UDC 531/534(045)

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PARAMETERS OF RADIOELECTRONIC DEVICES, WHICH ARE DETERMINED BY THERMAL MODES

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Abstract—*In this work discusses the main characteristics of reliability of radio electronic devices, methods of their calculation. Proposed mathematical models for determination of parameters of thermal fields and recieved an analytical solution for the calculation of temperatures in microassemblies that take into account the removal of heat from all surfaces of the plate-basics to the existing volume. The described complex software module for calculation of temperatures of the elements of the electronic structure established on the basis of microassembly, and performance of its reliability.*

Index Terms—Reliability; radio electronic devices; failure; microassembly; thermal field; heat; failure rate; reliability particular; automation; reliability calculation.

I. Statement of the Problem

For radio electronic apparatus (REA) reliability is crucial because methods of calculation are paying considerable attention while the design.

Statistics show that 60–75 % of failures during operation of REA determined by external destabilizing effects, which primarily include two: mechanical – vibration and shock, and thermal – ambient temperature. The external thermal effects are also added and internal – heat in the elements of the electronic structure (EES).

The total effect of external and internal thermal factors can lead to an unacceptable increase in temperature of individual EES, that is, until their exit from the system, and in most of these cases – to the abandonment of all REA. Statistics show that 40–55 % failure rate of REA is the result of thermal factors.

Temperatures EES directly related to the reliability of the latter, and that the reliability of all REA. Determination of temperature EES – a complex problem, first, because the methods of calculating the thermal field in structural constructive module (SCM) REA themselves are quite complex, and secondly – because such elements in a modern CEA may be thousands.

Calculations temperatures in SCM can be carried out by the equations derived from analytical solutions of systems of differential equations that describe thermal processes in SCM, if the latter can be represented geometrically regular shape object . Trouble of this approach is the difficulty of solving such a system.

For objects with complex geometric shapes using mesh methods when model thermal field serves as a set of basic interaction cells or volumes that are in mutual thermal contact. Parameters of the thermal field are the equations of thermal balance for each of the elementary objects method of successive iterations. In this case, to obtain the final result must carry out a large number of computational procedures that can significantly slow down the design process.

To calculate the reliability indices associated with temperatures of EES, there are semi-empirical models that make it possible to calculate , for example , the probability of failure-free operation , service life of each of the EES depending on its type, and later of all REA [1], [2].

All these factors lead to the need to compute the temperature and also reliability of EES and most of all REA object-oriented software modules of computer-aided design (CAD).

In these modules rational use of analytical solutions for the calculation of both the temperature and thus the associated reliability indices – is the most effective in terms of simplification algorithm and program module and speed up the calculations.

Problem creating CAD software modules to determine the temperature of EES SCM REA and reliability is always relevant.

II. Structural-Constructive Elements of REA

The basic structural-constructive modules of the first level (SCM1) any REA is called cell and microassembly (MAs) – functionally complete modules, EES and functional units are placed on plastic, metal or ceramic printed circuit board. In some of REA in SCM1 concentrated all electromagnetic processes, simulation whose determines the functionality of the device; on to the fate of other structural elements that are involved in supporting these processes are only providing electrical connections between modules; SCM1 may have a special frame and system of heat-shielding.

In the constructive hierarchy of REA, SCM1 are part of the designs second level – block frames (SCM2), and the last – in the designs of the highest third level (SCM3): shelves, container, panel. Of course protection against external mechanical impacts and climate destabilizing carry construction of second and third level systems equipped vibration-shock isolation and maintain the desired temperature.

In the total volume of all the various REA SDM1 constitute at least 67–85 % of the structural elements, so we can assume that they should be considered as the main objects for which the necessary to determine the temperature EES and indicators and their reliability.

III. The determination of the temperature of the EES cells and microassemblies

Thermal model SCM in most cases can be represented in the form of heat-conducting plate with dimensions $a \times b \times h$, where are located the heat-producing elements (HPE) (Fig. 1).

From each of HPE *2* heat flow of Q_i is passed through the basis area with conduction to the board *1* SCM1, and from the latter – with convection to the environment and elements of the structure (the criteria of heat transfer α).

