ISSN 0040-5795, Theoretical Foundations of Chemical Engineering, 2021, Vol. 55, No. 4, pp. 657–662. © Pleiades Publishing, Ltd., 2021.
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Methodology for Calculating Regulatory Indicators of the Reliability of Elements of Restored Gas Analytical Systems for Monitoring Chemical Environmental Pollution According to Experimental Reference Data[1]

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Received February 15, 2021; revised March 22, 2021; accepted March 23, 2021

Abstract—A method has been developed for calculating the standard indicators of the reliability of elements of restored gas analytical systems for monitoring chemical pollution of the environment according to experimental reference data which differ in the simultaneous use of different results of processing experimental information obtained by the standard method, the interval method, and the Kaplan–Meier method, making it possible to test the reliability of small (cost-effective) samples of products under the conditions of their possible elimination from observation for reasons not related to failure. This methodology makes it possible to reduce the cost of development work and reduce the degree of uncertainty in the development of a maintenance and repair strategy not only for the specialized gas analytical systems under consideration, but also to solve the problems of optimal control of the operational reliability of a wide class of refurbished complex chemical and technical systems at the design stage.

Keywords: restoration, gas analytical systems, failure rate, reliability, chemical process systems

DOI: 10.1134/S0040579521040308

INTRODUCTION

Gas analytical monitoring systems (GAMSs) of hazardous chemical environmental pollution are complex control and measuring systems consisting of sampling and sample-preparation devices, gas analytical converters, and universal analytical instruments that function using special software and information support [1, 2].

GAMSs are intended for measuring one or several components of a gas mixture in technological streams of chemical process systems (CPSs), evaluating the efficiency of fuel combustion processes, and environmental control and ensuring high reliability and safety during the operation of CPSs [3, 4].

The most important organizational way to ensure the reliability of a CPS is to change the operating modes based on the strategy of maintenance and repair (MR) [5, 6]. Optimizing the maintenance and repair strategy is practically carried out by mathematical modeling [7, 8]. To verify the mathematical model of operational reliability control, experimentally substantiated data on the reliability of GAMS elements are required [9, 10].

METHODS OF A SYSTEM APPROACH TO PROCESSING EXPERIMENTAL INFORMATION ON RELIABILITY INDICATORS OF GAS ANALYTICAL ENVIRONMENTAL MONITORING SYSTEMS TAKING INTO ACCOUNT THE SURVIVAL INDICATOR

The primary material for determining the quantitative characteristics of the failure-free operation of GAMS elements are the results of planned reliability tests [11, 12]. Based on experimental data, it is possible to construct an empirical distribution function of failures and test the statistical hypothesis about its assumed theoretical distribution using goodness-of-fit

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[1] Special Issue Dedicated to the Jubilee of Academician of the RAS Valery P. Meshalkin.

criteria, for example, the Pearson, Kolmogorov–Smirnov test, etc.

In real conditions, the substantiation of the empirical distribution function and a calculation on its basis of the probabilistic indicators of failure-free operation is difficult due to the large resource costs [13, 14]. Therefore, in practice, it is more rational to use methods of statistical analysis of experimental data, which allow calculating the indicators of failure-free operation based on an analysis of small samples, the methods of analysis of which are combined under the general label *survival analysis* [15, 16].

The peculiarity of survival analysis methods is that they are designed to analyze censored primary data. Censored data make it possible to describe the behavior of the object under study, taking into account the fact that observation right before the onset of failure is not always possible [17].

Survival analysis methods make it possible to use all available experimental data, both censored and uncensored.

The main experimental characteristics calculated by methods of survival analysis are the function of survival $S(t)$ and risk-intensity function $h(t)$ [18–20]. For a statistical population, function $S(t)$ determines the likelihood of a product to remain in good working order for more than time $\boldsymbol{t}$ from the start of observation and $h(t)$ determines the moment potential per unit of time for the occurrence of a failure that can occur provided that the product is operational before time $\boldsymbol{t}$.

