NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 5(1): 81–87
DOI 10.3897/nucet.5.34296

Research Article

Reliability of the RBMK-1000 coolant flow measurement system

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Academic editor: *Yury Kazansky* ♦ **Received** 10 November 2018 ♦ **Accepted** 29 January 2019 ♦ **Published** 11 April 2019

Citation: Pereguda AI (2019) Reliability of the RBMK-1000 coolant flow measurement system. Nuclear Energy and Technology 5(1): 81–87. https://doi.org/10.3897/nucet.5.34296

Abstract

An analysis of statistical data of diagnostic measurements of two parameters determining the performance of the RBMK-1000 SHADR-8A flowmeters – the minimum value of the negative amplitude half-wave at the transistor flow measuring unit (TIBR) input and the mean-square deviation over the flowmeter ball rotation period – made it possible to develop a mathematical model of the flowmeter parametric reliability. This mathematical model is a random process, which is a superposition of two delayed renewal processes. Studying the flowmeter operational reliability model provides an exponential estimate of the probability that the parameters determining the flowmeter performance will not exceed the specified levels. Using the Bernoulli scheme and the probability-estimating relationship for the flowmeter performance parameters, it is possible to calculate the probability of failure-free operation of both a single reactor quadrant and the coolant flow measurement system. In addition, it becomes possible to estimate the quadrant failure rate. Important for practice is the possibility of predicting the number of failed flowmeters depending on the system operation time. An indicator of the system reliability can be the average number of failed flowmeters, the relation for which is given in the paper. All the research results were obtained without any additional assumptions about the random values distribution laws.

The obtained results can be easily generalized for the cases when the vector dimension of the determining parameters is greater than two. The use of the results of this study is illustrated by calculated quantitative values of the flowmeter parametric reliability indicators and the coolant flow measurement system.

Keywords

Parametric reliability; coolant flow measurement system; random variables; time between failures; random process; mathematical time expectation; distribution function; exponential estimate

Introduction

Modern technical systems consist of a large number of elements and are largely automated. The increased complexity of systems has led to increased requirements for their quality and, as a result, to a sharply increasing interest in solving theoretical reliability problems that can provide a quantitative measurement of reliability indicators. Various influences accumulated by a system leads to the evolution of its indicators (changes in parameters),

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2018, n. 3, pp. 148-159.

as a result of which a system can pass from normal operation to other qualitative states. Measures to ensure system reliability include: (1) detecting all types of possible transitions from one state to another; (2) determining their causes and consequences; and (3) planning activities to limit the number of failures of technical systems to an acceptable level. Of course, estimating quantitative system reliability indicators is only a small part of the entire complex of practical activities on ensuring the required reliability level, but without a thorough probabilistic analysis of the system operation process it is impossible to elaborate any reasonable decisions.

Problem definition

The reliability indicators of any product can be obtained by studying the behavior of one or several its parameters, which will fully reflect this product quality. If the processes of parameter changes are observable, predictable and manageable, it becomes possible to plan measures to prevent product failures. Failures occur as a result of deviations of the determining parameters from their initial (nominal, calculated) values. Failures are manifested as parameters' overrunning the acceptable region (i.e., the area of normal operation).

The SHADR-8A flowmeters are designed to measure the volumetric water flow in process pipelines and pipelines of the control and safety system channels of the RBMK-1000 and RBMK-1500 reactors at nuclear power plants. Due to a failed flowmeter, this channel operation is stopped until its operability is restored during routine maintenance. A reactor emergency system contains 240 of more than 1600 flowmeters (Augutis et al. 2002, Dollezhal and Yemelyanov 1980). If 10 or more sensors fail in one reactor quadrant, the reactor is shut down, since its further operation may lead to an emergency situation.

The condition of coolant flowmeters is assessed by the results of measurements of parameters determining their performance, immediately prior to routine maintenance. If the diagnostic parameters deviate from the acceptable values, the corresponding flowmeter is replaced. The criterion for a gradual failure of a system (product) is a deviation of parameters determining its performance from a specified range of values.

