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On the Necessity to Improve the MIL-883E Standard

The necessity to improve the MIL-883 standard in order to more accurately determine the reliability indicators of thermoelectric generators (TEGs) is substantiated. It is shown that the failure time distribution law recommended by this standard follows from the assumption of a constant rate of relative degradation of the parameters of the tested products. Recommendations are given for the use of the MIL-883E standard for testing thermoelectric generators (TEGs). It is shown that the use of a diffusion-nonmonotonic failure time distribution instead of a logarithmic normal one allows for a significant reduction in relative errors, determination of TEG reliability indicators and a logical transition to the function of the probability of failure-free operation of an individual thermoelement.

Keywords: rate of relative degradation of product parameters, logarithmically normal law of failure time distribution, coefficient of variation of the rate of relative degradation of parameters of thermoelectric generator modules, diffusion-nonmonotonic law of failure time distribution, relative errors in determining reliability indicators.

1. Introduction

Awareness of the failure time distribution law of thermoelectric generator modules plays a key role in determining their reliability indicators. And those are often more important than the operating characteristics, which makes this work so topical. The basic standard, partially adapted to thermoelectricity, is the military standard MIL-883E [2]. The main model assumption for establishing the failure time distribution regulated by the mentioned standard was the assumption of a linear law of relative degradation β of the parameters of integrated circuits and semiconductor devices over time. and of constancy [1]. The mathematical

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expression for the linear model of relative degradation of the parameters is as follows:

$$\left(\frac{a_0-a_1}{a_0}\right)=\beta t \quad (1)$$

where t is time, a_0 and a_1 are the initial and final values of a certain parameter of the tested product, respectively. The resulting value is nothing but the criterion of its applicability established by the technical specifications for the product, the deviation from which is considered as a failure. From (1) it is clear that for fixed values of β and a_1, the time for reaching the same failures is determined by the initial parameters of the products. Let the technological process of manufacturing products ensure not only the ideal reproducibility of their initial parameters and the values of β. Then the distribution of failure times will be the same as the distribution of the initial parameters of the products, that is, due to the law of large numbers, normal or logarithmically normal [1]. This distribution is convenient for it does not require a special normalization procedure. It is with its use that reliability indicators in microelectronics are determined [1]. Based on such a distribution of failure times, the MIL-883E standard [2] requires improvement because the distribution of failure times of thermoelectric generator modules is not logarithmically normal. Reliability indicators in accordance with the mentioned standard are the terms of achieving 50 % and 16 % (more precisely 15.7 %) failures in the tested sample. and the logarithm of the ratio of these terms. The first of these terms is equal to the average operating time of the tested products to failure, and the mentioned logarithm characterizes the degree of deviation of the density of the failure time distribution from δ, the function, i.e. the deviation of the time dependence of the probability function of failure-free operation from an ideal rectangle, which is perfect in terms of reliability theory. The dispersion of the rates of relative degradation of the parameters of thermoelectric generator modules considers the diffusion-nonmonotonic law of the failure time distribution, developed by the Institute of Problems of Mathematical Machines of the NASU [3]. It should be noted that in the absence of variation in the rate of relative degradation of product parameters, reliability indicators such as equivalent constant failure intensity and γ, percentage resource, lose their meaning, and the question of the reliability and relative errors of determining reliability indicators within the framework of the diffusion-nonmonotonic failure time distribution [3] disappears. The function of the probability of failure-free operation has the form of:

$$P(t)=\Phi^{\cdot}{}_0\left(\frac{1-\frac{t}{\mu}}{\nu\sqrt{t/\mu}}\right)-exp\left(\frac{2}{\nu^2}\right)\Phi^{\cdot}{}_0\left(\frac{1-\frac{t}{\mu}}{\nu\sqrt{t/\mu}}\right) \quad (2)$$

