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Impact of Electronic Components Thermal Resilience on the Reliability of Radio-Electronic Equipment

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The article focuses on the impact of temperature on the reliability of electronic components, as in non-redundant radio-electronic equipment, the failure of any component typically leads to the failure of the entire device. The methods and approaches used to analyze the electronics reliability, predict operational lifespans, and to enhance it are considered. Thermal effects are among the most significant factors influencing reliability indicators of electronics, such as the probability of failure-free operation and mean time to failure. The sequence of accounting for thermal factors during the calculations of operational failure rate, mean time to failure, and the probability of failure-free operation according to the recommendations of Ukrainian State Standards is analyzed. The primary focus is on calculating the mean time to failure for various groups of resistors, capacitors, integrated circuits, and semiconductor components. Modern approaches to reliability assessment are used in the study, particularly a combination of failure physics and computer modeling. It was determined that the difference in the mean time to failure between the most and least thermally resilient electronic components of radio-electronic equipment can be very significant and only increases with rising temperatures.

Keywords: electronic; components; impact; temperature; reliability; calculation; software; thermal; resilience; mean; time; failure; MTTF

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Introduction. Statement of the problem

The reliability of electronic components (ECs) is a crucial factor in ensuring their failure-free operation over a long period of use. One of the main factors affecting the reliability of electronic components is their temperature. External thermal factors and internal heat generation from the device itself determine the thermal distribution, for example, across the printed circuit board, which serves as the foundation for placing electronic components. Incorrect thermal regimes typically impact reliability and functional performance, causing issues that can lead to overloads, reduced lifespan, changes in electrical characteristics, and an increased probability of failure.

The State Standard of Ukraine 2862-94 "Reliability of Equipment. Methods for Calculating Reliability Indicators. General Requirements" defines the features of calculating reliability indicators at various stages of research and development work, including the development of specifications, technical proposals, preliminary and technical projects. The objectives of such calculations are to determine reliability indicators, justify the optimal reliability variant of the design solution, identify the nomenclature of assembly units that limit the reliability of the overall object, develop measures to enhance reliability, verify the expected level of reliability against established requirements, and so on.

The main goal of this paper is to study the effect of temperature on the reliability of electronic components from different groups to identify the most and least thermal resilient at the stages of technical proposal and preliminary design.

1 Analysis of research and publications

To analyze the reliability of electronics, it is common to use the Physics of Failure (PoF) approach and computer modeling using software systems [1]. The PoF approach was formulated during the U.S. Air Force symposium in 1962 [2]. Its application helps engineers and researchers develop more reliable systems, predict their operational lifetimes, identify potential issues, and devise strategies to prevent failures. It is used in many fields, including electronics [3], aviation, machine components manufacturing [4], energy, and many others. For systems with multiple dependent components, prediction of maintenance [5] and reliability is performed using maintenance policies [6].

In the reliability calculation process, failure data collected during observations or experiments are used to determine parameters such as Mean Time to Failure (MTTF), failure rate (λ) and others. Physics of Failure approach also allows taking into account various factors, such as aging, temperature, voltage, vibration, etc., which can affect radio-electronic equipment reliability [7].

Modern electronics faces demands for economy, compactness, and high power density, which typically lead to increased operating temperatures. Therefore, in order to reduce the number of failures, new approaches and methods of reliability calculation are being developed and utilized [8]. The main idea is to study the causes of failures and their impact on system operation. Attention is given to the identification of potentially vulnerable areas, damage mechanisms, and defects that may lead to system failures for further prediction, measurement, and reliability assurance [9].

Various aspects are considered in studies of temperature impact on electronics reliability. One of the directions consists in determining the optimal range of operating temperatures [10], at which electronics function most efficiently and have the maximum duration of operation. Another direction involves studying the influence of extreme temperature conditions on the operation of electronics. The reliability and failure mechanisms associated with high temperature (175-250°C) and humidity are investigated in [11]. Low temperatures can also induce changes in electrical properties, therefore, work is carried out to enhance low-temperature reliability through electrothermal analysis [12].

The main factors influencing reliability under changing temperatures are being identified, such as thermal stress, material expansion, thermal degradation, and so forth. Research on the dependency of reliability on temperature effects is conducted in various fields, for instance: materials and compounds of electronic devices [13]; embedded electronics [14]; electric transport [11]; substation automation systems [15]; future power fusion machines [16], downhole electronics (operating in an environment of 200°C) [17].