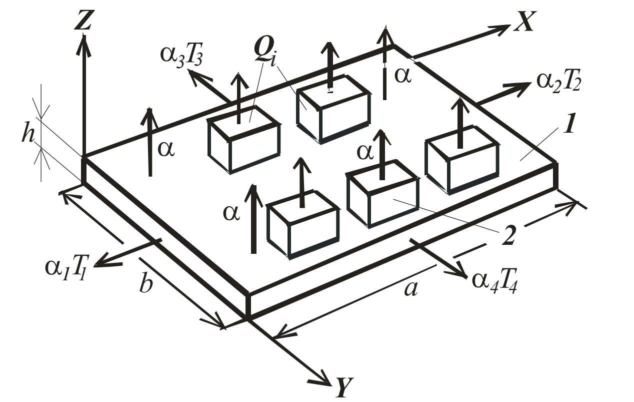


Fig. 1. Diagram of the heat flows for SCM1

From the side surface of each of the HPE the heat removes with convection and radiation (criteria of heat transfer α) to the environment, the temperature of which is T_c. In addition to accurate model must take into account the heat transfer from the end surfaces of the board (heat transfer criteria α_1, α_2, α_3, α_4) – it may be essential to MAs; in MAs often these end surfaces having a direct thermal contact with her body or with other elements of design SCM1, and therefore the value of α_i can be different. Temperatures of elements of the structure to which heat is given from the ends of the plate has labeled as T_1, T_2, T_3, T_4.

If the thickness of the plate h much smaller than its length *a* or width *b* (for most motherboards cells or wafers MAs) may be considered two-dimensional problem, and the temperature difference in thickness of the plate can be ignored, if the thickness of the base plate is relatively large, it is necessary to consider the three-dimensional model. In addition, the criteria MAs conductivity of the material of the basis in different directions can be different: λ_1, λ_2, λ are according to the directions of the coordinate axes *X, Y, Z*.

Microassembly in the SCM very often work in non-stationary regimes of heating or cooling -therefore is therefore useful to examine the model of non-stationary thermal process; temperature stationary process can be obtained according to the design equations of non-stationary as a partial case when the value of time is $\tau = \infty$.

The initial temperature distribution in the plate for non-stationary regime should be given as a function $\varphi(x,y)$; In some cases, these may be the same temperature throughout the plate: $T(x, y) = T_0$.

If we take the temperature $T_c = 0$, the differential equations of non-stationary process for the temperature field of the plate can be written as:

$$c\rho \frac{\partial T(x,y,\tau)}{\partial \tau} = \lambda_1 \frac{\partial^2 T(x,y,\tau)}{\partial x^2} + \lambda_2 \frac{\partial^2 T(x,y,\tau)}{\partial y^2} - \frac{\alpha}{h} T(x,y,\tau) + \sum_{i=1}^{n} \frac{q_i(x,y)}{h}, \tag{1}$$

where $T(x, y, \tau)$ are point temperature of the plate with coordinates x, y at the moment of time τ; c is specific heat of the material; ρ is density of him; q_i is surface density of heat flux from local HPE, whose coordinates of the basis centers is x_i, y_i, the size of the basics of each $\Delta x_i \times \Delta y_i$:

$$q_i(x_i, y_i) = q_i\ u(x_i)\ u(y_i);$$

$$u(x_i) = \begin{vmatrix} 1 \text{ for } (x_i - 0{,}5\Delta x_i) \geq x_i \leq (x_i + 0{,}5\Delta x_i); \\ 0 \text{ for } x_i \leq (x_i - 0{,}5\Delta x_i),\ x_i \geq (x_i + 0{,}5\Delta x_i); \end{vmatrix} \quad u(y_i) = \begin{vmatrix} 1 \text{ for } (y_i - 0{,}5\Delta y_i) \geq y_i \leq (y_i + 0{,}5\Delta y_i); \\ 0 \text{ for } y_i \leq (y_i - 0{,}5\Delta y_i),\ y_i \geq (y_i + 0{,}5\Delta y_i). \end{vmatrix} \tag{2}$$

The extraction of heat from the ends of the plate can be done in various ways – by convection or conduction; in the first case, you must set the values of criteria of convective heat transfer α_i, in the second – to determine the intensity of the heat flows q_i from each end.