where μ is mean-time-between-failures (MTBF), ν is a dimensionless coefficient of variation of the rate of relative degradation of the parameters of the tested thermoelectric generator modules, the function Φ_0 is determined by the formula (3). At zero coefficient ν of variation of the rate of relative degradation of the parameters of the tested thermoelectric generator modules, the time dependence of the probability of their failure-free operation $P(t)$ degenerates into an ideal rectangle with length μ and height 1. With increasing ν, its deviation from the ideal rectangle increases significantly, therefore, the errors in determining reliability indicators increase. The disadvantage of the maximum likelihood method proposed by the mentioned DSTU (State Standard of Ukraine) [3] is that it operates exclusively with failure terms and does not predict the time dependence of the probability of failure-free operation of the tested products. The estimates of the parameters μ and ν of the diffusion-nonmonotonic failure time distribution law are directly determined through the experimental values of the failure terms without taking into account the observed probabilities of their realization, and the corresponding analytical formulas for their calculation are derived by the maximum likelihood method. However, our studies have shown that the time dependence of the probability of failure-free operation of the tested thermoelectric generator modules approximated in this way significantly deviates from the predicting results and experimental data, therefore, the estimates of the parameters of the diffusion-nonmonotonic failure time distribution law obtained by the maximum likelihood method are considered by us as initial approximations, which are subject to refinement by the least squares method. The corresponding system of equations for the mentioned parameters is solved by the Newton iterative method. The number of iterations is chosen so as to obtain a significant reduction in the sum of the squares of the deviations of the points of the approximated time dependence of the probability of failure-free operation from the experimental data and the predicting results with the refined values of the law parameters compared to the parameters obtained by the maximum likelihood method. Our studies have shown that there was indeed a significantly better agreement of the function of the probability of failure-free operation, approximated by the least squares method, with the experimental data and the predicted results. It turned out that the refined value of ν is somewhat smaller than that obtained by the maximum likelihood method, as a result of which the relative error of determining 95 % of the resource of the tested thermoelectric generator modules with a confidence probability of 0.99 decreased from 66 % to 26.5 %, while the above-mentioned DSTU [3], exclusively in agreement with the customer, allows a maximum relative error of 40 %. The function Φ_0 in formula (2) is defined as follows:

$$\Phi_0\,(z) = 0.5\mathrm{erf}\left(\frac{\sqrt{2}z}{2}\right) + 0.5, \tag{3}$$

where – erf(…) the so-called error integral.

It is important to note that the dissolution of fluids of liquid degradation of their parameters attached to thermoelectric generator modules is not the same as the diffusion-non-monotonic law of the distribution of species, but rather the diffusion-monotonic law [3].

These laws are inconsistent with each other due to the nature of the long-term strength and the versatility of unmanned work due to the coefficient of variation in fluidity and the significant degradation of parameters tested viruses and mathematical formulas for calculating initial approximation parameters of laws using the maximum likelihood method. Care must be taken in the process of testing thermoelectric generator modules for the reliability of the implementation of specific terms within the framework of this method and does not guarantee the required accuracy

2. Research results and their discussion

Let us consider the application of the above approaches on the example of predicting failure terms using the Weibull degradation model, the mathematical expression of which for an arbitrary parameter of a thermoelectric generator module is as follows:

$$V(t) = V_0 \times exp\left(-\left(\frac{t}{\tau}\right)^{\delta}\right) \quad (4)$$

where V_0 is the initial value of the parameter-criterion of suitability of the thermoelectric generator module, δ is the shape parameter, τ is the scale parameter which are determined from the experimental data by the least squares method. The output power and efficiency of the tested thermoelectric generator modules were measured every 180 hours. As a result of predicting the terms of their loss of 20 % in the output power and efficiency, a tabular dependence of the probability of their realization was obtained (see table 1).

It should be noted that in this article we did not use the analytical expression (2) derived by the developers [3], but moved to it by numerically integrating over time the corresponding failure time distribution density given in [3]. At zero value of the coefficient of variation of the rate of relative degradation of the parameters of thermoelectric generator modules, the mentioned failure time distribution density degenerates into a δ-function, and the time dependence of the probability of failure-free operation of the tested thermoelectric generator modules turns into a perfect rectangle.