Researchers are also focusing on developing efficient cooling systems for microelectronics [18]. To enhance the reliability, performance, and longevity of modern compact and densely packed electronics, thermal management systems are being developed and improved for various operating conditions [17, 19, 20].

Various approaches are used to predict the reliability of electronic equipment, allowing reliability assessment based on statistical data, calculations, and experimental tests. Numerical modeling, finite element theory, the use of computer programs, and engineering tools allow for realistic predictions of temperature fields formed during the operation of electronics [21].

Basically, for the thermal analysis of electronics, various systems of automated design (CAD), such as SolidWorks, Ansys Workbench and others, are used [22]. For example, to calculate peak thermal loads on semiconductors to confirm the effectiveness of the High step-up DC-DC converter (HSDDC) thermal models in the PLECS environment are utilized [23].

To take into account the influence of the temperature effect on electronic components, models based on information about their geometry and materials are developed using the Finite Element Method (FEM). Such models, like the insulated gate bipolar transistor (IGBT) model, are aimed at ensuring simulation accuracy at the circuit level, as well as during overloads or even short circuits [24, 25]. Depending on the type of electronics and its characteristics, reliability prediction methods can have different aspects.

For predicting the lifetime of power electronics, the Stress-Strength Analysis Method (SSAM) is proposed [26], which utilizes the concept of structural reliability, where the physics of failure is taken into account.

To accurately predict reliability, using the physics of failure approach, one of the main problems is obtaining information from manufacturers about electronic components, their materials, reliability indicators, and manufacturing processes [27–29].

To predict the reliability of power electronic systems in unmanned aerial vehicle (UAV), the authors of [30] developed a model that allows taking into account different operating modes and operating conditions based on the flight mission profile. Component temperatures are recorded for different missions, and the obtained data are used to improve the calculation of mission-specific failure rates. For example, in the post-accident mode, component currents and temperatures increase, significantly affecting the failure rate of components.

In industrial sectors, such as automotive manufacturing, due to the increasing complexity and diversity of systems, the use of soft computing techniques is proposed to overcome the difficulties in reliability analysis using statistical models. The results of a comparative study [31] between software and statistical calculations demonstrated that the Adaptive Neuro-Fuzzy Inference System (ANFIS) model allows for the most accurate prediction of operational reliability.

In the articles [18] and [32], the authors propose strategies for optimizing the design of microelectronics cooling systems and addressing thermal management issues. For this purpose, they utilize the Cuckoo Search algorithm and the Generalized Spiral Optimization algorithm, respectively.

A 30% reduction in the maximum temperature was achieved by the authors of [33] using reliability-based design optimization (RBDO). This methodology is a combination of 3D finite element simulation, the Kriging substitution model, and an optimization procedure.

The article [34] discusses the optimization of thermal load distribution in tests at elevated temperatures to determine the durability of soldered joints. The influence of various heating and cooling gradients on the reliability of soldered joints is evaluated through thermomechanical finite element simulation. In article [35] the methods for modeling and optimizing the thermal regimes of electronic equipment are presented.

The reviewed publications demonstrate a wide range of research in the field of analysis and reliability prediction of electronic equipment. They primarily focus on general issues related to the impact of temperature on electronics, the development of thermal management systems, providing cooling, improving operating modes, and studying the behavior of specific components under thermal loads. This article is dedicated to the relevant research on the temperature dependence of the Mean Time to Failure for various groups of electronic components, which will primarily aid in identifying the most and least thermal resilient components.

2 Thermal impact on reliability indicators

The standard DSTU 2862-94 [36] recommends the use of a diffusion non-monotonic (DN) distribution of resource for radio-electronic products and electronic systems, the predominant failure mechanism of which is the aging process, fatigue, and various electrical processes. The probability of failure-free operation of electronic components that have a DN-distribution of operating time before failure is calculated by the formula:

$$P(t) = \Phi\left(\frac{MTTF - t}{\nu\sqrt{MTTFt}}\right) - e^{\frac{2}{\nu^2}}\Phi\left(-\frac{MTTF + t}{\nu\sqrt{MTTFt}}\right),$$

where $\Phi(u)$ is the normal distribution function (u is integration parameter); $MTTF$ is mean time to failure; t is required operating time of the object; ν is coefficient of variation of the product's operating time, assumed to be one if there are no additional experimental data.

