Methodical foundations of forecasting the reliability of products of aviation and rocket and space technology

Vasilii I. BIRYUKOV*

*Corresponding author
Department of Engineering Graphics,
Moscow Aviation Institute (National Research University),
4 Volokolamskoe shosse, 125993, Moscow, Russian Federation,
aviatex@mail.ru

DOI: 10.13111/2066-8201.2019.11.S.5

Received: 15 April 2019/ Accepted: 24 May 2019/ Published: August 2019

Abstract: *The study discusses various techniques and algorithms for determining the quantifiable characteristics of the reliability of products of aviation and rocket and space technology at the stages of research and development. The sequences of disaggregation of composite products into components and the drawing up of structural reliability schemes are given on the example of an electric rocket engine having mechanical units and electrical equipment of various types. Various methodological approaches are presented to determine the possibility of failure-free operation of the component parts of products, both with experience data on failure rates of elements and without official data on reliability. Recommendations are given to increase the VBR components, individual parts and the product as a whole.*

Key Words: *reliability, probability of failure-free operation, failures, failure rates, ERI electrical equipment, spacecraft (SC)*

1. INTRODUCTION

When creating pilot products of aviation and rocket and space technology (RST) at the stages of exploration and development (R & D) and development work (DW) special attention is paid to the reliability of their operation [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17].The technical specification [4; 12] for the development of such products establishes the active existence period (AEP) of the product, providing for the length and conditions of its storage prior to operation, and the operating time in continuous mode or with discrete switching. Storing time is subdivided into storage time in a de-energized state (it may include periodic checks of components) and time spent in orbit for RST in a loaded or de-energized mode at various external destructive influences. Under the reliability of the product, understood – the quality of the product to maintain the values of the established parameters of operation within certain limits, corresponding to the specified modes and conditions of use, maintenance, storage and transportation. For quantitative calculations of the reliability of products, the following criteria and indicators are used. Failure (loss of efficiency) and reliability, failure rate, probability of failure-free operation (FFP), perseverance, durability, resource, maintainability, etc. For products of rocket and space technology maintainability in the majority does not apply. Quality indicators might change over time. Changing them, beyond the allowable values, leads to a failure state (partial or total failure of the product). To assess the reliability of products, the following indicators are used: the average operation time prior the occurrence of a failure T_{av} – the time between the first failure; average work time per one failure, T – time between failures; failure rate $\lambda(t)$; fault flow parameter $w(t)$; average recovery time t_{in}; probability of failure-free operation during t [$P(t)$]; availability factor K g [1], [2], [3], [5], [6], [7], [8], [9], [10], [11], [18], [19], [20]. The law of distribution of period to failure determines the quantitative indicators of the reliability of non-recoverable products. The distribution law is written in differential method as a probability density $f(t)$, or as an integral form $F(t)$. There are following relations between reliability indicators and the distribution law:

$$P(t) = 1 - F(t) = exp\left[-\int_0^\infty \lambda(t)dt\right];$$
$$T_{\text{cp}} = \int_0^\infty t \cdot f(t)dt = \int_0^\infty P(t)dt; \tag{1}$$
$$\lambda = \frac{f(t)}{P(t)}.$$

For recoverable products, the probability of n failures during period t in the case of the simplest failure stream is determined by Poisson's law:

$$P_n(t) = \frac{\lambda^n}{n!} e^{-\lambda t}. \tag{2}$$

It follows that the probability of absence of failures during time t obeys the exponential law

$$P(t) = exp(-\lambda \cdot t)\,. \tag{3}$$

The probability of failure-free operation (FFW) for the nominated service life of a certain number of years for CT products should be very high, for example [4], [8], [9], [10], [11], [12]: P = 0.995 with a confidence level of 0.8 (lower limit of the confidence interval). The FBR of the sample in development shall be confirmed by calculation and by results of ground-level autonomous tests [21], [22], [23], [24]. To ensure the required high reliability, a reliability assurance plan (RAP) is drawn up, which includes measures at all design stages:

- structural detailing of the produce being created;
- a list of procured parts and components that have known high reliability;
- the use of materials with the essential properties and resistant to the effects of various destructive factors;
- modern high-tech processes of manufacturing parts and assembly procedures;
- the degree of compliance of technological processes with the requirements of manufacturing precision, automation of processes. Providing quality control at all phases of production;
- the degree of effectiveness of quality control within the framework of the quality controlling system, as well as a high level of acceptance checks and tests;
- identification of parts of the product with a relatively low reliability and the development of procedures to improve it, etc.