As is shown in (Gertsbakh and Kordonsky 1966), based on the mathematical theory of random variables, it is possible to find out how the initial quality, wear rate variation and simultaneous effect of several causes for failures affect a product. To solve the problem of predicting a product's reliability, models are proposed in (Druzhinin 1977) that make it possible to calculate the failure probabilities for various distribution laws of the initial load and initial load-carrying capacitance. If there are results of periodically measured parameters, the use of such data provides a better description of a product's operation process. The article presents methods for predicting, estimating and ensuring parametric reliability at the stages of design, manufacture, testing, and operation based on the general concept proposed in (Pronikov 2002).

A mathematical reliability model in many cases is the mathematical theory of continuous Markov random processes or the theory of Wiener processes. The determining parameter change is considered as a particle walk along the lattice with a time step Δt and a spatial coordinate step $\delta = (\Delta t)^{1/2}$. During the time $t = n\Delta t$, a particle receives the displacement $x(t)$ equal to the sum of n steps $\delta = \Delta x_k$ along the spatial coordinate. The probability of a particle receiving the displacement δ in one step is ½. When $\Delta t \to 0$, the transition probability of the considered random walk process tends to the Gaussian transition probability density. The Brownian process trajectory is quite cut ($\Delta x \sim (\Delta t)^{1/2}$, $\Delta x/\Delta t \to \pm\infty$), but it is continuous and with probability one is not differentiable at any point (Rytov 1976). The problem of parametric reliability in this case is set as follows.

Let the random process $\xi(t)$ take on a value of x at the initial time $t_0 = 0$. The question is: what is the probability that the random process $\xi(t)$ will for the first time reach the specified lower bound $a < x$, or the upper bound $b > x$, or just a bound if only one of them is specified?

Experimental studies confirm that Markovian models describe well the changes in parameters caused by the degradation processes of aging.

However, in order to apply these mathematical models, it is necessary to make sure that the actual system operation process is Markovian, and then, using the system operation process trajectories, evaluate the coefficients of diffusion and the Kolmogorov equation drift (Pugachev and Sinitsyn 2000, Prokhorov and Rozanov 1987, Korolyuk et al. 1978, Gikhman and Skorokhod 1968). The difficulties of solving such partial differential equations (or stochastic differential equations) are well known and, for this reason, other methods are being developed for calculating parametric reliability indicators.

For example, in (Abramov and Katueva 2005), the problem of designing analog technical systems is considered, taking into account the requirements for parametric reliability at various levels of initial information about parametric perturbances. Since a vector random process is considered, the authors of this paper propose to parallelize the process of finding a solution using statistical test methods.

The solution to the problem of maintaining uniform reliability and condition levels of the entire coolant flow measurement system is described in (Augutis et al. 2002). The technique is based on predicting the number of replaceable SHADR flowmeters for the overhaul period. For this end, the Monte Carlo numerical methods were used.

Since the purpose of the work is to estimate the coolant flow measurement system reliability in RBMK type reactors taking into account the system structure and failure criterion, it can be stated that the Bernoulli scheme can be used for a mathematical model of the system quadrant reliability. According to this scheme, the probability of occurrence of k events with n independent tests is defined as $P_{k,n}(t) = C_n^k P^k(t)(1 - P(t))^{n-k}$, where $P(t)$ is the probability of the failure-free flowmeter operation, which is to be estimated according to the results of diagnostic measurements. To estimate the probability of the failure-free flowmeter operation $P(t)$, we shall use the cumulative reliability model discussed in (Pereguda and Andreev 2007a, Pereguda and Andreev 2007b, Pereguda and Soborova 2006, Pereguda and Belozerev 2017).

For further presentation, we shall introduce the necessary notations and assumptions presented in more detail in (Pereguda and Belozerev 2017). Let the parameter values determining its performance be measured at times $t_0 \le t_1 \le t_2 \le \ldots$, and $\tau_i = t_{i+1} - t_i$, where $i > 0$, $t_0 = 0$. Thus introduced, the random variables τ_i are the lengths of time intervals between adjacent measurements of the determining parameter.

