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Analysis of the probabilistic characteristics of the electrical parameters of a broadband balanced mixer of microwave radio signals based on resonant tunneling diodes and an assessment of its reliability

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Abstract: The object of research is the broadband balanced SHF mixer (BM) based on resonant-tunneling diodes (RTDs). The research goals are to perform the statistical analysis of BMs design parameters technological errors impact on its electrical characteristics scatter, and to analyze the kinetics of these characteristics under the destabilizing factors influence. The ranging of BMs design parameters technological errors impacts on its electrical characteristics scatter revealed that the biggest impact is made by the technological errors of the BMs non-linear elements I-V characteristics. The BMs reliability study revealed that to ensure the studied BMs reliability during operation under high temperatures impact the design and technological optimization of the BMs electrical characteristics is required.

Keywords: resonant tunneling diode, nonlinear frequency converters of radio signals, reliability, computer statistical experiment

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1. INTRODUCTION

Nonlinear frequency converters (FC) are radiotechnical systems key elements since they are used to perform general radiotechnical conversions. FCs electrical parameters determine the electrical parameters of most radiotechnical systems. One of the ways to improve FCs electrical parameters is to use nanoelectronic devices, such as resonant-tunneling diodes (RTD) based on AlGaAs/GaAs multilayer heterostructures with transverse current transport [4]. The improvement of the FCs electrical parameters

is achieved by picking the optimal shape of the diodes current-voltage characteristic (I-V characteristic). The optimal shape of diodes I-V characteristic is obtained by varying thicknesses and chemical composition of the resonant-tunneling structures (RTS) layers [14,15]. The RTD usage allows to widen the operating frequencies range up to THz [1-3,6,10,13,16] and increase the FCs noise immunity. The RTD can be manufactured using proven microelectronics technologies.

During FCs design stage, the task of ensuring its reliability in given operating conditions is a priority one along with the task of ensuring the devices electrical parameters. To solve the former task the reliability assessment of the device being developed is required. As the reliability assessment by experimental means is costly, it seems topical to study the kinetics of RTD-based FCs electrical parameters under destabilizing factors impact considering the effect of its design parameters technological errors on its electrical parameters distributions and to assess the devices reliability for gradual failures by the means of computer statistical experiment. The FCs gradual failure is caused by the gradual deterioration of its electrical parameters. This deterioration is caused by the irreversible degradation of the RTDs I-V characteristic under destabilizing factors impact.

One of the possible ways to solve the task of ensuring the FCs reliability in given operating conditions is the micro- and nanodevices design methodology listed in [5]. This methodology proposes to introduce the design and technological optimization stage, which allows to determine the corrections of the devices design parameters and electrical characteristics, leaving the technological tolerances on its design parameters and designer-determined tolerances on the device's electrical parameters intact. The gamma-percentage time to failure is used as the goal function. The described approach supposes the usage of the imitational (including

probabilistic) modeling of the devices electrical parameters to determine their degradation patterns in given operating conditions, considering the technological errors and is based on the research results of the devices elements electrical parameters degradation processes in given operating conditions.

Based on the above, to solve the problem of ensuring the reliability of the frequency converter of radio signals, it seems most expedient to use a software package that allows analyzing the reliability of the frequency converter by calculation methods and perform the design and technological optimization of the RTD-based FCs electrical parameters to ensure the required reliability indicators in given operating conditions. Having such a software complex would allow to improve RTD-based FCs reliability and quality as well as improve their manufacturing efficiency. To improve optimization algorithms efficiency and speed it seems appropriate to determine the FCs design parameters making the main contribution to its electrical parameters' distribution. Thus, it seems relevant to solve the problem of determining the FCs design parameters, technological errors of which make the maximal contribution to the FCs electrical parameters distribution.

