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Development of the Methodology for Assessing the "Production Quality Factor" for the Failure Rate Model of Artificial Earth Satellites Electronic Means

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Abstract — This paper presents the methodology for assessing the «production quality factor» for the failure rate model of electronic means (EM) of artificial earth satellites (AES) in the design. The use of a quality management system (QMS) and activities regulated by regulatory and technical documentation (RTD) for the creation, production and operation is a distinctive feature of the proposed methodology. Implementation consists in applying an ontological approach to the formation of the questionnaire for subsequent expert evaluation for external and internal audits. The methodology allows to timely identify the advantages and disadvantages of a specific event, approved by the dependability program and specified in a certain section of the RTD, including QMS. The methodology let it possible to increase the effectiveness of the numerical evaluation when the target level of dependability indicators is achieved, also, to enhance the of the AES EM system and relieves the manufacturing organization from the procedure for additional tests. It is planned to use the developed methodology at the enterprises of the rocket and space industry and in private non-state manufacturing companies of the small AES.

Keywords — dependability, reliability, artificial Earth satellites, electronic mean, failure rate, production quality factor, ontological research

I. Introduction

Modern artificial Earth satellites (AES) are prone to complications due to the improvement of their components – electronic means (EM). This is determined by three reasons: firstly, the number of components is growing rapidly, secondly, there is a need for new responsibilities and, thirdly, the range of operating conditions is expanding [1]. To increase the competitiveness and profitability in the provision of space communications services in modern realities, it is necessary to develop an AES with an active lifetime of 15 years or more [2, 3]. This leads to high requirements to ensure the dependability of the satellite [3-5], because they are operated in extreme conditions. Norms and requirements implementation in the field of ensuring the reliability of such systems – of the AES type [3-5] is a difficult but necessary task, and hundreds of scientific works are devoted to its solution, for example, some of them are presented in sources [1, 2, 6-9]. A study of the sources [1, 2, 6-9] allows us to conclude that it is often not possible to satisfy the requirements for active lifetime by 2 or more times due to arising failures of the satellite during operation [2, 10] due to the low level of individual dependability measures, in particular, reliability [7, 11]. The situation is aggravated by the fact that the AES is a non-repairable system. However, the economic reasons and the need to ensure self-sufficiency of projects aimed at the provision of space communications services, explains the increase in requirements for AES active lifetime [2].

Indeed, at the present time, AES electronic means failures continue to occur, which is confirmed by open source [10]. This negatively affects the profitability of space communications services. The reasons for the failures are often not reported, but the failed component is indicated. It follows that, according to open data, it is practically impossible to determine the category of failure according to [11, 12]. An analysis of the source [10] and its visualization of data (see Fig. 1) allows us to conclude that the majority of AES failures occur in the United States, Russia is in second place and China is in third. However, if we consider the percentage of the number of satellite failures from their total number (in the USA 900, in Russia 150, in China 300), operating and in orbit by now between the compared countries, then Russia is in this inferior to both China and the United States. An analysis of the data shows that for the US, failure occurs for every 25 AES, for China - failure occurs every 60 AES, and for Russia - failure occurs for every 5 AES. Failures during the operation of the AES most often occur due to failures in the electronics of the radio devices, failures of the power supply system, command-measuring system and payload [1, 10].

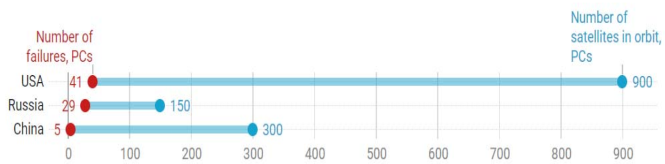

Fig. 1. The total number of AES in orbits of the Earth and the number of AES failures for 2010-2019

The current situation for Russia testifies to the shortcomings in the strategy for ensuring reliability at the design stages of the AES EM. An important role in the design is acquired by the quality management system (QMS) of the