Boundary conditions at the ends of the plate under convective heat transfer:

$$
\begin{aligned}
&-\lambda\frac{\partial T}{\partial x}+\alpha_1 T=\alpha_1 T_1 \quad \text{at } x=0;\\
&\lambda\frac{\partial T}{\partial x}+\alpha_2 T=\alpha_2 T_2 \quad \text{at } x=a;\\
&-\lambda\frac{\partial T}{\partial y}+\alpha_3 T=\alpha_3 T_3 \quad \text{at } y=0;\\
&\lambda\frac{\partial T}{\partial y}+\alpha_4 T=\alpha_4 T_4 \quad \text{at } y=b.
\end{aligned}
\tag{3}
$$

The initial condition – it a temperature distribution for the plane of the plate at the time moment $\tau = 0$: $T(x, y, 0) = \varphi(x, y)$; In the simplest case $\varphi(x, y) = 0$ – a state elements MAs after a long period of non-working.

The analytical solution of equation (1) with conditions (3) and $\varphi(x, y) = 0$ obtained in [4], [5] the method of finite integral transforms.

Kernels of integral transformations for two-dimensional plate with dimensions abh, the heat from which is removed from its ends too, according to [4], [5], have the form:

$$
\left.
\begin{aligned}
K(\mu_n,x)&=\sqrt{\frac{2}{a}}\frac{\mu_n\cos\left(\frac{\mu_n}{a}x\right)+\mathrm{Bi}_1\sin\left(\frac{\mu_n}{a}x\right)}{\sqrt{\left(\mu_n^2+\mathrm{Bi}_1^2\right)\left(1+\mathrm{Bi}_1+\frac{\mathrm{Bi}_2}{\mu_n^2+\mathrm{Bi}_2^2}\right)}};\\
K(\nu_m,y)&=\sqrt{\frac{2}{b}}\frac{\nu_m\cos\left(\frac{\nu_m}{b}y\right)+\mathrm{Bi}_3\sin\left(\frac{\nu_m}{b}y\right)}{\sqrt{\left(\nu_m^2+\mathrm{Bi}_3^2\right)\cdot\left(1+\mathrm{Bi}_3+\frac{\mathrm{Bi}_3}{\nu_m^2+\mathrm{Bi}_4^2}\right)}},
\end{aligned}
\right\}
$$

where μ_n, ν_m are roots of the characteristic equation:

$$\tan\mu_n=\frac{\mu_n\left(\mathrm{Bi}_1+\mathrm{Bi}_2\right)}{\mu_n^2-\mathrm{Bi}_1\mathrm{Bi}_2};\tan\nu_m=\frac{\nu_n\left(\mathrm{Bi}_3+\mathrm{Bi}_4\right)}{\nu_n^2-\mathrm{Bi}_3\mathrm{Bi}_4}$$

In these equations, the criteria Bio:

$$\mathrm{Bi}_1=\frac{\alpha_1 a}{\lambda_1};\quad \mathrm{Bi}_2=\frac{\alpha_2 a}{\lambda_1};$$

$$\mathrm{Bi}_3=\frac{\alpha_3 b}{\lambda_2};\quad \mathrm{Bi}_4=\frac{\alpha_4 b}{\lambda_2};\quad \mathrm{Bi}=\frac{\alpha h}{\lambda}.$$

The equation for calculating the temperature is the sum of the such components:

$$T_Q(x,y,\tau)=\sum_{i=1}^{k}16\frac{\mathrm{Bi}}{\alpha h^2}\frac{Q_i}{\Delta x_i\Delta y_i}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{\varphi_1(\mu_n,x)\varphi_2(\nu_m,y)}{K_nK_m}\frac{I_n(x_i)I_m(y_i)}{C_{n,m}}\Phi_{n,m}(\tau); \tag{5}$$

$$T_x(x,y,\tau)=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{4}{K_nK_m}\frac{\theta_{1(n,m)}}{C_{n,m}}\varphi_1(\mu_n,x)\varphi_2(\nu_m,y)\Phi_{n,m}(\tau); \tag{6}$$

$$T_x(x,y,\tau)=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{4}{K_nK_m}\frac{\theta_{1(n,m)}}{C_{n,m}}\varphi_1(\mu_n,x)\varphi_2(\nu_m,y)\Phi_{n,m}(\tau); \tag{7}$$

In equations (5) – (7):