As an example, we can quote the requirements for the reliability parameters of a corrective propulsion system (KPS) based on a pulsed plasma engine designed to correct the orbit of a spacecraft (SC) [4], [12]:

- the probability of failure-free work (FFW) during the lifetime of intended purpose of 5 years must be at least 0.995 with a confidence level of $P = 0.8$.
- KDU resource (guaranteed quantity of charge-discharge cycles for bit channels) – up to 1.5×10^7.
- KDU resource by the quantity of inclusions – up to 500.
- KDU should provide the obligatory operational and technical qualities for 5 years from the date of acceptance, including during the storage period – 3 years, including ground tests, transportation and autonomous storage on the ground and in flight as part of the spacecraft;

The failure criterion is the impossibility of making control actions.

Product development should be carried out taking into account technically and economically sound methods of standardization, unification and application of typical and uniform components and parts.

In the making of the prototype there should be used domestic and foreign element base and components that ensure the reliable operation of the developed product in space or rarefied atmosphere.

The prototype may contain electrical and electronic products (AEP) of domestic and foreign production (AEP FP) in accordance with regulatory documentation (ND), namely: Instructions on the use of electronic units, electrical components of foreign production in the components of the CT, on the basis of “The provisions of EKB-RKT”, as well as: RD134-0140-2005, RD134-0146-2006, RD134-0154-2007 and other guidance documents [2], [3].

The quantity and type of purchased components included in the product being developed is determined by the text document agreed with the customer-the List of purchased products.

This document specifies the name, brand, quantity of components, including materials and technical conditions for them. The reliability assurance plan (RAP) of a PKT product under development is regulated by a number of regulatory documents [2], [3], including the calculation of reliability in product design. In particular, a diagram is made of the reliability of the product, in which the component parts of the product are included in a sequential chain. The probability of failure-free operation of the entire product is determined by the product of the corresponding FBG components. Components with low reliability duplicate, i.e. include in parallel.

Such elements can be functionally permanently linked and loaded, in this case they speak of a “hot” backup, or parallel elements work only when the main ones fail, in this case they speak of “cold” duplication. Consider the method of calculating the reliability of various non-recoverable objects and the procedure for assessing reliability of the entire product at the design stages.

2. THE METHOD OF CALCULATION FOR ELEMENTS WITH KNOWN PARAMETERS OF RELIABILITY

These elements include procured components, which contain information on reliability parameters according to data from the passports of these elements, either in specifications or in reference books on reliability [25], [26], [27], [28], [29].

The determination of the probability of failure-free operation P for many non-recoverable elements of electronic equipment is made in relation to the exponential distribution of failures using the following expression:

$$P = exp\left[-\tau \times \left(\sum_{i=1}^{i=R} N_i \times \lambda_i\right)\right], \tag{4}$$

where τ is the operation time during which the parameter P is determined;

N_i – the quantity of elements of the i -th type; λ_i – the failure rate of the elements of the i -th type.

Failure rates λ_i for ERI, including ERI SP, of the product under development is determined by passport information and operations [6; 9; 18, 25-29] taking into account corrections for the real mode of operation for thermal and regime (current, mechanical, etc.) also taking into account the conditions during operation for a group of equipment [6], [7], [8], [9], [10], [11], [20], [25], [26], [27], [28], [29], including quality data expressed by the acceptance coefficient.

The VBP is calculated both for the operation of the product, taking into account the guaranteed resource, and, including storing in certain conditions and staying in flight in an off state for some period, otherwise for the whole active life (AEP) of the spacecraft.

In the first case, the failure rate λ_e for most of the ERI groups in the operation of the product is determined on the basic failure rate λ_b of the ERI group by the equation

$$\lambda_e = \lambda_b \times \prod_{i=1}^{p} K_i , \tag{5}$$

where K_i – ratio that takes into account changes in the operational failure rate depending on various factors, and n is the number of factors to be taken into account.