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enterprise [13-15], i.e. enterprise process management system and the dependability management system (DMS) included in the QMS, which provides a systematic approach to dependability and related aspects of management and business [16]. It is possible to characterize the functioning of the QMS, DMS, the fulfillment of the requirements for the development and manufacture of AES EM using the "production quality factor" K_A AES EM [12]. It takes into account the level of requirements for the design and manufacture of EM, i.e. development of the technological process and the level of organization of EM production. It is worth noting that an important stage before production is the design, on which the required level of dependability is laid down, regulated by the technical specification and regulatory and technical documentation (RTD) for the object of study. Also, K_A allows to take into account the stages of designing, manufacturing, issuing technological documentation, testing, exit control, repair, transportation, storage and enterprise management. However, the use of the existing document [17] governing the use of numerical values of K_A leads to an unreliable assessment of the characteristics of a single dependability measure - reliability [2, 10]. In this regard, it is necessary to conduct additional tests, which is unjustifiable for AES due to its high cost and uniqueness. Especially, the question of reliable dependability assessment remains open for private non-state manufacturing companies that produce small AES that are not certified by a standardized QMS and produce AES EM in accordance with the internal standards of the company itself. Therefore, the aim of this work is to increase the assessment credibility of target individual dependability measures, in particular, the reliability of the AES EM at the design stage, while assessing the level of design, manufacturing, technological documentation, production, testing, exit control, repair, transportation, storage and enterprise management. To achieve this goal, full detailing of the "production quality factor" is required.

II. ANALYSIS OF EXISTING EVALUATION DECISIONS «PRODUCTION QUALITY FACTOR»

The current status of existing solutions aimed at determining the "production quality factor" K_A, which is part of the failure rate model for assessing AES EM, has several drawbacks. Consider the approaches to estimating the numerical value of K_A recommended in the USA and Russia.

A. Evalution of «production quality factor» in Russia

The first approach is related to compliance with the requirements of the QMS, which are indicated in the current standards [13-15]. It is important to note that dependability is an integrating operational indicator of the AES EM quality measure [11, 18]. Dependability is ensured by the quality of design and production of AES EM. Consequently, dependability is secondary in relation to quality, and therefore DMS is included in the overall composition of the QMS [16].

A description of the quality management (MK) principles is given in the standard [18]. And the standard [14] is based on the principles specified by [18]. However, the principles themselves are not requirements, but they form the basis for those requirements that are established [14]. Previously, there was another version of the standard [18] - this is an international standard [19] from which it was necessary to transfer to December 2018 all enterprises to the standard [18]. In [20], the similarities and differences of the MK principles standards [18] and [19] are reflected. In addition, the current standard [14] has a new structure, contains new requirements and terms with new definitions. The main innovations [14] regarding the previous standard [13] are given in the source [20]. However, despite the constant change in measures aimed at improving quality, given in the standards [13-15] and source [21], it is not possible to conduct a numerical assessment of the "production quality factor" AES EM.

The second approach is aimed at fulfilling the requirements of the RTD to ensure a high level of dependability: GOSTs, OSTs, Regulations. However, despite the changes in the RTD and the correctness of the requirements fulfillment, the "production quality factor" K_A is integral and has only two variations. Namely, the reference book [17] regulates for the set of state military standards (SSMS) "Moroz-6, 7" that apply to electronic means and SSMS "Klimat-7" that apply to electronic devices (ED) to take $K_A = 1$, and according to the Regulation on the procedure the creation, production and operation of space systems take $K_A = 0.2$. The values of K_A are used in expression (1) according to [17] to assess the failure rate AES EM:

$$\lambda_{EM} = K_A \cdot \lambda_{\Sigma}, \tag{1}$$

where λ_{Σ} is the total failure rate electronic device, included in EM AES.

The third approach is focused on the acceptance coefficient $K_{ПР}$ refinement, i.e. the manufacturing quality influence [22]. From the example of integrated microcircuits (IMC) in the reference [22], it is seen that depending on the IMC quality level, the type of test and control, the numerical value of $K_{ПР}$ varies. It may be concluded that this approach is used only to assess the quality of electronic devises production, not the AES EM in general . However, the $K_{ПР}$ coefficient according to the references [17, 22] is related to the degree of the requirements stringency for quality control and acceptance rules, which is directly related to K_A, which makes it possible to assess the quality production of AES EM as a whole.