The practical method for describing the survival function, which consists of constructing a test-item uptime table, consists of three stages (the uptime table method):

Stage 1. Dividing the observation period into intervals.

Stage 2. Determining average values (over the observation interval) of the failure rate.

Stage 3. Determining the average (over the observation period) failure rate.

Let us consider the essence of the basic operations at each stage of the method. Stage 1 observation period T breaks down into equal spacing Δt by the Sturgess formula. At stage 2, the empirical function of instantaneous risk is determined $\hat{h}_i$ $\hat{H}_i$, which in this method serves as an estimate of the average failure rate $\overline{\lambda_i}$ on time interval Δt [18–20]:

$$\overline{\lambda_i} = d_i^0\left[0,5\left(x_i^0 - x_{i+1}^0\right)\Delta t\right]^{-1}, \tag{1}$$

where x_i^0, d_i^0 are the number of serviceable and failed products at the beginning of the *i*st interval. At stage 3, the average (over the observation period T) value of the failure rate is calculated as the arithmetic mean of the mean values (over the observation intervals) of the failure rate.

The second method is the moment method (the Kaplan–Meier method), which consists of three stages.

Stage 1. Calculating empirical probability $p(t_i)$ of surviving this moment.

Stage 2. Calculating an empirical estimate of the survival function $\hat{S}(t_i)$.

Stage 3. Calculating the average failure rate.

Let us consider the essence of the basic operations at each stage of the methodology. At stage 1, the time points are recorded t_i in which at least one product from the sample has failed and the empirical probability is calculated $p(t_i)$ to survive this moment according to the formula [18–20]:

$$p(t_i) = n(t_i)(v(t_i))^{-1}, \tag{2}$$

where $n(t_i)$, $v(t_i)$ are the number of serviceable and observable products at time t_i. At stage 2, knowing the number of products $d(t_i)$ failed by time t_i, calculate the empirical estimate of the survival function according to the formula [18–20]

$$\hat{S}(t_i) = \prod_{i=1}^{j} p(t_i) = \prod_{i=1}^{j}\left[1 - \frac{d(t_i)}{v(t_i)}\right]. \tag{3}$$

At stage 4, assuming that the probability of failure-free operation of the products is distributed exponentially, the average failure rate is calculated $\overline{\lambda}$ according to the formula [18–20]

$$\overline{\lambda} = \left(\sum_{i=1}^{n}\left[\hat{S}(t_i)(t_i - t_{i-1})\right]\right)^{-1}. \tag{4}$$

METHODS OF APPLYING REGULATORY METHODS FOR EVALUATING THE RELIABILITY INDICATORS OF ELEMENTS OF GAS ANALYTICAL ENVIRONMENTAL MONITORING SYSTEMS

Using normative methods for assessing the indicators of the reliability of GAMS elements consists of four stages.

Stage 1. Test planning.

Stage 2. Testing and collecting experimental data on reliability.

Stage 3. Analysis of experimental data and determining the operating time of products before failure and censoring.

Let us consider the essence of the basic operations at each stage of the methodology. At stage 1, conduct planning tests in accordance with GOST (State Standard) 27.410, or establish the number of products tested and the duration of tests, taking into account economic constraints. The planning result is a test program that specifies the methods, including accelerated test methods, failure, and test termination criteria. At stage 2, information about failures, operating time (TF_i) before the failure of *i*st products, and operating time (τ_j) before censoring is recorded. At stage 3, the failure rate of composite blocks is determined:

(a) with number of failures r more than 5, calculate a point estimate of the failure rate $\hat{\lambda}$ according to the formula [21]:

$$\hat{\lambda} = rN\left[\left(\sum_{i=1}^{r} TF_i + \sum_{j=1}^{c} \tau_j\right)(N-1)\right]^{-1}. \tag{5}$$