Q_i – capacity of individual HPE;

$$\varphi_1(\mu_n,x)=\mu_n\cos\left(\frac{\mu_n}{a}x\right)+\mathrm{Bi}_1\sin\left(\frac{\mu_n}{a}x\right);$$

$$\varphi_2(\nu_m,y)=\nu_m\cos\left(\frac{\nu_m}{b}y\right)+\mathrm{Bi}_3\sin\left(\frac{\nu_m}{b}y\right);$$

– functions of temperature distribution along the axes X and Y, respectively:

$$K_n=\left(\mu_n^2+\mathrm{Bi}_1^2\right)\left(1+\mathrm{Bi}_1+\frac{\mathrm{Bi}_2}{\mu_n^2+\mathrm{Bi}_2^2}\right);$$

$$K_m=\left(\nu_m^2+\mathrm{Bi}_3^2\right)\left(1+\mathrm{Bi}_3+\frac{\mathrm{Bi}_3}{\nu_m^2+\mathrm{Bi}_4^2}\right);$$

$$\Phi_{n,m}(\tau)=1-\exp\left\{-\frac{1}{c\rho}\left[\lambda_1\left(\frac{\mu_n}{a}\right)^2+\lambda_2\left(\frac{\nu_m}{b}\right)^2+\lambda\frac{\mathrm{Bi}}{h^2}\right]\tau\right\};$$

– function that takes into account the influence of time τ on the temperature field of the plate:

$$
\left.
\begin{aligned}
\theta_{1,n,m}&=\left[T_1\mu_n\mathrm{Bi}_1+T_2\left(\mu_n\cos\mu_n+\mathrm{Bi}_1\sin\mu_n\right)\mathrm{Bi}_2\right]\\
&\times\left[\sin\nu_m+\frac{\mathrm{Bi}_3}{\nu_m}\left(1-\cos\nu_m\right)\right];\\
\theta_{2,n,m}&=\left[T_3\nu_m\mathrm{Bi}_3+T_4\left(\nu_m\cos\nu_m+\mathrm{Bi}_3\sin\nu_m\right)\mathrm{Bi}_4\right]\\
&\times\left[\sin\mu_n+\frac{\mathrm{Bi}_1}{\mu_n}\left(1-\cos\mu_n\right)\right].
\end{aligned}
\right\}
$$

If the removal of heat from the end surfaces is slight, can take

$$T(x,y,\tau) \approx T_Q(x,y,\tau) + T_c.$$

Parameters of the thermal field plate in stationary state we obtain from the equations (5) – (7), taking $\tau = \infty$, which corresponds to the $\Phi_{n,m}(\tau) = 1$.

IV. Reliability indicators of HEE as a function of their temperature

Calculation of reliability of certain elements conducted in accordance with mathematical models [2]:

$$\lambda_w = \lambda_0 K_r \times \prod_{i=1}^{n} K_i, \qquad (8)$$

where λ_w is working (operational) failure rate of the element; λ_0 is initial (basic) failure rate at rated electrical load and ambient temperature $t_{\text{amb}} = 25$ °C; K_r is coefficient of regime that serves as a function of temperature T and coefficient of load α: $K_r = f(T,\alpha)$; K_i is coefficients that account for the change of operational failure rate as a function of various factors.

Expressions of the coefficients regime K_r in mathematical models for the majority of EES are presented in [2].

Other features specific EES (voltage, degree of rigidity conditions, etc.) are taken into account in the model (8) by K_i coefficients that need to be specified in the design process.

V. Software definition of parameters of reliability

For automatic calculation of temperature EES cells or MAs, and on them – reliability indexes – in an integrated software environment ***Visual Studio*** created a program ***ReliaREA***.

To calculate the temperature of EES and cell temperature field or MAs should be given significance criteria α heat transfer from the lateral surface of the base plate and the hot carrier temperature T_c in the internal volume of the shell.

These parameters are derived from preliminary design stages, which determine the shape and size of cells, REA shell, parameters of thermal conditions in the case.

In the early stages of design is used programs ***BlTermo1*** and ***BlTermo2***, described in [3]; first designed to calculate macro-indicators of the thermal regime of geometrical and perforated blocks, the second – for units with a dense arrangement.

Calculation of temperature HPE located on the plate with the dimensions of $a \times b \times h$, can be carried out using ***Termo5***, as described in [3]; temperature calculated using equations (5) – (7). To take account of heat from the end surfaces (for MAs) should be set criteria α_1, α_2, α_3, α_4 and temperature structural elements T_1, T_2, T_3, T_4, which is given by the heat of the ends [3].