B. Evalution of «production quality factor» in USA

The first approach is related to the determination of the "Quality factor" coefficient πQ, i.e. the manufacturing quality impact, according to the reference [22]. This approach is identical to that previously considered for Russia (see section A, third approach). Therefore, it is suitable only for assessing the electronic device quality production, and not for the AES EM in general.

The second approach is described in the source RIAC-HDBK-217Plus [23] and is considered in detail in [12]. In this case, the KA is presented in the mathematical model (2), then, the obtained result from model (2) is substituted into expression (1).

$$K_A = \Pi_P \cdot \Pi_{IM} \cdot \Pi_E + \Pi_D \cdot \Pi_G + \\ + \Pi_M \cdot \Pi_{IM} \cdot \Pi_E \cdot \Pi_G + \Pi_S \cdot \Pi_G + , \\ + \Pi_I + \Pi_N + \Pi_W \quad (2)$$

where Π_P is the parts quality process factor; Π_{IM} is the infant mortality factor; ΠE is the environmental factor; Π_D is the design process factor; Π_G is the reliability growth factor; Π_M is the manufacturing process factor; Π_S is the systems management process factor; Π_I is the induced process factor; Π_N is the can not duplicate (CND) process factor; Π_W is the wear out process factor.

Each coefficient in model (2) characterizes the category of failure. The EM percentage distribution failures by category is presented in Figure 2 (Π_E and Π_{IM} coefficients are not taken into account).

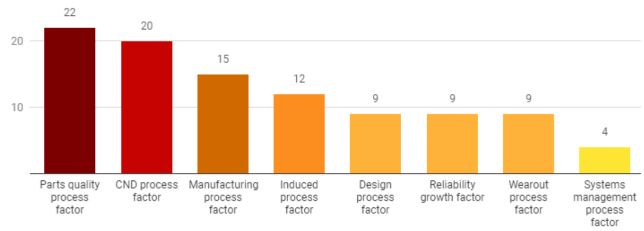

Fig. 2. The percentage distribution of EM failures by category, according to [23]

However, according to [23], the mathematical model for estimating the “production quality coefficient” K_A (2) takes into account a number of coefficients that are not relevant to the AES EM — Π_{IM} and Π_G coefficients.

A study of the source [23] showed that all the model coefficients (2), except for Π_{IM}, Π_E and Π_G, are estimated using expert judgment (external audit). The analysis of the questionnaire intended for the expert allows to draw the following conclusions that the questions for each of the coefficients used are of a chaotic order, there is no indication of belonging to the RTD and the questions are not divided by directions. Therefore, for clarity of the direction of the questions (personnel, product, process) for the coefficients Π_D and Π_P, a pie chart is shown (see Fig. 3, 4).

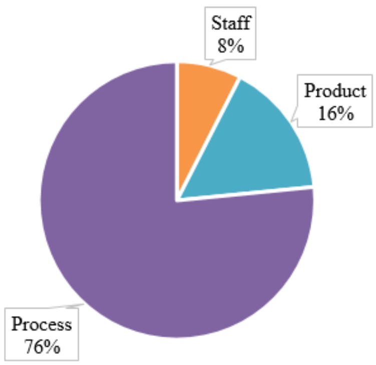

Fig. 3. The percentage distribution of the focus of questions for the coefficient Π_D

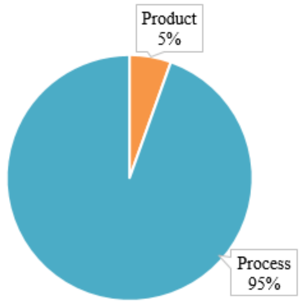

Fig. 4. The percentage distribution of the focus of questions for the coefficient Π_P

An analysis of Fig. 3 and 4 allows to say that for parts quality process factor the «Personnel» focus is not taken into account. Questions carry a semantic load on the process of agreement, technical management, organizational support of the project and technical [24].

Also, for each of the questions j, a weight coefficient W_{ij} and a numerical value G_{ij} are provided, depending on the answer, the R_i ranking which is carried out by expression (3):

$$R_i = \frac{\sum_{j=1}^{n_i} G_{ij} \cdot W_{ij}}{\sum_{j=1}^{n_i} W_{ij}}, \quad (3)$$

where n_i is the number of criteria i category of failure, W_{ij} is the weight coefficient j criteria i category of failure, Gij is the value of the j criteria i category of failure.