Note that if the random variable is equal to $\tau_0 = t_1 - t_0$, then $F(t) \ne F_1(t) = P(\tau_1 \le t)$, i.e., the τ_0 value is distributed differently than all other random variables τ_i, $i = 1, 2, \ldots$. Next, we shall assume that the functions $F(t)$ and $F_1(t)$ are not arithmetic and each of these random variables has finite first two mathematical moments, i.e., $M\tau < \infty$ and $D\tau < \infty$. The sequence $\{\tau_i, i \ge 1\}$ is usually called *the delay renewal process*, which we shall further denote as $\{T_x\}_{x>0}$ (Loehv 1962).

The T_x value is the random time between failures of a product at a given determining parameter value of x, which is defined as

$$T_{N_x} = \begin{cases} \sum_{i=0}^{N_2(x)} \tau_i, & N_2(x) = 1,\ 2,\ \cdots \\ 0, & N_2(x) = 0 \end{cases}, \tag{1}$$

where $N_2(x) = N_x$ is the random number of the determining parameter measurements made for the time before its crossing a specified level x.

Let us consider the second random process corresponding to the determining parameter change. Let γ_0 denote a random initial value of the parameter determining a product's performance, which is assumed to be independent of the sequence $\{\tau_i, i \ge 1\}$ and have the arbitrary distribution function $G_0(y) = P(\gamma_0 \le y)$. Let us introduce random variables γ_i, i.e., the determining parameter values measured at the timepoints t_i, $i = 1, 2, \ldots$. Thus, the random process $\{\gamma(t)\}_{t>0}$ at the set T of the real straight line is a process with independent increments, since for any values of $t_0 \le t_1 \le t_2 \le \ldots$ at the set T, the increments $\Theta_k = \gamma(t_{k+1}) - \gamma(t_k)$, $k = 0, 1, 2, \ldots$ are independent random variables. It is natural to assume that the random increments Θ_i, $i = 1, 2, \ldots$ are distributed with the same function $G(x)$.

The sequence $\{\Theta_i, i = 1, 2, \ldots\}$ generated by the functions $G_0(x) = P(\Theta_0 \le x) = P(\gamma_0 \le x)$ and $G_i(x) = P(\Theta_i \le x)$ will also be a delayed renewa l process, which will be further denoted as $\{\Theta\}_{t>0}$. Suppose that the mathematical expectations and variances of the random variables Θ_0 and Θ must satisfy the conditions $M\Theta_0 < \infty$, $M\Theta < \infty$, $D\Theta_0 < \infty$, $D\Theta < \infty$.

It is obvious that the total value of the parameter that determines a product's performance (accumulated load) at the time it crosses the specified bound can be determined by the equality

$$\Theta_{N_t} = \begin{cases} \sum_{i=0}^{N_1(t)} \Theta_i, & N_1(t) = 0,\ 1,\ 2,\ \ldots \\ 0, & N_1(0) < 0 \end{cases}, \tag{2}$$

where $N_1(t) = N_t$ is the random number of determining parameter measurements that occurred during the time $[0, t]$ or the number of process renewal cycles $\{\tau_i, i \ge 1\}$.

The purpose of the work is to construct a mathematical model of a product's parametric reliability and, based on the model analysis, to obtain exponential estimates of the probability that the determining parameters of SHADR-8A coolant flowmeters do not go beyond the specified performance bounds. It is also required to estimate the probability of failure-free operation of the flowmeters, their failure rate, the average number of failed RU quadrant flowmeters, and also, using the Bernoulli scheme, to estimate the probability of failure-free operation of the RBMK-1000 coolant flow measurement system.

Main results

When solving the problem, it is necessary first of all to estimate the probability that the product determining parameters are not beyond the specified performance bounds. For this purpose, we shall use Relations (1) and (2), which are sums of independent random variables, while the number of terms of these sums is random. In these relations, Θ_i and τ_i are sequences of identically distributed independent random variables with mathematical expectations $M\Theta_0$, $M\Theta$, $M\tau$ and variances $D\Theta_0$, $D\Theta$, $D\tau$. It is assumed that the random variable $N_1(t) = N_t$ is independent of Θ_i, and $N_2(x) = N_x$ is independent of τ_i. Let us calculate the first two moments, one of which is the initial moment of the first order (mathematical expectation), and the other one is the central moment of the second order (variance) of the processes $\{\Theta_t, t \ge 0\}$.