Comprehensive program ***ReliaREA*** allows calculating of reliability for the cell or MAs, determined by which the temperature of EES. In it for calculating temperature used program modules ***Termo5***.

Input for the program ***ReliaREA*** given in the application window or by downloading the input file.

Window to the input parameters of the base board is shown in Fig. 2.

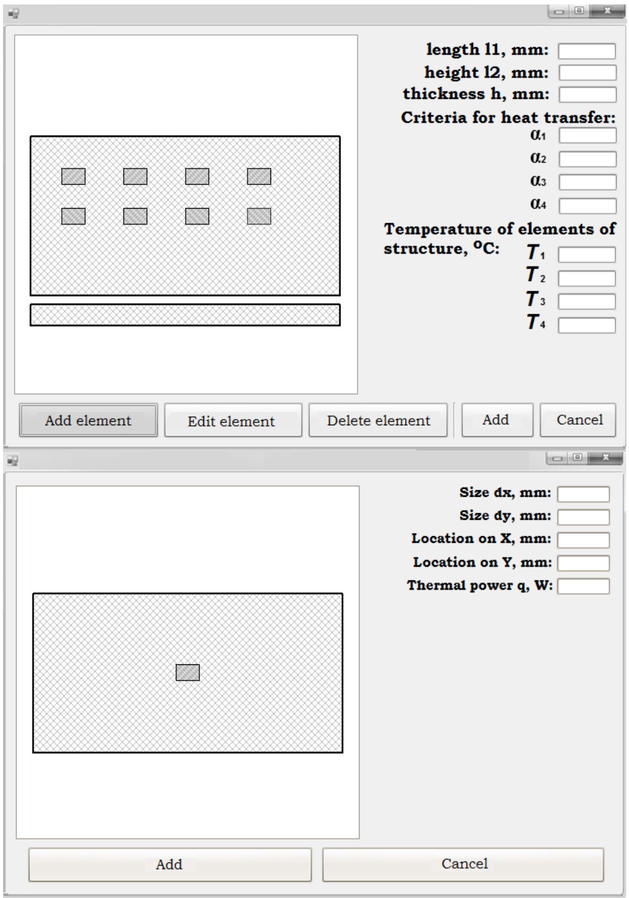


Fig. 2. Setting of the parameters of the board and elements on the board

In it must enter the size of the board: length a, width b, thickness h; criterion of thermal conductivity board material; heat transfer criteria α_1, α_2, α_3, α_4; temperatures T_1, T_2, T_3, T_4 are in the relevant cells.

Specifying the parameters of the board, it should be placed on HPE. For this in display excreted the window of setting options of the HPE: the size of the element, coordinate position on the board, the heat capacity. Location of the element displayed on the parameters of the board (see Fig. 2). Similarly, to the board is added the remaining elements. The program also provides the ability to edit the parameters of EES and boards.

If has multiple boards, need to calculate their sequently, using the "Add" button (see Fig. 2).

After entering parameters for the last EES the software modules (similar program modules ***Termo5***) calculated the temperature of each of EES and record them in the results file.

To calculate the reliability need in the next window (Fig. 3) for each of EES enter it type (with additional features that are always available), the coefficients K_L electrical loads and more additional coefficients K_i. The temperature of each EES is calculated by the program modules ***Termo5*** and entered into the appropriate cell window Fig. 3.

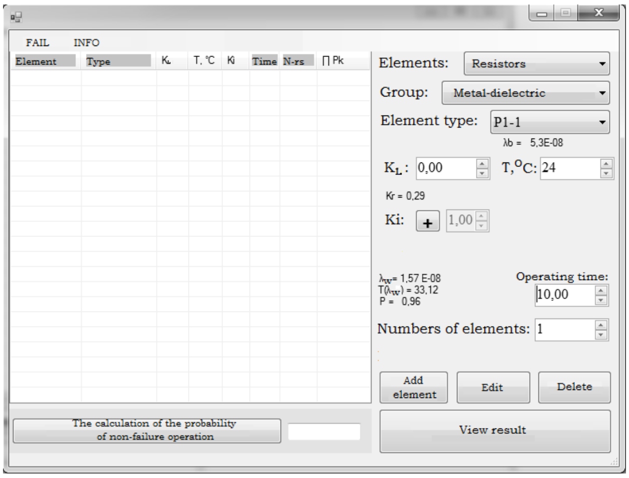


Fig. 3. Inputing the element parameters

In the program ***ReliaREA*** recorded database of EES, which is often used in the element schemes of REA:

– types of resistors Р, С, РП, СП, ПП, КМТ, ММТ, СТ, ТР, 301-319, НР, Б, ПР;

– capacitor types: К, СГМ, МБГ, ФТ, КТ, Б, КС, КБП;

– types of transformers ТА, ТН, ТО, ТВ, ТП, БТИ, МТИ, ММТИ, ТИ, ТИИ, ТИМ, ТИР, ФИТ, ГХ, ММТС, Т, ТВЛ,ТНЧ, ТОТ, ТУМ, ТФ;

– types of semiconductor devices Д, 2Д, 2Ц, 2В, 2ДС, 2С, 2Т, 1НТ, 2ТС, 2ПС, 2П, 3П, 2У, 2А, 3А;

– integrated circuits.

In cell "Elements", "Group", "Element type" (Fig.3) to be chosen from the database according to the circuit diagram. For example, select "Resistors" group "Metal-dielectric" and type "P1-1". The value of failure rate for the selected element are in the database, the program defines them herself.

If a group of identical values of EES K_L, T and K_i do not differ significantly, the number of EES can ask the entire group, the cell "number of items". In the same series box you must enter all parameters of EES.

According to these data, and the corresponding mathematical models (that are in the database), the program calculates the coefficient of regime K_r. Influence coefficients K_i are added by clicking with the sign "+".

After selecting all the options and fill in all the cells, to add an element of the device, you must press the "Add Item" box. Software provides options to edit and delete the added elements.

Obtained temperatures are used in the program to calculate the probability of failure-free operation of each EES according to the model DN-distribution (diffusion not-monotonic) [1]:

$$P(x) = \Phi\left(\frac{1-x}{\nu\sqrt{x}}\right) + e^{\frac{2}{\nu^2}}\Phi\left(-\frac{1+x}{\nu\sqrt{x}}\right),$$

where $\Phi(u) = \frac{1}{\sqrt{2\pi}}\int_{\infty}^{u}\exp\left(-\frac{u^2}{2}\right)du$ is function of the normal distribution; τ is time of the object work; $x = \tau/\mu$ is relative work time; μ is a basic spell that fully meets the functional life of the facility; ν is coefficient of variation of the distribution of failures.

The probability of failure-free operation of all of REA program ***ReliaREA*** calculated by assuming that the denial of each of the EES leads to failure of the entire of REA – as the product of the probabilities $P_k(\tau)$ of each element [1]:

$$P(\tau) = \prod_{k=1}^{m} P_k(\tau). \qquad (9)$$

The calculation results are stored in the appropriate file – is reliability: coefficient regime, operational failure rate, time between failures, probability of failure. Content source file may be viewed with any editor in operating system.

VI. THE RESULTS OF SIMULATION MODELING

With the help of ***ReliaREA*** the simulation temperature and determination of the reliability of the cell, on glass-textolite board of which set different EES – integrated circuits, semiconductors, resistors, capacitors, transformers.

As an example, shows the results of calculations of temperatures and reliability for eight EES (the program may enter up to 50 items). Arrangement of elements on the circuit board shown in Fig. 4.

The results of calculations of the parameters for each element are displayed in the window shown in Fig. 5 (box shows the group parameters for the first five elements) – power EES, nominal (base) temperature, failure rate λ, the probability of failure-free operation for each of the EES. According to the formula (9) for the whole cell is calculated probability of failure-free operation, which is also displayed in the window.