Further, the obtained values of R_i are used in formula (4) to estimate Π_i:

$$\Pi_i = \alpha_i \cdot (-\ln(R_i))^{\frac{1}{\beta_i}}, \quad (4)$$

where α_i and β_i are the constants for each failure cause category, given in Table [23].

The percentage distribution of the total weight coefficient $W_{i\Sigma}$ for the focus of questions (personnel, product, process) regarding the Π_D and Π_P coefficients is shown in the form of a pie chart in Figures 5 and 6.

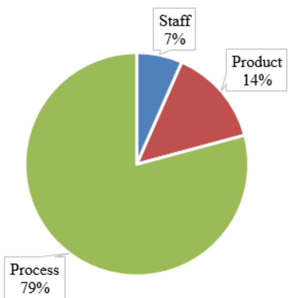

Fig. 5. The percentage distribution of the total weight coefficient $W_{i\Sigma}$ for the direction of questions of the coefficient Π_D

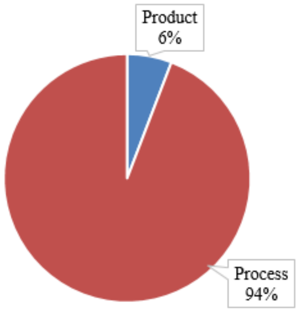

Fig. 6. The percentage distribution of the total weight coefficient $W_{i\Sigma}$ for the direction of questions of the coefficient Π_P

In connection with the indicated shortcomings of the considered approaches used both in Russia and in the USA, there is a need to clarify the calculated estimate of the "production quality factor" of the AES EM by developing an appropriate methodology based on the standard [23] taking into account not only the Regulation "..." but also taking into account the QMS, which ensures the stability of the quality of the AES EM and increases the customer satisfaction of space communications services.

III. DEVELOPMENT OF AN ESTIMATION METHOD OF «PRODUCTION QUALITY COEFFICIENT»

The proposed methodology structure for the "production quality factor" refinement of the artificial satellite complex is shown in Figure 7 as an IDEF-0 diagram. The methodology was developed in a universal form for use in countries involved in the AES EM production due to the distinguishability of the standards used.

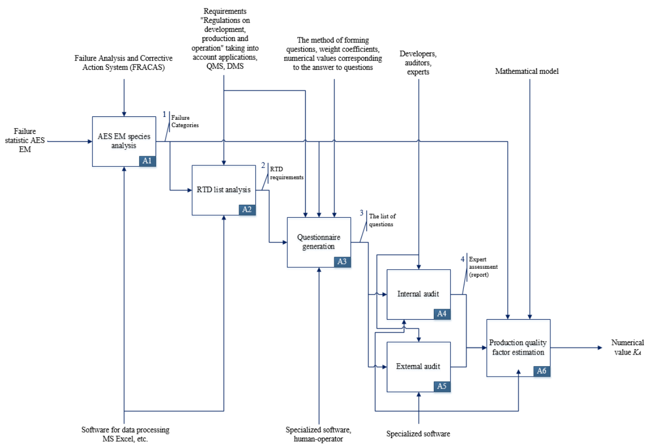

Fig. 7. Methodology for assessing the "coefficient of production quality" AES EM

The first stage (see Block A1, Fig. 7) involves an analysis of the AES EM failure types to form categories of failures as a percentage of the total number, for example Fig. 2. Therefore, the AES EM failure statistics is the object of study at this stage. To control the credibility of the processed data, a failure analysis and corrective action system (FRACAS) is used. To automate and increase the stage efficiency, it is recommended to use appropriate software, for example, MS Excel.

The second stage (see Block A2, Fig. 7) is necessary for the RTD list analysis during the creation, production and operation of the AES EP. The result of block A2 (see Fig. 7) is a set of the RTD requirements for the next operation (see Block A3, Fig. 7). It is also recommended to use appropriate software, for example, MS Excel, to automate and increase the efficiency of a stage.

