquire a new value $P_1(A) = Q_1(S_0) \cdot Q_1(S_1) \cdot \dots \cdot Q_1(S_M)$. This determines the connection between the system repair plans and the NPU's safety assessments.

The solutions to problem (5) also determine the assessments the useful life of NPU systems equipment. Indeed, since the constraint on the maximum permissible value of the system reliability indicator R_S^* is determined, then there is such a plan for the system repair on a sequence of annual operation intervals that will not satisfy the conditions of problem (5) without replacing the non-recoverable equipment or non-recoverable components of recoverable equipment.

In other words, when planning the repairs $c_k^i = C_k^i$, where the index $k=1, 2, 3, \dots$ denotes the interval number, and the index $i=0, 1, 2, \dots, I$ denotes the number of the element a_i it is necessary to solve the inequality

$$R_S[(c_k^i = C_k^i(\Delta t_k))] \leq R_S^* \tag{6}$$

relative to the variables Δt_k , which represent the duration of one k time interval.

If the value of the interval $\Delta t = \text{const}$, then, in this case, $\Delta t_k = k \cdot \Delta t$ is the duration k of the time intervals on each of which there is a solution to problem (5) and, therefore, inequality (6). Suppose that on the time interval $k+1, R_S[(c_k^i = C_k^i(\Delta t_k))] > R_S^*$. Then there is such an unrecoverable element a_i in the repair plan for

the time interval $k+1$, the replacement of which provides a solution to problem (5). Then the duration $\Delta t_k = k \cdot \Delta t$ of the system's serviceable condition with the probability $\gamma = R_s^*$ will be the gamma-percentile life of the element a_i to be replaced.

Conclusions

NPP accidents have unacceptable consequences for people and their environment. One of the ways to reduce the likelihood of accidents and the scale of their consequences is to calculate risk assessments in order to manage them on the basis of this knowledge, while improving the measures to ensure the safety of an NPU. Therefore, the problems related to the risk of their operation are studied comprehensively. An important aspect of this problem is reflected in the organizational and technical activities of maintenance and repair, part of which is planning the volume of repairs of a NPU, monitoring the spending of the equipment useful life, and its timely replacement.

For the planning of repairs, a method of calculating the system reliability indicator is used, based on the graphological scheme of the system, consisting of basic structures with information images recognizable on a computer and with computable reliability indicators. A schematic compression process is applied, which makes it possible to evaluate the reliability indicator of a system with a large number of elements.

The solution of the problem of planning repairs, based on the mathematical modelling of the system reliability indicator, allows planning repairs based on taking into account their structure and maximum permissible values of reliability indicators. It is shown that there is a relationship between the system repair plan, the safety assessment and the gamma-percentage life of the NPU equipment. The presented approaches to planning system equipment repairs and assessing their gamma-percentage resources can be used to solve problems of extending the operation of NPUs.

The software, oriented to the application of the presented approaches in practice, can be included, as an independent software complex, in the information and analytical systems that ensure the solution of problems of effective management of the maintenance and repair system of NPUs.

References

1. Rast, J. & Weevir, L. (1980). *Bezopasnost yadernoy energetiki* [Safety of nuclear energy]. Moscow: Atomizdat, 183 p. (in Russian).
2. Ostreykovskiy, V. A. (1994). *Stareniye i prognozirovaniye resursa oborudovaniya atomnykh stantsiy* [Aging and forecasting of the resource of equipment of nuclear power plants]. Moscow: Atomizdat, 288 p. (in Russian).
3. Polovko, A. M. & Gurov, S. V. (2006). *Osnovy teorii nadezhnosti* [Basics of reliability theory]. St. Petersburg: BKHV-Peterburg, 704 p. (in Russian).
4. Venttsel, Ye. S. (1972). *Issledovaniye operatsiy* [Operations research]. Moscow: Sovetskoye radio, 550 p. (in Russian).
5. Zevin, L. I. & Krol, H. H. (2019). Calculation of indicators of reliability of technical systems by the typical structural scheme method. *Journal of Mechanical Engineering*, vol. 22, no. 2, pp. 53–59. <https://doi.org/10.15407/pmach2019.02.053>.

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Оптимізація планів ремонтів систем та оцінка ресурсу обладнання атомних станцій

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Наведені метод планування на електронно-обчислювальних машинах обсягів ремонтів систем енергоблоку атомної станції і метод обчислення його гамма-відсоткового ресурсу. Планування здійснюється на основі прогнозування показника надійності – ймовірності безвідмовної роботи за певний час, а гамма-процентний ресурс обладнання визначається шляхом розв'язання відповідних рівнянь. Розглянуті завдання пов'язані з важливою проблемою енергетики – продовженням термінів експлуатації енергоблоків. Її важливість визначена, в основному, економічною доцільністю – дешевше оцінити ресурс енергоблоку і на цій дослідницькій основі продовжити його експлуатацію, ніж створити нову установку. Також показано, що розрахунок ймовірності радіаційної аварії на енергоблоці пов'язаний з результатами планування ремонтів його систем, з оцінками ресурсу

обладнання. Формулюється задача оптимізації: потрібно знайти такий план обсягів ремонтних робіт системи, щоб за обмежених витрат на її ремонт показник надійності системи за час заданої тривалості найменш відхилявся від гранично допустимого значення. Розв'язання задачі ґрунтується на розрахунку структурної надійності системи. Будується графологічний образ системи у вигляді композиції графологічних образів типових структур. Після обчислення показника надійності типових структур останні замінюються окремими структурними елементами, що дає можливість спростити в обчислювальному сценарії вихідний графологічний образ системи і обчислити показник її надійності. Визначення плану ремонту здійснюється шляхом застосування версії покоординатного методу оптимізації. Для оцінки гамма-процентного ресурсу приймається модель, в якій відновлювані компоненти обладнання мають необмежений ресурс, хоча, звичайно, «старішають», а невідновлювані компоненти витрачають свій ресурс до рівня, коли їх заміна стає обумовленою порушенням вимоги до гранично допустимого значення показника надійності системи. Оцінка гамма-процентного ресурсу обладнання здійснюється шляхом планування ремонтів системи на послідовності інтервалів, в межах яких енергоблок виробляє енергію щорічно.

Ключові слова: атомна станція, енергоблок, система, план ремонту, ресурс, оптимізація.

Література

1. Безопасность ядерной энергетики / под ред. Дж. Рагга и Л. Уивира: пер. с англ. М.: Атомиздат, 1980. 153 с.
2. Острейковский В. А. Старение и прогнозирование ресурса оборудования атомных станций. М.: Энергоатомиздат, 1994. 288 с.
3. Половко А. М., Гуров С. В. Основы теории надежности. С. Пб: БХВ-Петербург, 2006. 704 с.
4. Вентцель Е. С. Исследование операций. М.: Сов. радио, 1972. 550 с.
5. Zevin L. I., Krol H. H. Calculation of indicators of reliability of technical systems by the typical structural scheme method. *J. Mech. Eng.* 2019. Vol. 22. No. 2. P. 53–59. <https://doi.org/10.15407/pmach2019.02.053>.