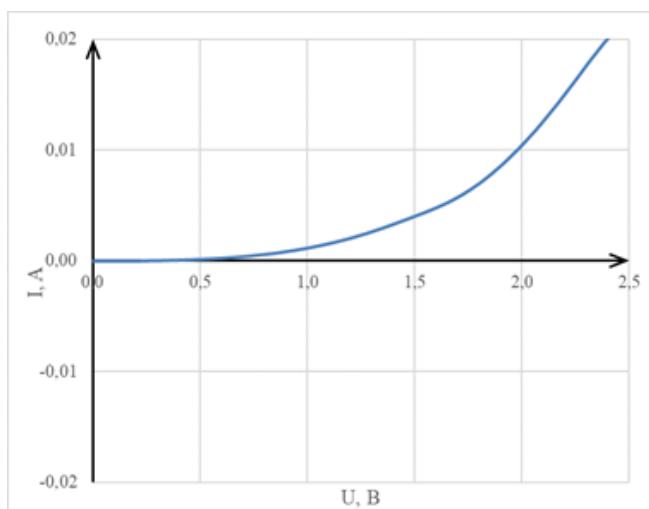


Fig. 1. The initial section of the RTDs I-V characteristic

2. RESEARCH OBJECTS DESCRIPTION

In this paper the RTD-based broadband balanced microwave frequency mixer (RTD BM) of 4-8 GHz range is being studied. The initial section of the RTDs I-V characteristic is shown in **Fig. 1**. The simulation of the BMs electrical parameters is performed in the AWR Microwave Office CAD.

3. STUDY OF THE RTD-BASED BMS DESIGN PARAMETERS TECHNOLOGICAL ERRORS IMPACT ON ITS ELECTRICAL PARAMETERS DISTRIBUTION

The conversion losses of the output signals spectrum components (OSSC) 1-1 and 2-2 are considered as the RTD BMs electrical parameters (**Fig. 2**). The first index in the OSSCs number designates the n -th harmonic of the signal, the second one – m -th harmonic of the heterodyne, which form the OSSC $n\cdot m$: $n\cdot f_s \pm m\cdot f_b$. Signals frequency is f_s , heterodynes f_b .

The RTD BM's design parameters are separated into 3 groups: nonlinear elements (NE) I-V characteristic, BMs topology parameters and substrates parameters. All parameters distributions obey the Gauss law. NEs I-V characteristics distribution is caused by the combined impact of the NEs design parameters technological errors: RTS and near-contact areas thicknesses and chemical compositions, mesas and ohmic contacts areas. Microstrip transmission lines widths and lengths are considered as the

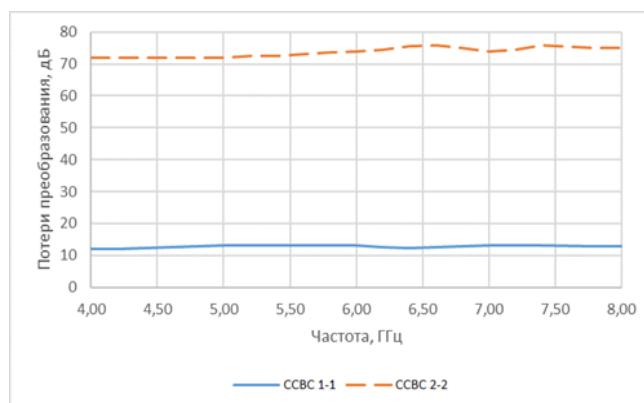


Fig. 2. Nominal values of the OSSC 1-1 and 2-2 conversion losses of the studied RTD BM.

Table 1.
RTD design parameters maximum deviations values

Parameter	Maximum deviation
Thickness of spacers, well and barriers	± 1 monolayer
Al doping level in barriers and spacers	$\pm 1\%$
Ohmic contacts' contact resistivity	$\pm 0.25 \mu\text{Ohm}\cdot\text{sm}^2$ (nominal value – $1 \mu\text{Ohm}\cdot\text{sm}^2$)
Mesa diameter	$\pm 2 \mu\text{m}$ (nominal value $20 \mu\text{m}$)

BMs topology parameters. Tolerances on these parameters is $\pm 12 \mu\text{m}$. Substrate parameters are its thickness and relative permittivity. The substrate is considered to be made of polycor, its relative permittivity is $9.8 \pm 0.1 \text{ F/m}$, thickness – $1 \pm 0.03 \text{ mm}$. Since modern microelectronics CADs dont have RTD models allowing to calculate the diodes I-V characteristic basing on RTDs design parameters, special software complex was developed by the authors. This complex allows to simulate the initial section of the RTDs I-V characteristic, simulate its kinetics in given operating conditions and carry out the computer statistical experiment studying the impact of the RTDs design parameterstecnological errors on the I-V characteristics distribution [15]. To carry out the study, a bunch of 100 diodes was modelled (RTDs design parameters maximal deviations listed in **Table 1**, current distribution in the operating point (1.36 V) – on **Fig. 3**).