Before calculating the moments of the random variable Θ_t, it is necessary to write the Laplace–Stieltjes transformation. Since all the random variables in (2) are independent and equally distributed (perhaps, except for Θ_0), the desired transformation can be written as:

$$\Theta^*(s) = M\exp(-s(\Theta_0 + \sum_{i=1}^{N_1} \Theta_i)) =$$
$$= M\exp(-s\Theta_0)\sum_{i=1}^{n} M\exp(-s\Theta n)P(N_1 = n),$$

where the sum on the right-hand side is the generating function of the random variable Θ [8, 16]. Differentiating the function $\Theta^*(s)$ with respect to the variable s and inserting $s = 0$ into the resulting derivative, we obtain the mathematical expectation Θ_t:

$$M\Theta_t = M\Theta_0 + MN_1 \cdot M\Theta, \quad (3)$$

where $MN_1 = H_1(t)$ is the process renewal function $\{\Theta_t, t \geq 0\}$.

When calculating the variance of the random variable Θ_t, it is necessary to twice differentiate the function $\Theta^*(s)$ with respect to the variable s and subtract the square of Relation (3), as a result of which we obtain

$$D\Theta_{N_1(t)} = D\Theta_0 + (M\Theta)^2 DN_1(t) + H_1(t)D\Theta. \quad (4)$$

Using the strengthened elementary renewal theorem (Bajkhelt and Franken 1988), we shall rewrite the resulting Relation (3) again:

$$\lim_{t\to\infty} M\Theta_{N_1(t)} = M\Theta_0 + \left(t/M\tau + \sigma_\tau^2/2(M\tau)^2 - 0.5\right)M\Theta. \quad (5)$$

It is worth reminding that all the results of the renewal theory obtained asymptotically are valid for each initial distribution $F_1(t)$. For this reason, in Relation (5) and further, the random variable t_1 will be absent:

$$\lim_{t\to\infty} D\Theta_{N_1(t)} = \sigma_{\Theta_0}^2 + (M\Theta)^2\, t\sigma_\tau{}^2/(M\tau)^3 + \left(t/M\tau + \sigma_\tau^2/2(M\tau)^2 - 0.5\right)\sigma_\Theta^2. \quad (6)$$

If the limiting value of the determining parameter change is specified,

$$x = M\Theta_{N_1(T_\Theta)},$$

it is possible to obtain from (6) the average time between failures of a product T_Θ before the specified bound is crossed:

$$T_\Theta = \left((M\Theta_{N_1(T_\Theta)} - M\Theta_0)/M\Theta - M\tau^2/2(M\tau)^2 + 0.5\right)M\tau\,. \quad (7)$$

Thus, using Relation (2) and the Laplace–Stieltjes transformation, we obtained the expectation and variance of the random variable Θt as well as the average time between failures of a product T before the specified performance bound is crossed.

It is much more difficult to solve the problem of calculating the probability of failure-free operation of a product affected by a periodically varying load. It proved to be impossible to calculate the probability of failure-free operation of a product operating in the above conditions, even under the assumption that all random variables have an exponential distribution. Therefore, there is a need to obtain relations that will make it possible to approximately estimate the probability that the determining parameter will cross the specified bound of a product's performance. Note that the normalized sum of a large number of independent random variables has a distribution that is close to the Gaussian one (Prokhorov and Rozanov 1987, Loehv 1962).

It is known (Loehv 1962) that exponential estimates are the best. As a rule, such estimates can be obtained from Chebyshev's inequality (Loehv 1962) of the form

$$P(L_t > x) \leq Mg(L_t)/g(x),$$

where L_t is the random accumulated load; $g(x)$ is the non-decreasing non-negative function defined on the interval $[0, \infty)$, and the function and its derivatives are continuous and differentiable in this neighborhood and $g(x) > 0$.