Table 1

Time dependence of the probability of failure-free operation of the tested thermoelectric generator modules, determined by the Weibull degradation model

P(t)	8/9	7/9	2/3	5/9	4/9	1/3	2/9	1/9	0
t год	9725	10690	11140	11220	11760	12230	16660	22660	66780

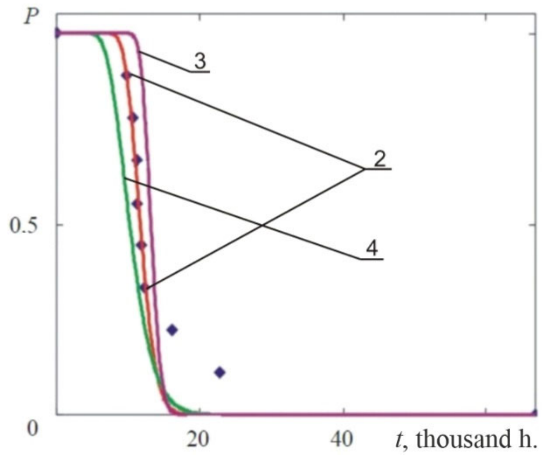

Fig. 1

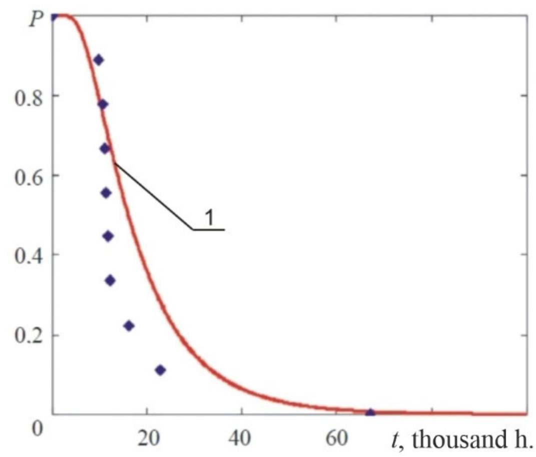

Fig. 2

Approximation of this dependence by the diffusion-nonmonotonic law of failure time distribution by the least squares method gave the following standardized reliability indicators of the tested thermoelectric generator modules: MTBF11770 h with a relative error of determination being 11.9 %; 95 % resource is 9170 h with a relative error of determination of 26.5 %, with a confidence probability of 0.99. The approximate time dependence of the probability function of failure-free operation obtained by the maximum likelihood method deviates sharply from the predicting results compared to the approximate dependence determined by the least squares method, as can be seen from Fig. 1 and 2.

In Fig. 1: 2 is the curve of the probability of failure-free operation of the tested thermoelectric generator modules, approximated by the least squares method; 3 and 4 are the limit curves taking into account the errors in determining the reliability indicators of the tested thermoelectric generator modules with a confidence probability of 0.99. In Fig. 2 the curve 1 denotes the probability of failure-free operation, approximated by the maximum likelihood method. The points in both figures are the results of predicting failure terms using the Weibull degradation model. Comparison of the results of predicting failure terms using the Weibull degradation model with their values observed at the stage of running-in of thermoelectric generator modules gives a relative discrepancy that does not exceed 10.6 %. Such predicting accuracy can be considered acceptable. The equivalent constant failure rate of the tested thermoelectric generator modules was $\lambda = 8.172 \cdot 10^{-5} h^{-1}$ with a relative error of 10.5 %. At first glance, such a failure rate of the thermoelectric generator modules seems significant, but it corresponds to the failure rate of one thermoelement equal to $6.435 \cdot 10^{-7}$ h^{-1}, which is approximately 3.1 times less than the value given in the literature [4], which is equal to $2 \cdot 10^{-6} h^{-1}$. The above-mentioned failure rate λ of the tested thermoelectric generator modules as a whole relative to their loss of 20 % of the output power is within $5 \cdot 10^{-5}$–10^{-4} h^{-1}, which meets the requirements of the IEC607-49-23 and JEDEC JESD-22A104 standards. The specified standards provide for a service life of thermoelectric generator modules from 10 thousand h. to 20 thousand h. From Figures 1 and 2 it is clear that the curve of the probability of failure-free operation of the tested thermoelectric generator modules, approximated by the method of least squares, passes through a larger number of points, and the limit curves of the probability of failure-free operation of the tested thermoelectric generator modules lie sufficiently close to each other, which ensures proper accuracy and reliability of determining the reliability indicators. Let us consider that the failure intensity given in this article is acceptable for the use of the tested thermoelectric generator modules both in industry and everyday life. To predict the failure times of thermoelectric generator modules with a service life of over 100 thousand hours. for military and space applications, it is advisable to use not the Weibull degradation model, but its more generalized modification [5], which takes into account the presence of their limiting resource, which corresponds to the complete loss of the performance of the tested thermoelectric generator modules. The probabilities of realizing different values of the limiting resource in the tested sample were found by approximating the observed time dependences of the output power and efficiency of the tested thermoelectric generator modules by the least squares method and are given in Table 2. Approximation of this function of the distribution time of complete failures of the tested thermoelectric generator modules in accordance with the diffusion-nonmonotonic law of the distribution time of failures (2), carried out by the least squares method (Fig. 3), enabled determining the following indicators of the limiting resource stability of the materials used in the tested thermoelectric generator modules [5]: average operating time to complete failure (average limiting resource) 2.91·106 h with a relative error of 5.3 % at a confidence probability of 0.95; 95 % limit resource 2.61·106 h with a relative error of 12.9 % at the same confidence probability equivalent constant failure rate $\lambda = 3.38\cdot10^{-6}h^{-1}$ with a relative error of 15.1 %. Such equivalent constant failure rate corresponds to the minimum achievable equivalent constant failure rate of one thermoelement equal to $2.64\cdot10^{-8}h^{-1}$, which is quite acceptable for practical application of the tested thermoelectric generator modules.