For power supplies and other complex components, the total failure rate of which consists of independent ERI failure flows, the model for calculating their failure rate is [13], [14], [26], [27], [28], [29]:

$$\lambda_e = \sum_{j=1}^{m} \lambda_{bi} \times \prod_{i=1}^{p} K_{ij} \tag{6}$$

where λ_{bj} – the basic failure rate of the j rate of failures;
m is the number of independent streams of ERI failures and components of the product;
K_{ij} – ratio taking into account the influence of the i factor in the j stream of failures;
n_j – the number of factors taken into account in the j flow of failures.

FBG design formula for storing mode

$$P = \exp\left[-\tau \times \left(N_i \times \lambda_{xp\,i} \times K_{t\,x} \times K_e \times K_{pr}\right)\right] \tag{7}$$

where K_{tx} – ratio taking into account the effect of temperature during storage;
K_{PRi} – the quality ratio of equipment production (coefficient of acceptance), takes into account the level of requirements for the development and manufacture of equipment.

It shows the average difference in the ERI failure rate in equipment developed and manufactured according to the requirements of various ND, for example: according to the “Moroz” standard set, K_{pr} = 1.0; on the position of the Republic of Kazakhstan - K_{pr} = 0,2.
K_e – coefficient taking into account the severity of operating conditions for hardware groups. It shows how many times the failure rate of an ERE in the equipment of a particular class (operation group according to GOST RV 20.39.301-98) is higher with all other conditions being equal than in ground fixed equipment (group 1.1) [26], [27], [28], [29];
$\lambda_{xp\,i}$ is the failure rate of ERI elements of type i during storage according to [26], [27]

$$\lambda_{xp\,i} = \lambda_{be} \cdot K_X \tag{8}$$

K_X – coefficient taking into account the conditions during storage (in flight or in stock).

When calculating the reliability of equipment that is in operation the main part of the time is in standby mode (storage) in a de-energized state with periodic performance monitoring, it is recommended to use the values of failure rates $\lambda_{e.x}$ of ERI groups calculated by the models: for fixed objects:

$$\lambda_{e.x} = \lambda_б \cdot K_x \cdot K_{tx} \cdot K_{conv}. \tag{9}$$

$$\lambda_{ex} = \lambda_{xpi} \cdot K_{tx} \cdot K_{conv} \cdot K_{\mathrm{acc}} \tag{10}$$

for mobile objects:

$$\lambda_{ex} = \lambda_B \cdot K_x \cdot K_{t.h} \cdot K_e \cdot K_{acc} \tag{11}$$

$$\lambda_{e.x} = \lambda_{xp.i} \cdot K_{t.x} \cdot K_e \cdot K_{acc} \tag{12}$$

where $\lambda_{xp.i}$ is the ERI failure rate according to the results of product testing for perseverance in the packaging of manufacturers at a temperature of 5 ... 40°C and relative air humidity up to 80% (at a temperature of + 25°C);
λ_{b} – the basic failure rate of type (group) ERI [26], [27];
$K_{\mathrm{t.x}}$ – ratio taking into account the change in the failure rate $\lambda_{x.c.g}$ depending on the ambient temperature. The values of $K_{t.x}$ are given in the corresponding tables of the sections of reference books [26], [27];
K_{acc} – the ratio of acceptance; K_e – the ratio of operation;
K_{conv} – ratio taking into account the change in the intensity of failures $\lambda_{\mathrm{x.c.g}}$ depending on the operating conditions in the standby mode (storing).

For example, the recommended values of K_{conv}: in a heated room – 1.0; in an unheated room – 1.2; under a canopy – 1.4 [26]. The total value of the probability of failure of the element is equal to:

$$P = P_e \times P_{xp} \tag{13}$$

With hot duplication, when elements work in parallel and simultaneously, FBG is determined by the formula:

$$P = 1 - (1 - P)^2 \tag{14}$$

For ERI used in a pulsed mode, for example, capacitors in the accumulative battery, the manufacturer in the ERI passport information results in a guaranteed number of failures. for large capacitors manufactured by the Italian company “ICAR”, according to the catalog of the company [4], [12] FBG of these capacitors is equal to 0.97 for 10^5 hours of operation or 3 failures per number of discharge impulses n = 1.8 10^{12} imp. From here, the failure rate per one-bit pulse will be:

$$\lambda_э = \frac{3}{n} = \frac{3}{1,8 \times 10^{12}} = 1,67 \times 10^{-12} \, \frac{1}{imp}$$

Then the reliability of a block of capacitors relative to the number of discharge impulses can be defined as:

$$P = exp\,(-\lambda_{be} \times N \times n), \tag{15}$$

where N is the number of capacitors in the battery;
λ_{be} – the basic operational failure rate per one discharge pulse;
n is the total number of bit pulses per engine life.