To assess the impact of RTD BMs design parameters technological errors on its electrical parameters distribution several batches of RTD BMs were modelled, per 100 devices each. In the first one only RTDs design parameters were

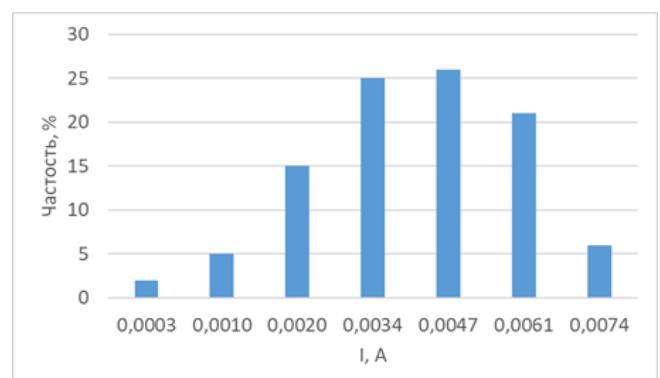


Fig. 3. RTD I-V characteristics current distribution in the operating point.

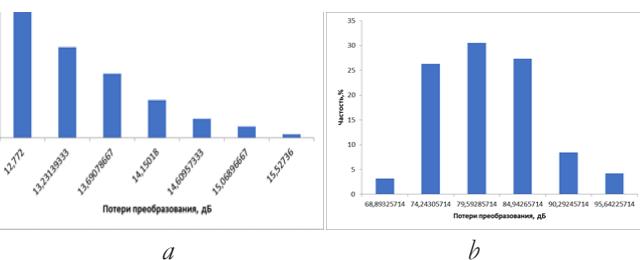


Fig. 4. Simulated distributions of OSSC 1-1 (a) and 2-2 (b) conversion losses at the signal frequency 7.5 GHz under the combined impact of technological errors of NEs I-V characteristics, microstrip lines sizes, and substrates thickness and relative permittivity.

varied while other parameter groups were set constant and equal to their nominal values. In the second batch microstrip lines lengths and widths were varied, in the third one – substrates thickness, in the fourth – substrates relative permittivity. Finally, the fifth batch was modelled using combined impact of all listed parameters technological errors.

Simulated distributions of the BMs electrical parameters for the combined impact of all design parameters technological errors case are shown on the Fig. 4a,b, distributions parameters are listed in Table 2. Dispersions of the BMs electrical parameters under the separate impact of various BMs design parameters groups can be assessed basing on the Table 2 and contributions of said parameters groups in the total dispersion (Fig. 5, 6).

To rank contributions of different RTD BMs design parameters technological errors in the total dispersion of its electrical parameters graphs showing each technological errors contribution

Table 2. Parameters of simulated distributions of OSSC 1-1 (a) and 2-2 (b) conversion losses at the signal frequency 7.5 GHz under the combined impact of technological errors of NEs I-V characteristics, microstrip lines sizes, and substrates thickness and relative permittivity

Electrical parameter	Mean value, dB	Standard deviation, dB ²	Dispersion, dB ²
OSSC 1-1 conversion losses	13.8	0.66	0.44
OSSC 2-2 conversion losses	79.59	5.35	28.62

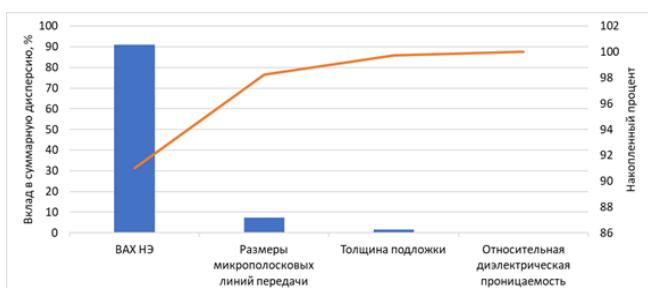


Fig. 5. Contributions of OSSC 1-1 conversion losses dispersions under the impact of different RTD BM's design parameters technological errors in the total dispersion.

in the total dispersion were plotted. Each technological errors contribution is evaluated by the ratio of the electrical parameters dispersion under the impact of said design parameters technological error to the dispersion of that electrical parameter under the combined impact of all design parameters' technological errors (Fig. 5, 6).