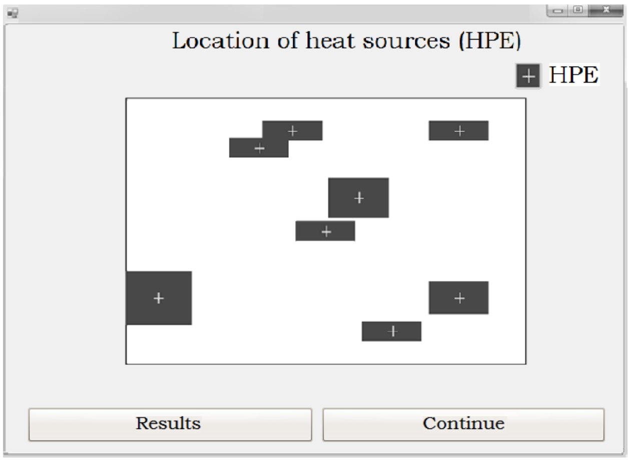
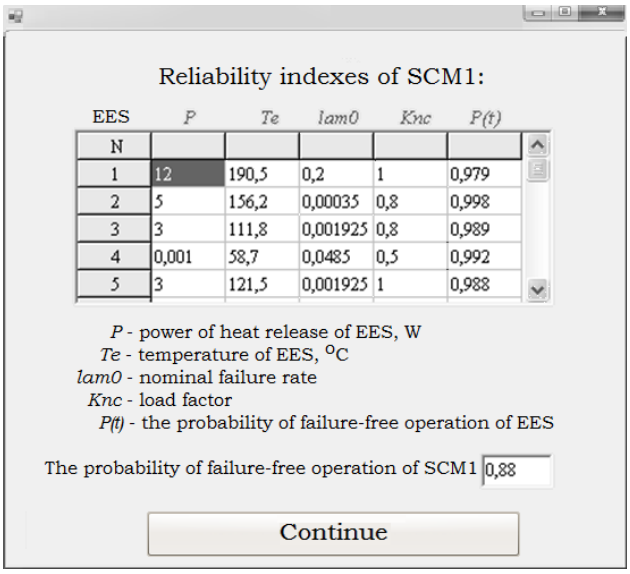


Fig. 4. Location of EES on board



EES N	P	Te	lam0	Knc	P(t)
1	12	190,5	0,2	1	0,979
2	5	156,2	0,00035	0,8	0,998
3	3	111,8	0,001925	0,8	0,989
4	0,001	58,7	0,0485	0,5	0,992
5	3	121,5	0,001925	1	0,988

Fig. 5. The results of calculations

VII. Conclusion

Thermal processes in structural design modules - cell, microassemblies – to a large extent determine the functional suitability of all radio-electronic apparatus. Reliability parameters of last is calculated in accordance with relevant mathematical models as a function of temperature EES when designing. Due to the variety of designs CEA is often necessary to create methods for calculating temperatures in them, and the equation for calculating the temperature it is advisable to obtain an analytic solution of differential equations of the mathematical model of the thermal field.

In today REA number of different nomenclature EES can reach hundreds and thousands , so their temperature and reliability might actually calculated only using CAD applications that need to create and improve.

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Received 15 February 2014.

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Б. М. Уваров, А. В. Нікітчук. Показники надійності радіоелектронних апаратів, що визначаються тепловими режимами

Розглянуто основні характеристики показників надійності радіоелектронних засобів, методи їх розрахунку. Запропоновано математичні моделі для визначення параметрів теплового поля та одержані аналітичні рішення для розрахунків температур у мікрозбірках, які враховують відвід теплоти з усіх поверхонь пластини-основи до оточуючого її об'єму. Описаний комплексний програмний модуль для розрахунків температур елементів електронної структури, встановлених на основі мікрозбірки, та показників її надійності.

Ключові слова: надійність; радіоелектронні засоби; відмова; мікрозбірка; теплове поле; тепло; показники надійності; автоматизація; розрахунок надійності.

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Напрям наукової діяльності: радіоконструювання.
Кількість публікацій: 2.
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Уваров Б. М., Никитчук А. В. Показатели надежности радиоэлектронных аппаратов, определяемые тепловыми режимами

Рассмотрены основные характеристики показателей надежности радиоэлектронных средств, методы их расчета. Предложены математические модели для определения параметров теплового поля и получены аналитические решения для расчетов температур в микросборках, учитывающие отвод теплоты со всех поверхностей пластины-основы к окружающему ее объему. Описан комплексный программный модуль для расчетов температур элементов электронной структуры, установленных на основе микросборки, и показателей ее надежности.

Ключевые слова: надежность; радиоэлектронные средства; отказ; микросборка; тепловое поле; тепло; интенсивность отказов; показатели надежности, автоматизация, расчет надежности.

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Направление научной деятельности: вероятностные функциональные характеристики РЭА, радиоконструирование.
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Направление научной деятельности: радиоконструирования.
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