With respect to scale and shift, the error function «erf» coincides with the probability normal distribution function, therefore it is more convenient to use the equivalent formula in the calculation process:

$$\Phi(u) = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{u}{\sqrt{2}}\right)\right].$$

The mean time to failure is determined by the equation:

$$\sqrt{\frac{MTTF}{2\pi\tau_b^3}}\exp\left[-\frac{(\tau_b - MTTF)^2}{2\tau_b MTTF}\right] = \lambda_{op},$$

where λ_{op} is the operational (working) intensity of failures, which takes into account the operating conditions; τ_b is the test duration (in hours), during which the value of the basic failure intensity λ_b is obtained.

The values of λ_b for most electronic components listed in the handbooks were determined in accelerated tests over a period of time $\tau_b(1\ldots5)\cdot10^4$ hours, while the value of the actual failure intensity λ_{op}, in turn, is related to λ_b by a dependency:

$$\lambda_{op} = \lambda_b K_{op}\prod_{i=1}^{n} K_i,$$

where λ_b is the initial (baseline) failure intensity at nominal electrical load and normal ambient temperature 25°C; K_{op} is the operating mode coefficient provided by the temperature function (T) and the load coefficient, for its calculation, it is advisable to use analytical models provided in reliability handbooks for radioelectronic products; K_i are coefficients that account for changes in failure intensity depending on various factors (requirements for the development and manufacture of equipment, operating conditions severity, equipment complexity, etc.); n is the number of factors taken into account.

Therefore, the reliability of each electronic component depends on: the baseline failure intensity; the mode coefficient determined by the load (IC complexity) and the component enclosure temperature; coefficients that account for other various factors. Some of the K_i coefficients (K_{tx}, K_{t1}, K_{Tnt}, K_{t2}, K_t, K_T, K_{T1}, etc.) also depend on temperatures: ambient, housing, transistor junction, etc. Therefore, the temperature conditions of component operation are crucial for their reliability indicators and the reliability of electronic equipment as a whole.

The calculation of reliability metrics, such as mean time to failure, depending on temperature for various groups of electronic components is a rather complex task. It is necessary to take into account the diverse properties of each component, and real devices may contain hundreds or thousands of components of different types, with calculations individually performed for each of them. Performing such calculations manually requires significant time spent searching for a large volume of parameters for each component and repetitive calculations, with the risk of errors due to operator negligence. Therefore, the development and use of computer programs is mandatory.

Automation of the considered calculations with the help of software makes it possible to quickly and efficiently take into account a vast number of factors and improves the design process.

3 Temperature dependence of MTTF for electronic components from different groups

For determining the thermal resilience of electronic components from different groups, it is advisable to calculate the MTTF dependencies on their temperature. In order to automate the calculation of reliability indicators (according to DN-distribution), software was developed.

The calculations presented in this article were performed for a temperature range from 0 to 110 °C. The load factor is set to 0.8, meaning that in the conducted calculations, K_{op} depends solely on the temperature of the ECs.

MTTF, as a function of parameters λ_{op} and τ_b (for $\tau_b = 3 \times 10^4$ hours), was calculated using the approximation expression:

$$MTTF(\lambda_{op}) = a \log_{10}(\lambda_{op}) + b,$$

where $a = –1{,}574$; $b = 2{,}697$.

The research was conducted for ECs from 59 different groups across four categories: resistors, capacitors, integrated circuits (ICs), and semiconductor devices.

Figure 1 shows dependence of MTTF on T for a set of nine fixed non-wirewound resistors.

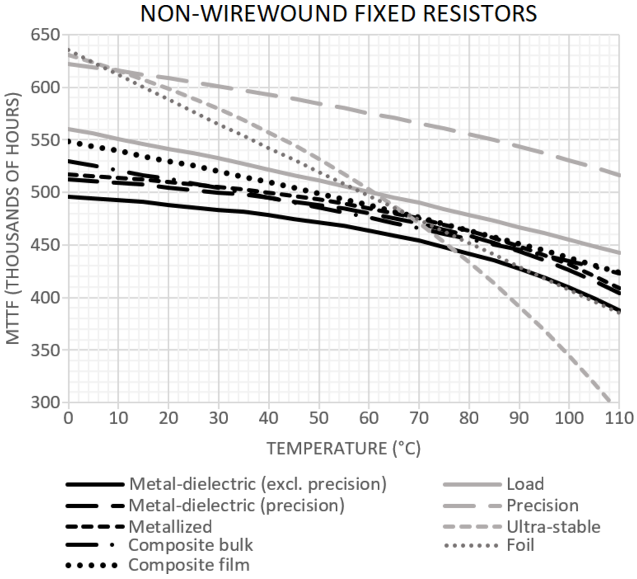

Fig. 1. Dependence of MTTF on T for non-wirewound fixed resistors

The precision resistors were the most reliable (at temperatures above 10°C), while the greatest reduction in MTTF with increasing temperature was observed in the Ultra-stable resistors.