The third stage (see Block A3, Fig. 7) is needed to form the questionnaire (see Fig. 8) in order to monitor the implementation of the necessary actions regulated in the RTD (the result of Block A2, Fig. 7). The questionnaire is classified according to failure categories (result of Block A1, Fig. 2). Indeed, each category of failures according to the "Regulation on the Development, Production and Operation" of the AES EM corresponds to a certain RTD list. In turn, the RTD consists of sections (see Column 1, Fig. 8), and sections can be divided into directivity (see Column 6, Fig. 8). Also, for even more specificity, directivity can be characterized by classification (see Column. 7-8, Fig. 8). Then, each question will have a strict hierarchy.

RTD: GOST R 56518-2015					Directivity	Classification	
Section	Question		Weight coefficient, *G*	Numerical value, *D*		Group	Subgroup
	№	Content					
1	2	3	4	5	6	7	8
Responsibility and authority	1	Is there the unit (srvice) responsible for: 1)quality control, 2) work organizing on improving the QMS at all stages of the production life cycle, 3) monitoring and analyzing the QMS degree of compliance with the established requirements and expectations of the customer?	3	1, if fulfilled p.1-3; 0.6, if 2 of 3 paragraphs are fulfilled; 0.3, if 1 of 3 paragraphs are fulfilled; 0, if not fulfilled p.1-3;	Process	Project organizational support	Quality control
	2	Are managers with responsibility and authority to take corrective actions informed of non-compliant products or processes?	3	1, if "Yes"; 0, if "No";			
	...						
Planning	1	Has top management defined quality objectives for the appropriate levels of management, departments, services in the implementation of the quality policy?	5	1, if "Yes"; 0, if "No",	Process	Technical management	Project planning
	2	Does senior management maintain integrity during planning and implementation of changes to the quality management system?	7	1, if "YES"; 0, if "No";			
	...						
Infrastructure	1	The organization establishes and provides supervision of technological equipment and a periodic assessment of their: 1) technical condition, including control of technological accuracy, 2) testing of software used in computer-aided design, product manufacturing and control (testing), and 3) carries out appropriate maintenance?	7	1, if fulfilled p.1-3; 0.6, if 2 of 3 paragraphs are fulfilled; 0.3, if 1 of 3 paragraphs are fulfilled; 0, if not fulfilled p.1-3;	Process	Project organizational support	Infrastructure management
	2	Has the organization developed action plans that provide the ability to fulfill customer requirements in emergency situations to minimize the consequences of such situations?	5	1, if "Yes"; 0, if "No";			
	...						

Fig. 8. Part of the questionnaire for assessing the coefficient characterizing the category of failure – systems management process factor Π_S

The questions have the following focus types: staff (management, developers, etc.), product (item, assembly unit, detail) - classification for Russia, according to [25], process (system life cycle processes - classification for Russia, according to [24]). For example, in Figure 8, a schematic representation of the questionnaire is given for the failure category associated with the imperfection of the Π_S control system (in Russia, the standard [15] is used for the focus of the "process" and classification according to [26]).

The proposed structure adaptation of the questionnaire is completely possible. For a better understanding, the structure of the questionnaire is presented in Figure 9 as an IDEF-5 diagram (standard for ontological research). The fact is that the ontology includes a set of terms and rules according to which these terms can be combined to build reliable statements about the state of the system at some point in time (based on the results of external and internal audits). Based on these statements, appropriate conclusions can be made that allow to make system changes to increase the efficiency of its functioning.

Note: in Figure 9, the red color indicates the path (affiliation of the issue) from the subgroup to the main document "Regulation on the Development, Production and Operation" AES EM.