The basic working failure rate is determined by the formula (1). Considerations for the effects of a number of factors through the corresponding coefficients [13], [14], [26], [27], [28], [29] in formulas (5) and (6), for example:
K_p – the ratio of the mode (is a correction, taking into account the actual temperature of the environment or the body of the product);

K_{acc} – the ratio of acceptance (reflects the degree of stringency of requirements for quality control and rules for acceptance of products);
K_{ii} is the ratio that takes into account the effect of acting ionizing radiation of natural and artificial origin on reliability ($K_{ii} \geq 1$) [26];
K_C – ratio taking into account the effect of capacitor capacitance;
K_e – ratio taking into account the operating conditions of the equipment group according to GOST RV20.39.304-98.

In turn, each ratio reflects the real physical influence of all significant factors affecting an element during work or storage.

For example, the values of the coefficient regime K_p for ERI type capacitor are calculated according to a mathematical model that takes into account the electrical load and thermal regime [26]:

$$K = A\left[\left(\frac{U/U_H}{N_S}\right)^H + 1\right] exp\left[B\left(\frac{t+273}{N_t}\right)^G\right], \tag{16}$$

where A, B, N_t, G, H, N_S are constant coefficients of the model;
t is the ambient temperature, C; U – operating voltage, V;
$U\ n$ – rated voltage, V.

However, the given example does not reflect all the features of the wide nomenclature of this kind of ERI, which should be taken into account in determining the FBG. For more accurate estimates, it is necessary to take into account the entire spectrum of factors affecting the failure rate of definite elements [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [25], [26], [27], [28], [29].

The reliability parameter in storage mode, considered in the example of ICAR high-volume capacitors, is determined based on the durability parameters, according to which MSR25 capacitors remain operable after being in $\tau = 0.6042 \cdot 10^5$h (7 years) at temperature conditions up to 85° with 98% probability.

Based on these parameter values, the failure rate in the storage mode at a temperature of 85°C will be $\lambda_{XT} = 0.51\ 10^{-9}$ 1 / hour, [12].

The values of the temperature coefficient K_{tx} in the temperature range 40 ÷ 60°C can be calculated by the mathematical model [26]:

$$K_{tx} = A\, exp\left[B\left(\frac{t+273}{N_t}\right)^G\right], \tag{17}$$

where A, B, N_t, G are the constant ratios of the model;
t is the environment temperature, °C.

The definition of the components (ratios) of models and other characteristics of reliability is given in the sections of reference books [13], [14], [26], [27], [28], [29]. Sources of information for reference books are: the results of periodic tests of ERI for reliability, durability, life and storage, the results of their experimental storage and the results of special controlled operation of ERI as part of equipment of different classes, as well as information on the reliability of ERI from the results of testing and operation of equipment for various purposes.

The results of experimental and theoretical work on the study of reliability and analysis of the causes of failures of ERI, performed by manufacturers.

For connectors, wires and soldered joints, expression (5) is used with the value of λ_i, presented in [26], moreover, only those that provide for the process of joining and disconnecting during operation are counted as connectors. For temperature sensors [4], [12], information of technical conditions is used, for example B616.036.012 TU.

3. THE METHOD OF CALCULATION FOR ELEMENTS THAT DO NOT HAVE OFFICIAL INFORMATION ON RELIABILITY

These elements include, first of all, parts manufactured by the product developer himself, for example, in MAI [4], 12].

The estimation of the probability of failure-free operation for such elements is made in accordance with [6], [7], [20], [29], through the quantile U_p, which is a parameter depending on the safety factor of a critical factor for a given element, as well as on the value of the possible variation of strength and load characteristics. The value of quantile is calculated by the formula [6], [11]:

$$U_p = -\frac{K-1}{\sqrt{(K' V_R)^2 + V_p^2}}, \tag{18}$$

where K is the margin of resistance to the critical influencing factor;
V_R – ratio of variation of the characteristics of the material from which the element of the product is made, also depending on the quality of production and quality control;
V_P – the ratio of variation of the loading of the element by mechanical or other factor, for example, thermal factor.