Figure 2 shows dependence of MTTF on T for a set of four fixed wirewound and foil resistors.

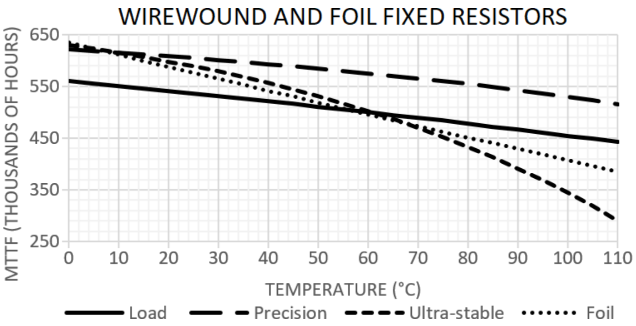

Fig. 2. Dependence of MTTF on T for wirewound and foil fixed resistors

Here again, the precision resistors were the most reliable (at temperatures above 10°C), while the greatest reduction in MTTF was observed in the ultra-stable resistors.

Figure 3 shows dependence of MTTF on T for a set of six variable resistors.

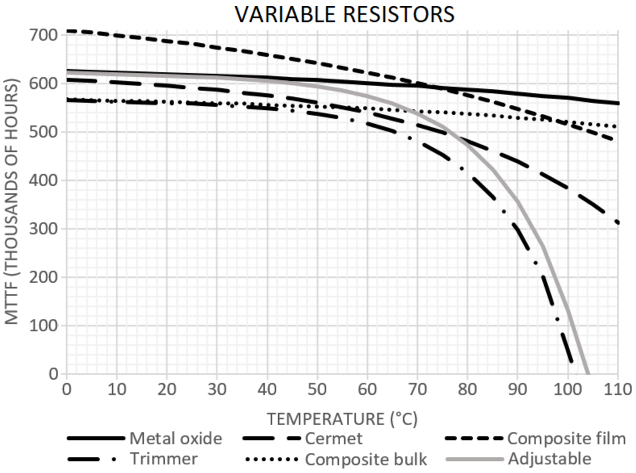

Fig. 3. Dependence of MTTF on T for variable resistors

The results significantly differ from the previous sets of resistors. Metal oxide and composite bulk resistors demonstrated the greatest resilience to temperature increase, while adjustable and trimmer resistors showed the least, with a sharp decline in MTTF above 70 °C.

Figure 4 shows dependence of MTTF on T for a set of nine fixed capacitance capacitors.

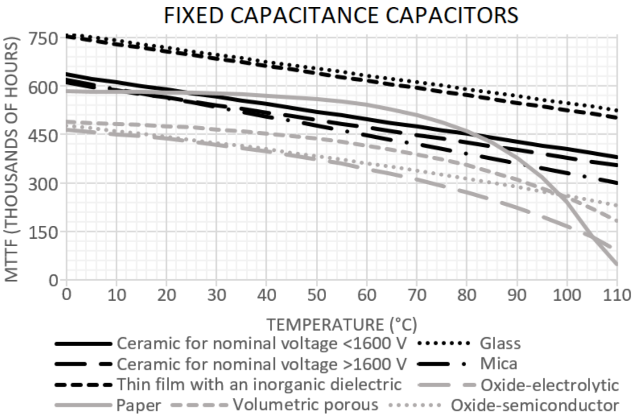

Fig. 4. Dependence of MTTF on T for fixed capacitance capacitors

The glass capacitors were the most reliable, while the least reliable were the oxide-electrolytic capacitors. It is noteworthy that glass and thin film with an inorganic dielectric capacitor at minimum temperature are more reliable than all previously considered groups of resistors.

Figure 5 shows dependence of MTTF on T for a set of eight capacitors with organic synthetic dielectric and trimming capacitors.