The analysis of different RTD BMs (microstrip lines sizes, substrates thickness and relative permittivity) and its NEs design parameters groups technological errors impacts on the RTD BMs electrical parameters distribution revealed that the maximal contribution in the total dispersion of the RTD BMs electrical parameter is made by the RTDs I-V characteristics technological error – RTD BMs electrical parameters dispersion under this factors influence is 91% from the total dispersion (Fig. 5, 6). In turn, the technological error of RTDs I-V characteristic is caused by the

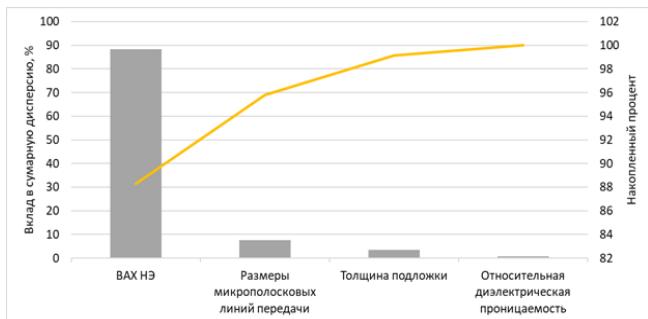


Fig. 6. Contributions of OSSC 2-2 conversion losses' dispersions under the impact of different RTD BM's design parameters technological errors in the total dispersion

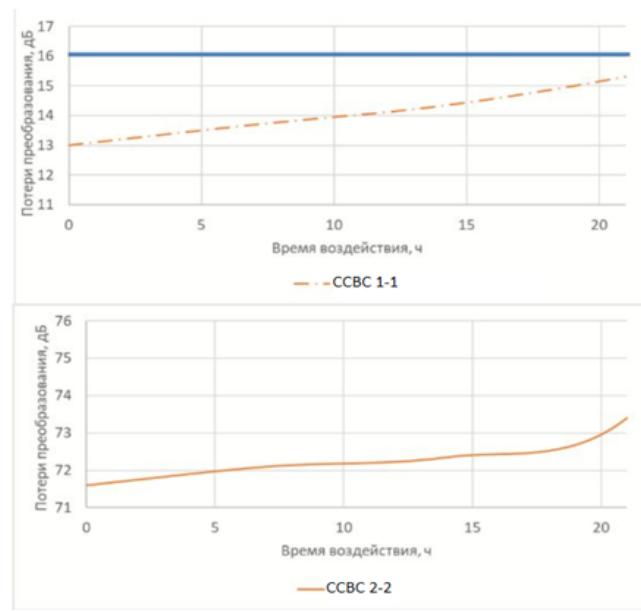
combined influence of RTD's design parameters technological errors: RTS layers thicknesses and chemical compositions, mesas area, and RTDs ohmic contacts parameters. Thus, it can be concluded that the NE's I-V characteristics technological error is the dominant factor determining the properties of the RTD BMs electrical parameters distribution. Obtained distributions of the RTD BMs electrical parameters under the combined impact of all design parameters technological errors are required for carrying out the BMs reliability assessment.

4. THE STUDY OF THE RTD BM'S ELECTRICAL PARAMETERS' KINETICS DURING OPERATION

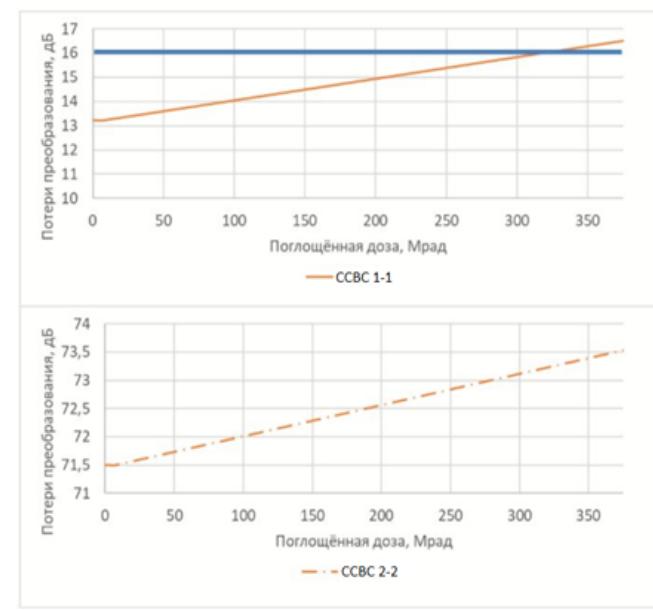
For the nonlinear elements the impact of 250°C temperature during 21 h and gamma-irradiation dose of 375.1 Mrad was modelled. The measured I-V characteristic of the RTD of the given type was used as the initial I-V characteristic, the kinetics was modeled by the means of the software complex developed by the authors, using the models described in [7,11-12]. Obtained I-V characteristics were put into the studied BMs model in the AWR Microwave Office CAD as approximated polynomial current-voltage