4. THE METHOD OF CALCULATION FOR ELEMENTS WITH ANALOGUES WITH IDENTIFIED RELIABILITY PARAMETERS

These elements can be attributed, for example, to AIPD, transformers in ignition circuits, made in MAI [1], [2].

For transformers, a standard type of serially manufactured transformers can be adopted as an analogue, the reliability parameters of which are given in [5; 18].

Though, the latter differ from the ignition system transformers in that they are not designed for high-voltage impulse loading.

Thus, the reliability parameter P for such transformers is determined both by the formula (5) in accordance with the data of [26] and by the formula (18), based on the calculated electrical strength.

The reliability of the spark plugs [4], [12], where automobile spark plugs are considered as an equivalent, is determined in a similar way. From the above calculations by formulas (5) and (18), the reliability option with the lowest FBG value is chosen.

5. METHOD OF SELECTING CRITICAL ELEMENTS

According to the results of the calculation carried out according to the above methods, the reliability parameter of the experimental sample of the product as a whole is determined.

As an example, we consider the reliability parameters of the components of the electric propulsion engine – AIPD, given in [12]. The block diagram of one of the engines, which includes the engine components: the main elements and components, as well as their reliability parameters, is shown in Picture1.

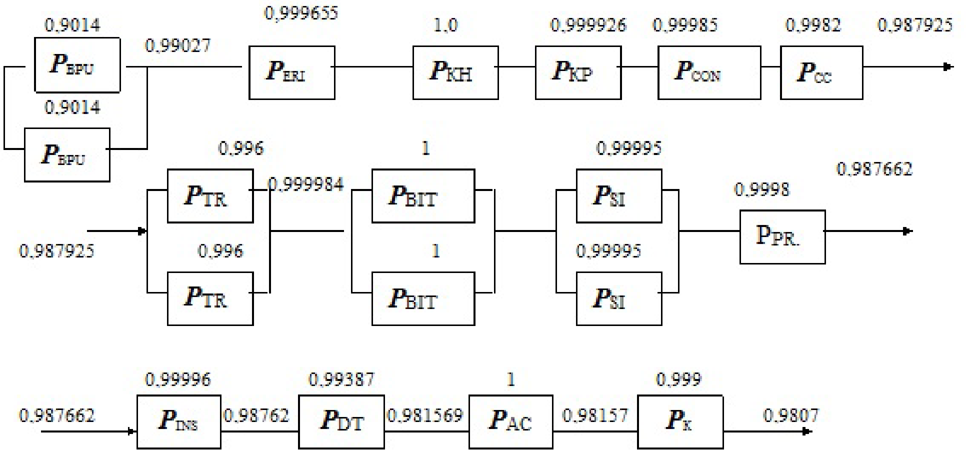

Fig. 1 – The block diagram of the reliability of the product AIPD

In Figure 1, the notation has the following meanings:

P_{BPU} – the reliability of the power supply and control;
P_{ERI} – dependability ERI (resistors, small capacitors);
P_{KH} – dependability of accumulating capacitor battery;
P_{KP} – dependability of capacitors in the ignition circuit;
P_{CON} – dependability of connectors;
P_{CC} – dependability of connecting chains;
P_{TR} – dependability of high-voltage transformers;
P_{PR} – dependability of the springs in the nodes supplying counters RT;
P_{INS} – dependability of the insulating elements;
P_{DT} – dependability of the temperature sensor;
P_{BIT} – dependability of dischargers controlled by RU83;
P_{SI} – dependability of the spark ignition;
P_K – dependability of structural elements, including fixing units;
P_{AC} – dependability of acceleration channels.
Indices: *o* – main, *p* – reserve.

The probability of trouble-free operation of an ablative pulsed electric propulsion engine [12] P_{AIPD} will be expressed as the product of the reliability parameters of the elements included in the structural diagram:

$$P_{AIPD} = P_{BPU}\, P_{ERI}\, P_{KH}\, P_{KP}\, P_{CON}\, P_{CC}\, P_{TR}\, P_{PR}\, P_{INS}\, P_{DT}\, P_{BIT}\, P_{SI}\, P_K\, P_{AC}\, P_{AC} \tag{19}$$

The values of the parameters shown in the block diagram, see figure 1, correspond to the calculation taking into account the redundancy of elements and duplication of components.