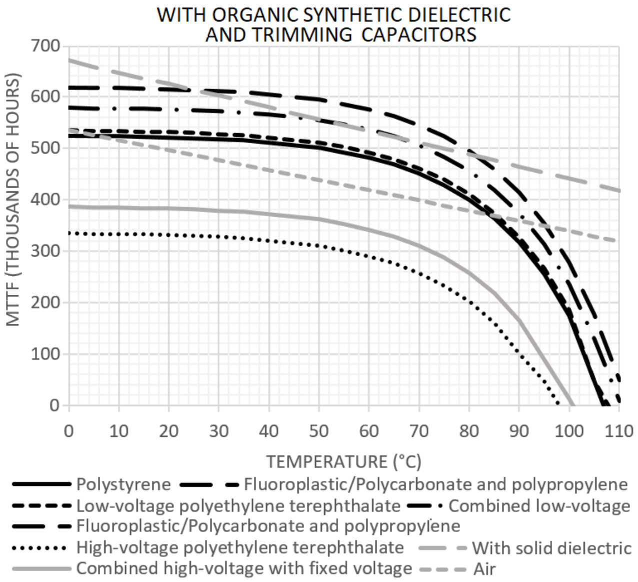

Fig. 5. Dependence of MTTF on T for capacitors with organic synthetic dielectric and trimming capacitors

All capacitors with organic synthetic dielectric show a significant drop in MTTF when reaching a certain temperature, and at the maximum temperature, almost all groups experience failure. The MTTF dependence on T for trimming capacitors (with solid dielectric and air capacitors) appears to be linear.

Figure 6 shows dependence of MTTF on T for a set of six groups of integrated circuits (ICs). In the reference guide, each of them is divided into subgroups based on the number of elements and bits. Calculations were performed for the IC with the maximum number of elements/bits in each group.

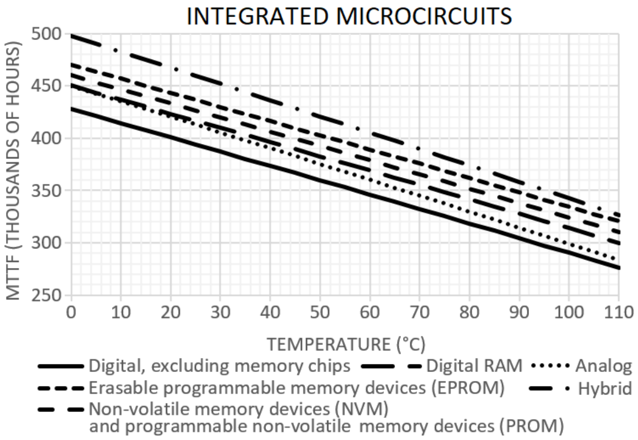

Fig. 6. Dependence of MTTF on T for ICs

The reduction in MTTF for all groups of ICs is linear and averages 150 thousand hours for the given temperature range.

Figure 7 shows dependence of MTTF on T for a set of nine semiconductor devices (excluding the microwave range).

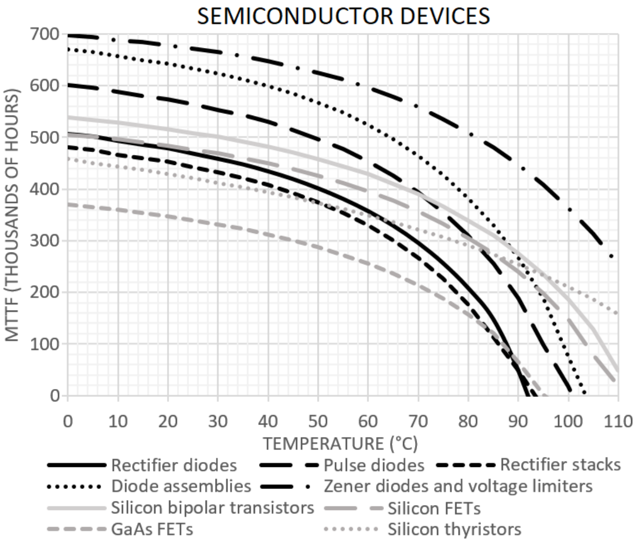

Fig. 7. Dependence of MTTF on T for semiconductor devices (except for microwave range)

Figure 8 shows dependence of MTTF on T for a set of eight semiconductor devices (microwave range).