Suppose that the function $g(x) = \exp(\lambda x)$, where λ is a constant, then for any $s \geq 0$ we have

$$P(L_t > x) = P(\Theta_0 + \sum_{i=1}^{N_t}\Theta_i > x) \leq \exp(-\lambda x)\cdot M\exp(\lambda L_t). \quad (8)$$

The estimate of the mathematical expectation of a random variable is written as:

$$M\exp(\lambda L_t) \leq \exp(\lambda ML_t)\left(1 + 0.5\lambda^2\sigma_{L_t}^2 + 0.5\lambda^2\sigma_{L_t}^2\left((1-\lambda A/3)^{-1} - 1\right)\right),$$

where $|L_t - ML_t| \leq A$ (A is a constant). Assuming that $\lambda < 2/A$, we shall rewrite the estimate as:

$$M\exp(\lambda L_t) \leq \exp(\lambda ML_t)\left(1 + 0.5\lambda^2\sigma_{L_t}^2(1+\lambda A)\right) \leq \exp(\lambda ML_t)\exp(0.5\lambda^2\sigma_{L_t}^2(1+\lambda A)).$$

Inserting the obtained estimate of the random variable $M\exp(\lambda L_t)$ into (8), we obtain

$$P(L_t > x) \leq \exp(-\lambda x)\exp(\lambda ML_t)\exp(0.5\lambda^2\sigma_{L_t}^2(1+\lambda A)). \quad (9)$$

Estimate (9) can be somewhat improved, for which it is necessary to minimize the function

$$F(\lambda) = \exp(-\lambda x)\exp(\lambda ML_t)\exp(0.5\lambda^2\sigma_{L_t}^2(1+\lambda A)) = \exp(-\lambda x_a + \lambda^2 B + \lambda^3 B_1),$$

where $B = 0.5\sigma^2_{Lt} = 0.5(\sigma^2_0 + H(t)\sigma^2_\Theta + (M\Theta)^2\sigma^2_{Nt})$; $B_1 = 0.5A\sigma^2_{Lt} = 0.5A(\sigma^2_0 + H(t)\sigma^2_\Theta + (M\Theta)^2\sigma^2_{Nt})$; $x_a = x - M\Theta_0 - H(t)M\Theta$.

Then the value of the λ_0 parameter, which ensures the minimum of the function $F(\lambda)$, is optimal and is found as a solution of the algebraic equation $-x_a + 2\lambda_0 B + 3\lambda_0{}^2 B_1 = 0$. Therefore,

$$\lambda_0 = -B/3B_1 + B/3B_1(1 + 3Ax_a/B).$$

In this case, the probability of a product's failure-free operation in the conditions of discrete degradation will be determined by the relation:

$$P(\Theta_0 + \sum_{i=1}^{N_t}\Theta_i \leq x) \geq 1 - \exp(-\lambda_0 x_a + \lambda_0^2 B + \lambda_0^3 B_1),$$

where B, B_1, λ_0 and x_a are the values entered earlier.

If the value of $3Ax_a/B$ is small, the λ_0 parameter can be written as:

$$\lambda_0 \approx -B/3B_1 + B/3B_1(1 + 3B_1x_a/2B^2) = x_a/2B_1.$$

In this case, the estimate of the probability of a product's failure-free operation will take a simpler form:

$$P(\Theta_0 + \sum_{i=1}^{N_t} \Theta_i \le x) \ge 1 - \\ -\exp(-x_a^2/4B(1 - x_a B_1/2B^2)). \quad (10)$$

Estimate (10) is a pessimistic estimate of the probability of a product's failure-free operation under the influence of a periodically varying load. Note that the estimate is calculated quite simply and provides accuracy that is sufficient for practical use.

Statistical material for measuring the control parameters of the flowmeters makes it possible to determine the predicted value of the average time between failures before any of the determining parameters crosses the specified level and calculate the quantitative values of the reliability indicators of both the flowmeters and coolant flow measurement system. Thus, the coolant flow measurement system of RBMK type reactors is a rather cumbersome, consisting of 240 homogeneous elements, each of which can be in one of three possible conditions, when

- both determining parameters has not reached the specified levels;
- the first determining parameter has crossed the specified level;
- the second determining parameter has crossed the specified level.