When the number of failures is less than 5, the estimate of the upper confidence limit of the failure rate is calculated $(\bar{\bar{\lambda}})$ according to the formula [21]

$$\bar{\bar{\lambda}} = 0.5N^{-1}\lambda\chi_q^2(2N), \tag{6}$$

where $\chi_q^2(2N)$ is the quantile of the chi-square distribution with the number of degrees of freedom $2N$ at confidence level q, and, in the absence of failures, an estimate of the upper boundary of the failure rate is calculated $(\bar{\bar{\lambda}})$ according to the formula [21]

$$\bar{\bar{\lambda}} = -\ln(1-q)\left(\sum_{j=1}^{c} \tau_j\right)^{-1}. \tag{7}$$

Developing the calculation of standard indicators of the reliability of elements of restored gas analytical systems for monitoring chemical pollution of the environment according to experimental and reference data consists of five stages.

Stage 1. General analysis of the functioning of GAMS elements as objects of reliability research.

Stage 2. Determination of the failure rate of composite blocks of GAMS elements based on reference information on the reliability of electrical radio products (ERPs).

2.1 Allocation of ERPs groups with a single set of coefficients of the mathematical model of reliability (MMR).

2.2 Drawing up maps of ERP operating modes and determining the values of the coefficients of MMR.

2.3 Calculating the ERP failure rate in accordance with the MMR.

2.4 Determining the failure rate of composite blocks of GAMS elements.

Stage 3. Receiving and processing experimental data on reliability composite blocks of GAMS elements.

Stage 4. Determining standard indicators of reliability of GAMS elements according to experimental and reference data.

4.1 Determining the probability of failure-free operation of GAMS elements.

4.2 Determining the failure rate of GAMS elements by approximation

4.3 Determining the GAMS availability factor using various methods of experimental data processing.

4.4 Determining the sufficiency of experimental data by assessing the influence of methods of experimental data processing on the results of determining the availability factor of GAMS.

Let us consider the essence of the basic operations at each stage of the methodology. At stage 1, the result of a general analysis of the functioning of GAMS elements as objects of reliability research is their decomposition into constituent blocks and the compilation of a structural block diagram of reliability, while blocks consisting of electric radio elements and blocks for which it is necessary to conduct experimental studies to determine the failure rate are distinguished. The building blocks should be statistically independent and as large as possible, without structural redundancy, and should themselves be represented by a consistent reliability block diagram.

At step 2.1, depending on the operating conditions, ERPs in each unit are divided into groups (resistors, capacitors, etc.), for which a uniform set of coefficients of the adopted MMR is established [17]:

$$\lambda = \sum_{k=1}^{l} \lambda_k \prod_{j=1}^{m_k} K_{kj}, \tag{8}$$

where λ_k is the initial (base) failure rate of the *k*th flow of failures for ERP; l is the number of independent flows of failures of the components of the ERP that are accounted for, for example, case failure (leakage, etc.) or crystal failure (breakdown, etc.); K_{kj} is the influence of the *j*th factor in the k flow of failures for ERP; m_k is the number of factors taken into account in k stream of refusals.

At step 2.2, a map of modes is compiled, a table in which for each ERP, based on an analysis of operating conditions, coefficients K_{kj} in the MMR are determined. At step 2.3, for ERP, the failure rate is calculated in accordance with the MMR using formula (1). In step 2.4, the failure rate of the composite units is calculated as the sum of the ERP failure rates.

Table 1. Initial data for computational experiments to determine the GAMS availability factor

Test item name	ECS	Valve	Flow stimulator	Emitter
Number of tested products	93	16	11	10
Test plan according to RD 50-690-89	NUZ	NUZ	NUZ	NUZ
Number of failed products	1	2	0	0
Number of products dropped out of supervision	2	3	1	0

At stage 3, planning and testing are carried out with the subsequent processing of experimental data according to formulas (1)–(7).