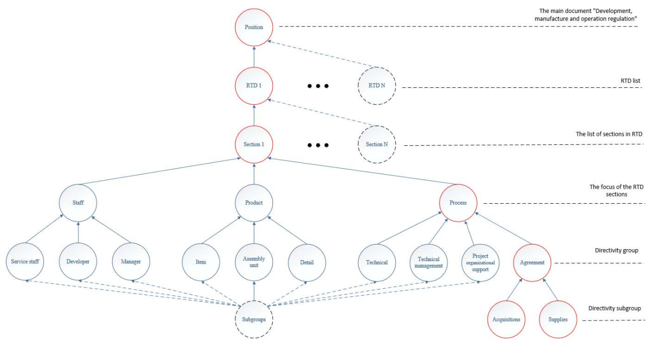

Fig. 9. Ontological structure for constructing a questionnaire for evaluating the coefficients characterizing the failure category

Based on this principle (ontological method of forming and researching issues), the construction of the questionnaire reveals the significant advantages and disadvantages of the manufacturing organization at the stage of designing AES EM according to the results of a numerical evaluation K_A. This becomes possible if it is envisaged that the calculated values of the coefficients that determine certain categories of failures and the coefficients of the direction of questions, taking into account the classification in specialized software, will be output into separate fields (see Fig. 8). This will lead to the timely identification of the advantages and disadvantages of a specific event, indicated in a specific section of the RTD, include QMS. This stage involves the use of specialized (requiring development) software, in addition to the human operator. The result of block A3 (see Fig. 7) is a list of questions (the number of the question is denoted by i), which corresponds to the categories of failures j and takes into account the RTD requirements to minimize the occurrence of possible failures. Each question (see Column 3, Fig. 8) is assigned a weight coefficient G_{ij} (see Column 4, Fig. 8) and numerical value D_{ij} (see Column. 5, Fig. 8) depending on the answer to the question during steps 4 and 5 (see Blocks A4 and A5, Fig. 7).

To meet the RTD requirements the fourth and fifth stages (see Blocks A4, A5, Fig. 7) require an audit to determine the correctness of the necessary actions (the result of Block A2, Fig. 7). In these stages the AES EM developers, which are directly related to the design process (see Block A4, Fig. 7), and external auditors / experts are involved. To automate the implementation of the fourth and fifth stages, specialized (requiring development) software is used. The result of these steps is an expert assessment, which is used in performing the next step number 6 (see Block A6, Fig. 7).

The sixth stage (see Block A6, Fig. 7) is the final one and allows to quantify the value of the quality factor K_A according to the mathematical model (5) in general form:

$$K_A = \sum_j \frac{\%_j}{100} \cdot K_j , \qquad (5)$$

where $\%_j$ is the failure rate j failure categories, K_j is the coefficient characterizing the category of failure and evaluated according to expression (6) in the general case:

$$K_j = \frac{\sum_{i=1}^{a_j} \left\{ \left[\left(G_{inkpj} \cdot D_{inkpj} \right) \cdot \frac{\%_n}{100} \right] \cdot \frac{\%_k}{100} \right\} \cdot \frac{\%_p}{100}}{\sum_{i=1}^{a_j} G_{inkpj}} , \qquad (6)$$

where $\%_n$ is the percentage of questions characterizing their orientation; n is the number of orientation types (staff, item and process); $\%_k$ is the percentage of sections characterizing sections in the RTD; k is the number of sections in the RTD; $\%_p$ is the coefficient characterizing a specific RTD; p is the amount of RTD; a_j is the number of criteria j failure categories.

The obtained numerical value of the “production quality coefficient” K_A can be used in expression (1) to clarify the AES EM failure rate, as well as for other EM developed for various application conditions.

IV. Conclusion

The article considers the approaches used in the USA and Russia, aimed at assessing the dependability, in particular, the reliability of the AES EM. The study shows that none of them gives a quantitative assessment of the reliability characteristics taking into account the QMS in addition to the RTD requirements, which is a significant drawback in the design. Also, the approaches are generalized for the EM, used in many industries, but not taking into account the features of the EM functioning in the space environment. To solve this problem, a methodology has been developed, where the distinguishing feature is the use of the "production quality factor" K_A, considering not only the "Regulations on the procedure for the creation, production and operation" relevant RTD, but also the QMS, which ultimately leads to a veracious assessment of the AES EM reliability measures at the design stage. The methodology will improve the achieving efficiency of the AES EM target dependability measure and increase the profitability of countries in the provision of space communications services.

In addition, the developed methodology makes it possible to identify an achievable level of the AES dependability measures designed by private non-state manufacturers of small satellites with an active lifetime of 2 to 10 years.

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