Since random processes corresponding to changes in the determining parameters are independent, the task of calculating the reliability indicators of the coolant flowmeters is somewhat simplified, but it also becomes necessary to consider two problems of estimating the flowmeter reliability indicators for each of the determining parameters separately.

For the analysis, we took the data obtained as a result of annual measurements (from 1999 to 2013) for 50 SHADR-8A flowmeters. The analysis of statistical data obtained from diagnostic measurements made it possible to estimate the mathematical moments of the determining parameters, i.e., the minimum value of the negative amplitude half-wave at the input of the transistor flow measuring unit (TIBR) and the mean-square deviation over the flowmeter ball rotation period. The results of estimations of the mathematical moments necessary for further calculations are shown in Table 1 (for the first determining parameter of the flowmeter's performance) and in Tables 2, 3 (for the second determining parameter). They represent the values of the overhaul period expectation and variance.

Table 1. Mathematical expectation and variance of the minimum negative amplitude half-wave value at the TIBR input.

MA_{min}	DA_{min}	$MA_{min\,0}$	$DA_{min\,0}$
– 4.552	131.221	120.728	387.654

Table 2. Mathematical expectation and variance of the mean-square deviation over the flowmeter ball rotation period.

M_T	D_T	M_{T0}	D_{T0}
$1.588\cdot10^{-4}$	$4.568\cdot10^{-6}$	$7.067\cdot10^{-3}$	$1.988\cdot10^{-6}$

Table 3. Mathematical expectation and variance of the overhaul period.

M	*D*
8645	34590

Using the parameters of the random variables of the minimum negative amplitude half-wave at the TIBR input and those of the overhaul period (see Tab. 1, 3), we can calculate the probability that the first determining parameter of the flowmeter has not crossed the specified level.

The value of the specified level for the first parameter, which determines the performance of the flowmeter, is A_0 = 10 mV; the specified level for the second parameter is σ^2_0 = 0.02. Since the criterion for a coolant flowmeter's failure is the crossing of the specified performance level by any of the determining parameters, the probability of the flowmeter failure-free operation is $P(t) = P_1(t)P_2(t)$. The time dependences $P(t)$, $P_1(t)$ and $P_2(t)$ are shown in Fig. 1.

Note that the failure criterion for the reactor quadrant is failure of 10 or more flowmeters in one quadrant. Consequently, the quadrant will function properly if less than 10 out of 60 flowmeters are in failure mode. Let $F(t)$ denote the probability of the quadrant failure-free operation. To obtain the formula by which $F(t)$ can be calculated, the Bernoulli scheme can be applied (Pugachev and Sinitsyn 2000, Prokhorov and Rozanov 1987), then

$$F(t) = \sum^{9} C_{60}^i \times (1 - G(t))^i G(t)^{60-i}.$$

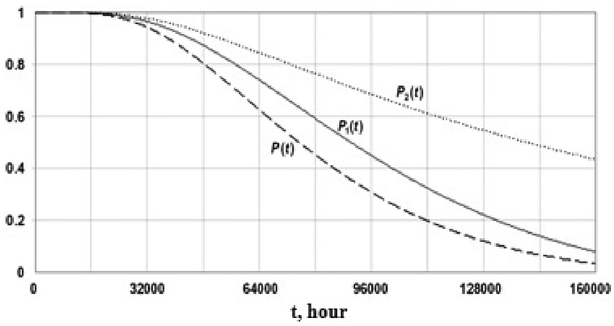

Figure 1. $P(t)$ is the SHADR-8A flowmeter failure probability; $P_1(t)$ is the probability for the first determining parameter to cross the specified performance level; $P_2(t)$ is the probability for the second determining parameter to cross the specified performance level.