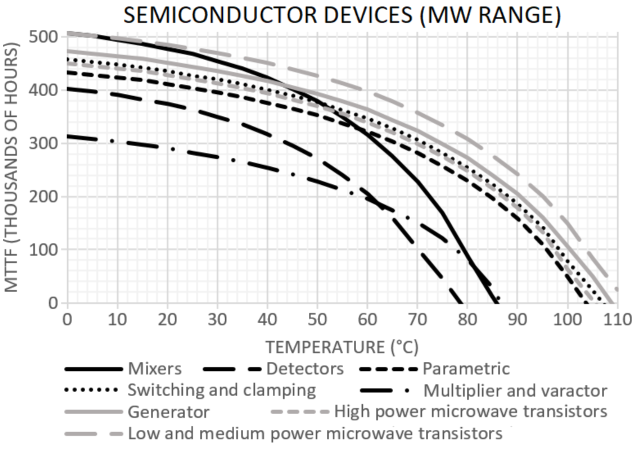

Fig. 8. Dependence of MTTF on T for semiconductor devices (microwave range)

The MTTF of all the presented semiconductor components rapidly decreases with increasing temperature. Only components from a few groups have a non-zero MTTF value, with Zener diodes and voltage limiters being the most thermal-resilient.

Table 1 presents the MTTF of the most and least thermal-resilient electronic components, among all those considered, under different temperature regimes.

Table 1 – MTTF of the most and least thermal resilient ECs

T, °C	**$\mathrm{MTTF}_{\min}$, thousand hours**	**$\mathrm{MTTF}_{\max}$, thousand hours**	**Δ_{MTTF}, thousand hours**
25	281	706	425
40	253	674	421
60	195	632	437
80	0 (1 group)	589	589
110	0 (17 groups)	558	558

Under the same temperature conditions, the MTTF of different groups of electronic components varies significantly, and with increasing temperature, the least resilient components significantly lose their reliability. Components that are very resilient to temperature increases have also been identified. Accordingly, it was found that the difference in the MTTF between the most and least thermal resilient electronic components of radio-electronic equipment can be very significant and only increases as the temperature rises.

Conclusions

The results of the conducted research demonstrate a significant impact of temperature on the reliability of all considered types of electronic components — resistors, capacitors, integrated circuits, and semiconductor devices.

Based on the obtained dependences between mean time to failure and temperature, significant differences in thermal resilience among components from different groups were identified. Specifically, the most thermal resilient components in each group were found to be: fixed precision resistors, metal oxide variable resistors, glass capacitors, hybrid ICs, Zener diodes and voltage limiters. The least resilient components were also identified, for which the MTTF indicator sharply decreases with increasing temperature. Of the 59 examined groups of ECs, at a temperature of 80 °C, components from one group (semiconductor detectors) demonstrated a zero MTTF, and at 110 °C, the number of such groups increased to 17.

Minimizing the average temperature of electronic components can lead to an uneven decrease in their reliability over time, and, in unredundant electronic equipment, the failure of even one, least thermal resilient component can cause premature failure of the entire electronic device. Therefore, to enhance the overall reliability of radio-electronic equipment, it is essential to consider the differences in thermal resilience among various groups of components from the early stages of design.

MTTF can be considered the most effective characteristic for the integrated assessment of electronic components reliability at the stages of technical proposal and preliminary design of radio-electronic equipment.

The software developed and used in this research is a very effective tool for automating the reliability calculations of radio-electronic equipment ECs.

The obtained results provide a foundation for further work aimed at achieving optimal reliability variants of design solutions, including through multi-criteria parametric optimization.

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Вплив теплової стійкості електронних компонентів на показники надійності радіоелектронної апаратури

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У статті основна увага приділяється впливу температури на надійність електронних компонентів, оскільки, в радіоелектронній апаратурі без резервування, відмова будь-якого компоненту зазвичай призводить до відмови всього пристрою вцілому. Розглянуто методи і підходи, що застосовуються для аналізу надійності електроніки, прогнозування термінів експлуатації, а також їх збільшення. Теплові впливи є одними із найбільш вагомих, що впливають на такі показники надійності електроніки, як імовірність безвідмовної роботи та час напрацювання до відмови. Проаналізовано послідовність врахування теплових факторів при виконанні розрахунків експлуатаційної інтенсивності відмов, середнього часу напрацювання на відмову та ймовірності безвідмовної роботи відповідно до рекомендацій Державних стандартів України. Основний акцент зроблено на розрахунок середнього часу напрацювання до відмови для різних груп резисторів, конденсаторів, інтегральних мікросхем та напівпровідникових компонентів. У роботі використано сучасні підходи до оцінки надійності, а саме, застосовано комбінацію фізики відмов та комп'ютерного моделювання. Визначено, що різниця у середньому часі напрацювання до відмови між найбільш та найменш стійкими до теплових впливів електронними компонентами радіоелектронної апаратури може бути дуже значною і з підвищенням температури тільки збільшується.

Ключові слова: електронний; компонент; вплив; температура; надійність; розрахунок; програма; тепло; стійкість; середній; час