Table 2

t, hour	$2.624\cdot10^6$	$2.934\cdot10^6$	$2.992\cdot10^6$	$3.335\cdot10^6$
P(t)	0.75	0.5	0.25	0

It should be mentioned that the introduction of the equivalent constant failure rate to the list of standardized reliability indicators of thermoelectric generator modules is appropriate and justified because, for any non-ideally rectangular time dependence of the probability of failure-free operation of the tested thermoelectric generator modules, there is a time interval counted from the start of the tests, during which the number of suitable thermoelectric generator modules will decrease by 2.71828 times. The value inverse to the duration of this interval is equal to the equivalent constant failure rate of the tested thermoelectric generator modules. The obtained indicators of resource stability of materials can rightfully be called integral, since it is difficult to reasonably attribute them to individual materials that significantly differ from each other in resource stability.

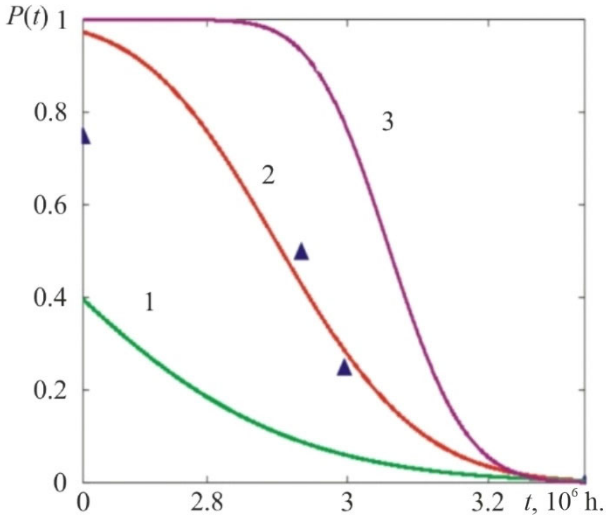

Fig. 3. Dependences of the probability of realizing a certain marginal resource of thermoelectric generator modules on the value of this resource: 1 – approximated by the maximum likelihood method in accordance with the diffusion-nonmonotonic law of failure time distribution, 2 – approximated by the least squares method. 1,3 – marginal curves taking into account errors at a confidence probability of 0.95, triangles – results of predicting the marginal resource according to the probabilistic theory of degradation

It should be also noted that the failures of thermoelectric generator modules during accelerated tests cannot be explained by layer-by-layer cracking of thermoelectric legs under the action of thermomechanical stresses transverse to the temperature gradient, the relaxation of which is facilitated by the regulated and controlled pressing of the tested thermoelectric energy converters to the hot heat exchanger.