At step 4.1, the probability of the failure-free operation of the GAMS elements for a certain period of time is calculated using the theory of reliability of nonrecoverable technical systems based on the structural block diagram of the reliability of the elements and results of determining the failure rate of composite blocks using experimental reference data [16]. In step 4.2, the probability of uptime is approximated by an exponential function, for example, by the method of least squares or graphically. At step 4.3, a complex indicator of the GAMS reliability is calculated: the availability factor (F_a) using a computer semi-Markov model of the GAMS operational reliability control process and the results of determining the failure rate by using various methods of experimental data processing. At step 4.4, the availability factor values (F_a), calculated using various methods of experimental data processing, are compared with each other. If the difference in availability factors can be neglected, it is concluded that the experimental information on the reliability of the constituent blocks is sufficient; otherwise, reliability tests are carried out with an increased number of products.

RESULTS OF COMPUTATIONAL EXPERIMENTS ON THE SEMI-MARKOV MODEL OF THE GAMS OPERATIONAL RELIABILITY CONTROL PROCESS USING DIFFERENT DATA-PROCESSING METHODS

To determine the quantitative characteristics of the failure-free operation of the GAMS elements, reliability tests of the GAMS components were carried out: electrochemical sensors (ECSs), infrared emitters, electromechanical valves, and flow stimulators. The tests started in 2015 and ended in March 2020. Initial data for carrying out computational experiments to determine the GAMS availability factor are given in Table 1.

Examples of the results of calculating the survival function $\hat{S}_i$ and instant risk $\hat{h}_i$ according to experimental data for ECSs and valves are shown in Figs. 1 and 2.

The results of computational experiments to determine the GAMS availability factor, obtained using a semi-Markov computer model of the process of managing the operational reliability of GAMS and the

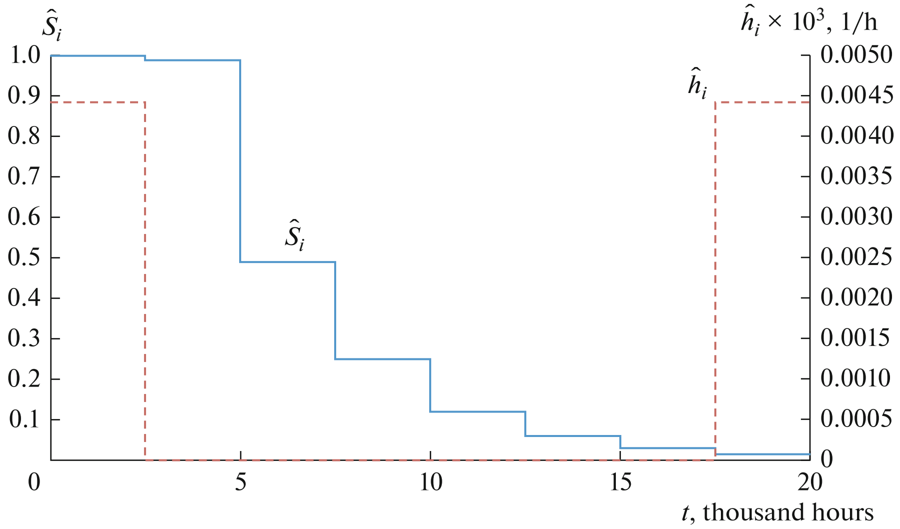

Fig. 1. Survival functions $\hat{S}_i$ and instant risk $\hat{h}_i$ for ECS.