The specific value of P_{AIPD} It is compared with the value of FBG given in the product specification for product development. Next, elements are selected that have the greatest impact on reducing the value of P_{AIPD}. These elements can be categorized as critical. The critical elements should also include those elements that do not have sufficient information on reliability, as well as elements that operate as part of the engine in modes that differ in parameters from the passport data. Selected critical elements must pass the required amount of experimental development.

The study of the criticality of the component parts of the product is carried out in accordance with GOST 27.310-95 “Analysis of the types, consequences and criticality of possible failures” (ATCCF). ATCCF is a combination of a qualitative analysis of the types and consequences of failures with quantitative assessments of the criticality of the elements of the systems and the product as a whole.

ATCCF is used in the design stages of product development, as well as later in its manufacture and ground testing to improve reliability.

After receiving additional information at the subsequent stages of the life cycle, an additional analysis of the types, consequences and criticality of failures is performed and the list of critical elements is specified. The essence of ATCCF is the disaggregation of the structure of the product and the allocation of systems and elements that have signs of criticality and the analysis is carried out:

- possible failures at various levels;
- causal relationships causing the occurrence of failures;
- possible consequences of failures.

This makes a qualitative assessment of the severity of the consequences, the frequency of failure, the identification of critical elements with the definition of organizational and technical measures to reduce the probability of their occurrence.

6. WAYS TO IMPROVE THE DEPENDABILITY OF THE ELEMENTAL BASE OF RKT PRODUCTS

At the stage of product development [2], [7], [8], [17]: the use of fundamentally new technologies, allowing to attain a new parametric quality; the use of materials with improved physico-chemical characteristics, and new elements with increased noise immunity with respect to destructive factors and reliability compared to those used earlier; reservation, including hardware (elementwise), temporary and informational; development of noise-free programs and noise-free coding of information; selection of optimal operating conditions and the most effective protection against adverse internal and outside influences; the use of effective control, allowing not only to ascertain the technical condition of the product (simple control) and establish the causes of the failure condition (diagnostic control), but also to foresee the future state of the product in order to prevent the occurrence of failures (predictive control).

In the production process: the use of advanced material processing technology and progressive methods of joining parts; application of actual methods of quality control (including automated and statistical) of technological operations and quality of products; the development of rational ways of testing products that reveal concealed manufacturing defects; reliability tests, excluding the acceptance of unreliable products.

During operation: ensuring the indicated conditions and modes of operation; carrying out maintenance work and ensuring the redundancy of products, ERI, parts, assemblies and units; diagnostic monitoring, warning of failures.

In the course of technological development, new features of the problem of ensuring reliability arise.

For example, the use of large-scale integrated circuits made with modern technologies with a design standard of less than 0.25μm requires fundamentally new procedures for calculating their reliability indicators, assessing resistance to ionizing radiation of outer space in the form of cumulative doses, as well as fail-safety and failure calculations due to the impact of heavy charged high-energy particles during solar events (SCR) and from the flux of galactic radiation (GCR).

7. CONCLUSIONS

1. One of the core quantitative indicators of the reliability of products of aviation and rocket and space technology is the probability of failure-free operation, determined during their real operation in relation to the planned working conditions.
2. Improving the reliability of the products is attained on the one hand by the use of components with known high rates of FBG, on the other hand by redundancy of the elements used, or a block loaded or unloaded backup.
3. The required high reliability, generated as a result of R & D products of aviation and rocket-space technology, can only be provided by a systematic approach, namely: FBG calculations of all components and devices as a whole, analysis to increase FBG of critical elements and measures to improve dependability all stages of design, manufacture and experimental development of prototypes.