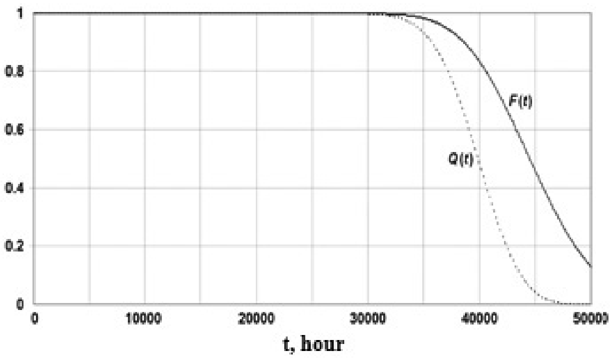

Figure 2. Probability of failure-free operation of the quadrant $F(t)$ and the coolant flow rate measurement system $Q(t)$.

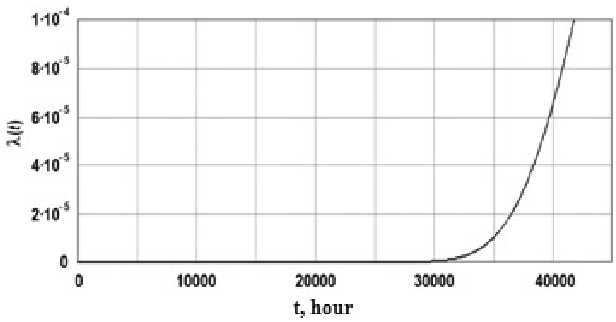

Figure 3. Failure rate diagram of the coolant flow measurement system quadrant.

Since a system failure occurs when at least one quadrant fails, the probability of failure-free operation $Q(t)$ of the reactor coolant flow measurement system is calculated by the formula $Q(t) = (F(t))^4$. The calculated probability of failure-free operation of the quadrant and the system is shown in Fig. 2

Along with the probability of failure-free operation of elements and systems, other reliability indicators play an important role in system analysis. For example, using the probability of failure-free operation of the quadrant $F(t)$, one can estimate the quadrant failure rate by the formula (by definition) $\lambda(t) = -dF(t)/dt \times 1/F(t)$. Figure 3 shows a graph of the quadrant failure rate versus time. The presented dependence fully reflects the features of the coolant flow measurement system quadrant operation.

Of practical interest is the possibility of predicting the number of failed flowmeters depending on the system operation time. Such an indicator of reliability can be the average number of failed flowmeters defined by the formula

$$Mk(t) = \sum_{i=0}^{60} iC_{60}^{i} \times (1 - P(t))^{i} P(t)^{60-i},$$

where $k(t)$ is the random number of failed flowmeters in the quadrant. A graph of $Mk(t)$ versus operation time is shown in Fig. 4. The above graphs clearly show that the timing of routine maintenance can be somewhat increased, especially since the quadrant failure rate with relatively short operation times is almost zero.

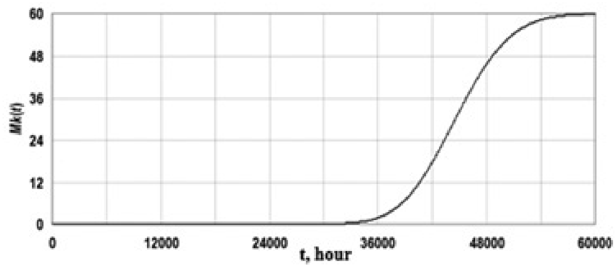

Figure 4. Forecast of the average number of failed flowmeters depending on the system operation time.

Conclusions

A mathematical model of parametric reliability has been developed that takes into account the statistical data of diagnostic measurements of two parameters that determine the efficiency of the SHADR-8A flowmeters of the RBMK-1000 reactor, i.e., the minimum value of the negative amplitude half-wave of the TIBR input signal and the mean-square deviation over the flowmeter ball rotation period. The mathematical model of the flowmeter reliability is a random process, which is a superposition of two delayed renewal processes. Studying the mathematical model of the coolant flowmeter reliability made it possible to obtain an exponential estimate of the probability that both parameters determining the flowmeter performance did not cross the specified levels. The probability of failure-free operation of one reactor quadrant and the coolant flow measurement system was found. The estimated quadrant failure rate and the relation for calculating the average number of failed flowmeters depending on the system operation time were obtained. In studying the mathematical model of parametric reliability, no assumptions were made about the random values distribution laws.

The author is grateful to V.L. Mironovich for his very useful comments and suggestions in the preparation of this paper.

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