3. Conclusions and recommendations

It is shown that the logarithmically normal law of failure time distribution follows from the model assumption of the constancy of the rate of relative parameter degradation, which is not inherent in thermoelectric generator modules. The dispersion of the values of the rate of relative parameter degradation inherent in thermoelectric generator modules takes into account the diffusion-nonmonotonic law of failure time distribution regulated by DSTU [3], developed by the Institute of Problems of Mathematical Machines of the NASU. Preliminary predicting of failure terms of thermoelectric generator modules is advisable to be carried out on the basis of a probabilistic model of degradation of their parameters according to certain failure characteristics. The simplest of them, the Weibull model, is advisable to use at the stage of running-in of thermoelectric generator modules for highly reliable thermoelectric systems, and also to assess and predict the reliability of materials, including thermoelectric ones, it is necessary to use a more generalized degradation model that assumes the presence of their limit resource [5]. The parameters of the degradation models are determined by appropriate approximation of the time dependences of the parameters of the tested thermoelectric generator modules obtained during the tests by the least squares method. Further, the failure terms determined for each of the tested thermoelectric generator modules are arranged in ascending order, then, taking into account the volume of the tested sample and assuming the gradual nature of failures, a table of the predicted time dependence of the probability of failure-free operation of the tested thermoelectric generator modules is constructed according to Table 1.After that, in accordance with the diffusion-nonmonotonic failure time distribution law [3], estimates of the parameters of the diffusion-nonmonotonic failure time distribution law are determined by the maximum likelihood method directly through the failure terms predicted by the degradation models, namely: the average operating time of the tested thermoelectric generator modules before failure and the coefficient of variation of the rate of relative degradation of their parameters, namely, parameters of the diffusion-nonmonotonic failure time distribution. We consider these estimates only as an initial approximation for approximating tabular data by the least squares method. The corresponding system of equations regarding the parameters of the diffusion-nonmonotonic failure time distribution law is solved by Newton's iterative method. Further on, based on the found parameters of the diffusion-nonmonotonic failure time distribution law, taking into account the volume of the tested sample, the γ-percentage resource of the tested thermoelectric generator modules and the equivalent constant intensity of their failures and the relative errors of determining these reliability indicators for a given confidence probability are additionally found. The main difference of the approach we used to approximate the probability function of failure-free operation of the tested thermoelectric generator modules is a significant reduction in the relative errors of determining their reliability indicators for a given confidence probability. It should be noted that the diffusion-nonmonotonic failure time distribution law [3] instead of the logarithmically normal [1] in combination with the probabilistic theory of degradation of thermoelectric generator modules can be used, taking into account the cycle duration, to determine the indicators of cyclic stability of thermoelectric generator modules. It is important to note that using the approach described in this article, we can find the equivalent constant failure rate with acceptable accuracy, regardless of the accuracy with which the approximation of the constant failure rate is confirmed by experimental data, since it is regulated by many international standards and determines the most appropriate areas of application of the tested thermoelectric generator modules. According to the known temperature dependence of the equivalent constant failure rate found in the process of accelerated tests, assuming the validity of the Arrhenius law, it is possible to find the activation energy of defects that cause failures of the tested thermoelectric generator modules, and then identify these defects. If we assume that identical defects have the same activation energy, then due to the Arrhenius law, only the average and γ-percentage resources of the tested thermoelectric generator modules and the equivalent constant intensity of their failures will depend on the temperature, because the coefficient of variation of the rate of relative degradation of their parameters, being a relative value according to [3], will not depend on the temperature. Therefore, the relative errors in determining the reliability indicators of the tested thermoelectric generator modules will also be temperature independent.

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Про необхідність удосконалення стандарту MIL-883E

Обґрунтовано необхідність удосконалення стандарту MIL-883 з метою більш точного визначення показників надійності термоелектричних генераторів(ТЕГ). Показано, що рекомендований цим стандартом закон розподілу часу відмов випливає з припущення про сталість швидкості відносної деградації параметрів випробовуваних виробів. Даються рекомендації щодо використання стандарту MIL-883E до випробування термоелектричних генераторів (ТЕГ). Показано, що використання дифузійно-немонотонного розподілу часу відмов замість логарифмічно нормального дозволяє істотно знизити відносні похибки, визначення показників надійності ТЕГ та закономірно перейти до функції імовірності безвідмовної роботи окремого термоелемента.

Ключові слова: швидкість відносної деградації параметрів виробів, логарифмічно нормальний закон розподілу часу відмов, коефіцієнт варіації швидкості відносної деградації параметрів термоелектричних генераторних модулів, дифузійно-немонотонний закон розподілу часу відмов, відносні похибки визначення показників надійності.

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