REFERENCES

[1] * * * GOST 23743-88 *Aviation products. The nomenclature of flight safety indicators, reliability, testability, operational and repair technology*, 1988. Available at https://www.twirpx.com/file/1568774/
[2] F. I. Kuzmin, *Federal system of certification of space technology. Collection of governing system-wide document*, Mashinostroyeniye, 2006.
[3] * * * RD 50-960-89. *Methodical instructions. Reliability in technology. Methods for assessing reliability indicators from experimental data*, 1989. Available at http://docs.cntd.ru/document/1200035567
[4] V. I. Biryukov, O. Yu. Pronin and A. V. Radchenko, Algorithm for predicting the reliability of products of aviation and rocket and space technology at the design stage, *Bulletin of the Moscow Aviation Institute*, vol. **2**, no. 20, pp. 72-79, 2013.
[5] E. B. Volkov, R. S. Sudakov and T. A. Syricin, *Fundamentals of the theory of reliability of rocket engines*, Mashinostroyeniye, 1974.
[6] D. N. Reshetov, I. A. Ivanov and V. Z. Fadeev, *Reliability machines*, Mashinostroyeniye, 1988.
[7] E. I. Krinetsky (Ed.) *Flight tests of rockets and spacecraft*, Mashinostroyeniye, 1979.
[8] A. A. Kuznetsov, A. A. Zolotov, V. A. Komyagin and M. I. Titov, *Reliability of the mechanical parts of the aircraft structure*, Mashinostroyeniye, 1979.
[9] Yu. K. Belyaev, V. A. Bogatyrev and V. V. Bolotin, *Reliability of technical systems*, Radio i svyaz, 1985.
[10] K. Kapoor and L. Lumberson, *Reliability and system design*, Mir, 1980.
[11] V. M. Trukhanov, *Methods to ensure the reliability of engineering products*, Mashinostroyeniye, 1995.
[12] V. I. Biryukov, N. N. Antropov, V. K. Tyutin, *Calculation of the reliability of an experimental sample of an ablative pulse plasma engine AIPD-155*, in Technical Report OCD «IPDU MT», MAI, 2010.
[13] A. I. Berg, *Cybernetics and reliability*, Nauka, 1964.
[14] V. A. Kuznetsov, *Reliability of electronic equipment*, Sovetskoye radio, 1968.
[15] D. Lloyd and M. Lipov, *Reliability*, Sovetskoye radio,1964.
[16] I. Bazovsky, *Reliability. Theory and Practice*, Mir, 1965.
[17] P. N. Orlov, *Technological quality assurance of parts finishing methods*, Mashinostroyeniye, 1988.
[18] A. S. Pronikov, *Reliability machines*, Mashinostroyeniye, 1978.
[19] B. V. Gnedenko, Yu. K. Belyaev and A. D. Soloviev, *Mathematical methods in the theory of reliability*, Nauka, 1968.
[20] Ya. B. Shor, *Statistical methods for analyzing quality and reliability*, Vysshaya shkola. 1988.
[21] J. A. Flores-Cruz, G. E. Delgado, J. E. Contreras, M. Quintero, L. Nieves and P. Grima-Gallardo, Structural characterization of the new diamond-like semiconductor $CuNbGaSe_3$, *Periodico Tche Quimica*, vol. **15**, no. 29, pp. 228-233, 2018.
[22] L. F. Sirazijeva, S. N. Stepin and L.Yu. Makhotkina, Dispersing agents for emulsion-type coating compositions (review), *Lakokrasochnye Materialy i Ikh Primenenie*, no. **10**, pp. 25-28, 2004.
[23] A. A. Kulzhumiyeva and Z. A. Sartabanov, On multiperiodic integrals of a linear system with the differentiation operator in the direction of the main diagonal in the space of independent variables, *Eurasian Mathematical Journal*, vol. **8**, no. 1, pp. 67-75, 2017.

[24] E. S. Lomakina and V. V. Fitsak, Basics of mathematical field theory in relation to geophysical fields in development of systematic nature of applied physical reasoning, *International Journal of Applied Engineering Research*, vol. **12**, no. 22, pp. 12451-12453, 2017.
[25] * * * *Reliability of ERI. American standard MIL – HDBK – 217 F,* February 1995. Available at https://www.twirpx.com/file/1264677/
[26] * * * *Reliability of radio products. Directory. Publisher TSNII 22 MO*, 2006. Available at https://chipinfo.pro/books/Reliability_(2006).pdf
[27] * * * *Reliability ERI IP. Directory. Publisher TSNII 22 MO*, 2006. Available at https://docmesh.ru/12075-nadyozhnost-elektroradioizdelij-spravochnik
[28] Yu. V. Koritsky, *Handbook of electrical materials,* Energoatomizdat, 1986.
[29] Ya. B. Shor and F. I. Kuzmin, *Tables for analysis and control of reliability,* Sovetskoye radio, 1968.