dependencies. Basing on the results of modeling of the studied RTD BMs electrical parameters, their kinetics under the ionizing irradiations and high temperatures impact at the signal frequency of 7.5 GHz is plotted (Fig. 7a,b). During the analysis, the failure is considered to occur if at least one of the following conditions is completed: OSSC 1-1 conversion losses are more than 16 dB; OSSC 2-2 conversion losses are less than 66 dB.

As shown in the Figures above, OSSC 1-1 and 2-2 conversion losses kinetics has a monotonously increasing trend both in the case of ionizing irradiation and high temperatures impact. The horizontal lines indicate the threshold values, on exceeding which a failure is recorded. Thresholds for OSSC 2-2 conversion losses are beyond the plot area since they're the lower boundary while conversion losses are increasing monotonously under destabilizing factors impact. Thus, the failure is only possible to occur because of the OSSC 1-1 conversion losses exceeding their threshold value. In the case of the ionizing irradiation exposure, the failure corresponds to 325 Mrad dose. The failure under the high temperatures impact wasnt registered on the studied time span. By the OSSC 1-1

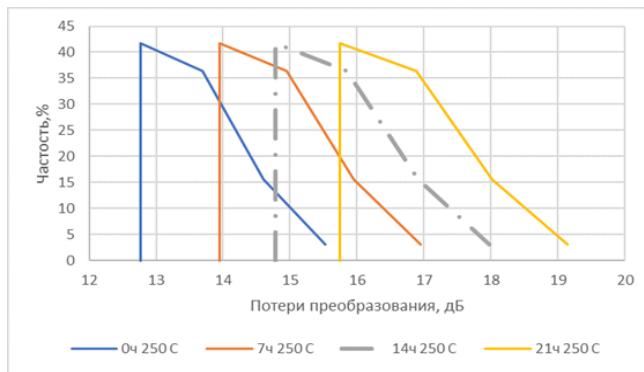


a



b

Fig. 7. Kinetics of the RTD BMs OSSC 1-1 and 2-2 conversion losses at the signal frequency of 7.5 GHz: (a) under the impact of 250°C temperature; (b) under the ionizing irradiations doses impact.



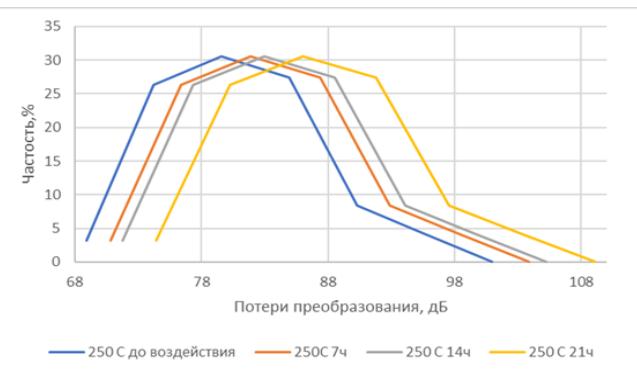
a

Fig. 8. The group kinetics of the RTD BM's OSSC 1-1 (a) and 2-2 (b) conversion losses at the signal frequency of 7.5 GHz under the impact of 250°C temperature.

conversion losses kinetics curve extrapolation it was revealed that the failure corresponds to the 25 h of exposure to the 250°C temperature.

Basing on the RTD BMs electrical parameters kinetics obtained for the single device in given operating condition (Fig. 7a,b) and the distributions of said electrical parameters obtained during the previous research (Fig. 4a,b), the group kinetics of the RTD BMs electrical parameters in given operating conditions were plotted (Fig. 8, 9a,b).