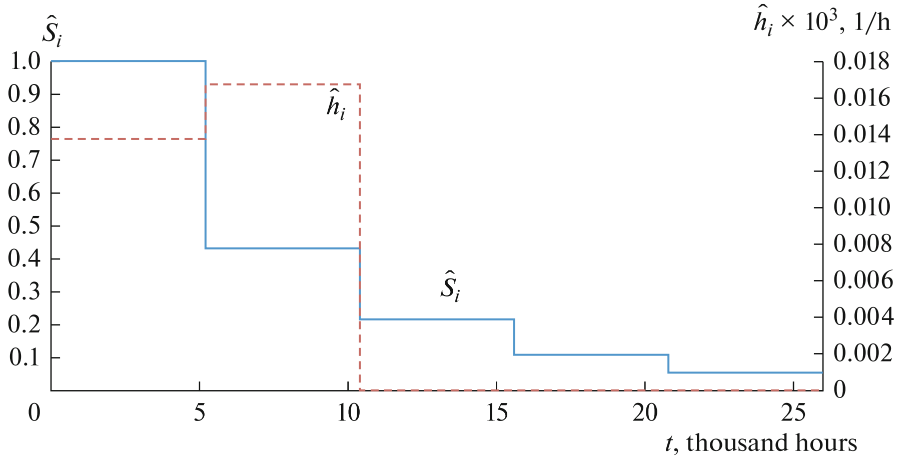

Fig. 2. Survival functions $\hat{S}_i$ and instant risk $\hat{h}_i$ for valves.

Table 2. Results of computational experiments to determine the GAMS availability factor

Parameter	Failure rate of GAMS components, 1/h					F_a
	AMD-01	AMD-02	Valve	Valve control unit	Control and signaling unit	
RD 50-690-89	2.2×10^{-5}	2.2×10^{-5}	3.0×10^{-9}	4.9×10^{-7}	3.5×10^{-7}	0.9997
Interval method	1.4×10^{-5}	1.4×10^{-5}	2.5×10^{-9}	4.9×10^{-7}	3.5×10^{-7}	0.99975
Kaplan–Meier method	1.4×10^{-5}	1.4×10^{-5}	3.5×10^{-9}	4.9×10^{-7}	3.5×10^{-7}	0.99975

results of determining the failure rate obtained using various methods of processing experimental data, are given in Table 2.

CONCLUSIONS

A method for calculating the standard indicators of reliability of GAMS elements has been developed which makes it possible to determine the values of the availability factor using small (cost-effective) samples of products under conditions of their possible retirement from observation for reasons not related to failure. Using a systematic approach to analyzing experimental data, it is substantiated that the duration of determinative tests for reliability and the number of tested components can be taken as sufficient on the basis of an assessment of the influence of experimental data on reliability on the calculated value of the GAMS availability factor. The results of practically applying this methodology for determining the indicators of the reliability of components and the availability factor of GAMS are presented.

FUNDING

This study was carried out with financial support from the Russian Foundation for Basic Research, project no. 18-29-24094 MK, and according to State Task project no. FSWF-2020-0019.

NOTATION

c	number of items withdrawn from testing for reasons not related to failure
d	number of failed products
F_a	availability factor
h	risk intensity function, h^{-1}
K	coefficient taking into account the influence of various factors in the MMR
l	number of independent counted failure streams in the MMR
m	number of factors taken into account in a separate stream of failures in the MMR
n	number of observation intervals
N	number of tested products
p	empirical probability of a product to “survive” a given point in time
r	number of failures
S	survival function
t	time, h

TF	time to failure, h
v	number of monitored products at a certain moment
x	number of serviceable products
Δt	duration of the interval for dividing the observation period, h
χ_q^2	quantile of chi-square distribution with degrees of freedom $2N$ at confidence level q;
λ	failure rate, h^{-1}
τ	operating time before censoring, h

SUBSCRIPTS AND SUPERSCRIPTS

i	number of the product that failed during testing—number of the observation interval
j	factor number in the k flow of failures—number of the product withdrawn from testing
k	failure stream number
q	confidence level
0	number of products at the beginning of the observation interval
$\hat{u}$	empirical estimate of a physical quantity
$\bar{\lambda}$	physical mean
$\bar{\bar{\lambda}}$	estimate of the upper boundary for the value of a physical quantity

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