To obtain the gamma-percentage time to failure for $\gamma = 0.99$ corresponding to the actual operating conditions, the obtained values were converted into time to failure in actual operating conditions, using the technique described in [7,11-12]. The studied RTD BMs is supposed to be a part of near-earth orbit space crafts (SC) onboard equipment. The impact of the temperatures up to +200°C and ionizing irradiation doses up to 30 krad/year (according



b

to [8-9,17], the absorbed dose for the onboard SCs equipment behind the mass protection of 1...2 g/cm² (which corresponds to typical values for protective material used in SCs), is 10...30 krad/year).

The obtained results analysis revealed that RTD usage as the BMs NE doesn't ensure proper reliability of the mixer during its operation under the high temperatures impact (the gamma-percentage time to failure $t_\gamma = 0.99$ under the 200°C temperatures impact doesn't exceed 6.5 years). Thus, it seems promising to develop the design and technological optimization algorithms along with the software complex implementing them to improve the mixers reliability.

To assess the studied BMs gamma-percentage time to failure under the ionizing irradiations impact the gamma-radiations dose causing the failure was converted into the operating time. Gamma-percentage time-to-failure $t_\gamma = 0.99$ for this case is more than 25 years, which proves high

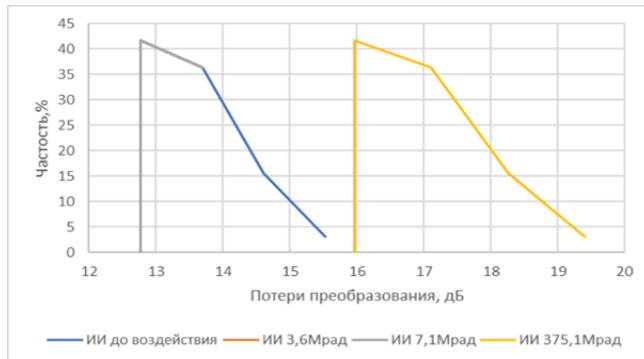
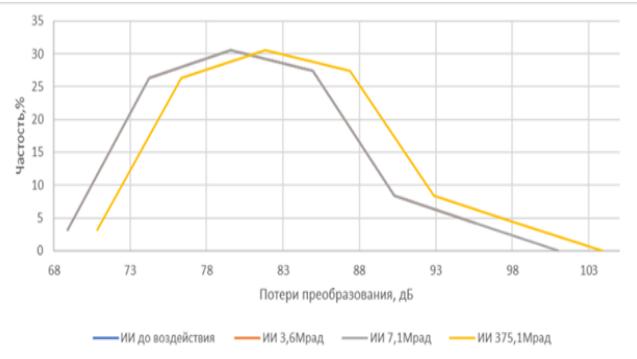


Fig. 9. The group kinetics of the RTD BM's OSSC 1-1 (a) and 2-2 (b) conversion losses at the signal frequency of 7.5 GHz under the gamma-irradiation impact.



reliability of the studied BM under the ionizing irradiations impact.

5. CONCLUSION

The technique of assessment of the RTD-based FCs reliability for gradual failures in give operating conditions, considering the impact of the FCs design parameters technological errors on its electrical parameters distribution is developed.

The analysis of different groups of the broadband RTD BMs design parameters technological errors impact on the distribution of its electrical parameters was performed. The distributions of the RTD BMs electrical parameters under the impact of its design parameters (BMs topology, RTDs I-V characteristic, substrate thickness and relative permittivity) technological errors were obtained. It is revealed that the maximal contribution to the RTD BMs electrical parameters distribution is made by the technological error of RTDs I-V characteristic.

The broadband RTD BMs electrical parameters kinetics under ionizing irradiation and high temperatures impact was studied. The RTD BMs electrical parameters kinetics in given operating conditions is obtained. It is revealed that the BMs failure occurs due to the growth of the mixers conversion losses. Assessments of the BMs gamma-percentage time to failure corresponding to the operating conditions as part of the SCs onboard equipment at the near-earth orbit were obtained. The studied RTD BM doesn't provide sufficient reliability under the high temperatures impact. To increase the RTD BMs reliability under the said factors reliability it seems promising to perform the design and technological optimization of the RTD BMs electrical parameters.

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