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INFLUENCE OF POLYMER AGING ON RELIABILITY INDICES OF A TYPICAL PRINTED-CIRCUIT ASSEMBLY OF RADIOELECTRONIC EQUIPMENT

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Mathematical modeling of nonlinear nonstationary temperature fields of a typical printed-circuit assembly of radioelectronic equipment has been performed in a three-dimensional formulation with account for the convective and radiative heat exchange with the environment. On the basis of the data of the numerical experiment the "aging" (degradation) indices of polymer materials under prolonged thermal action have been determined. It has been established that the reliability of an object modeled with account for the real temperature fields is five times lower compared to the realization of normalized thermal conditions.

Introduction. Reliability of radioelectronic equipment is a complex index depending on many factors, including the intensity of ageing of polymer materials used in both making individual electroradio elements (ERE) and designing assemblies and parts of radioelectronic equipment (REE). The change in the properties of polymer materials with time is a complex physicochemical process proceeding under the combined action of internal and external factors in the process of operation of radioelectronic equipment [1, 2].

Under a prolonged thermal action a change in the micro- and macrostructure of polymer materials occurs [1], the resistance of dielectrics decreases, the dielectric loss increases, and the dielectric constant changes [3].

Aging of the elemental base is an irreversible process directly affecting the reliability of radioelectronic products. For a wide circle of EREs their "life" cycle has three periods of operation, for which the aging index has a different value [4]. The first period is connected with the shaking down. At this stage the reliability depends on the technology of producing the individual elements. The aging of EREs thereby is not taken into account in determining the reliability indices of REEs. The second period is the longest in the "life" cycle and is connected with the long-duration operation. At this stage the influence of aging processes is insignificant compared to the period of operation when the limiting service data, including the normalized thermal conditions, are observed. Therefore, the question on the error of such interpretation in the realization of nonnormalized (real) thermal conditions of functioning of radioelectronic products under both external thermal action and possible local superheating is still to be elucidated. In the last stage of the "life" cycle, aging of the elemental base combined with external and internal factors is of crucial importance in determining the reliability indices and in problems of predicting the remaining life. For individual EREs and structural elements used in radioelectronic engineering, whose compositions include polymer materials, the most significant factors during the whole "life" cycle are the temperature conditions of functioning of a given article.

The aim of the present paper is to determine the reliability indices of a typical printed-circuit assembly of REE by the data of the mathematical modeling of spatial nonlinear nonstationary temperature fields in which, as a diagnostic variable in the estimation of the reliability indices, the characteristic of the degradation of polymer materials used in radioelectronic engineering was taken into account.

Formulation of the Problem. The degradation process of polymer materials has an exponential character [2] and is described by the equation

$$\frac{d\eta}{dt} = (1 - \eta)\, k \exp\left(-\frac{E}{RT}\right). \tag{1}$$

At the initial instant of time $t = 0$, $\eta = 0$.

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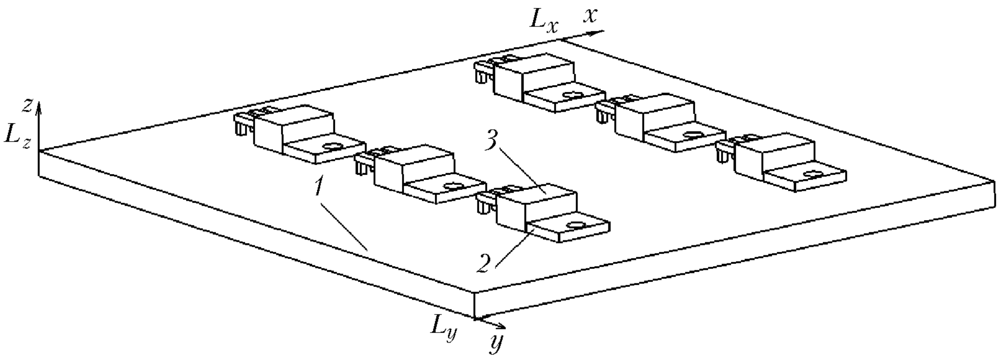

Fig. 1. Geometry of the solution domain: 1) printed-circuit board; 2) heat removing surface; 3) transistor case.

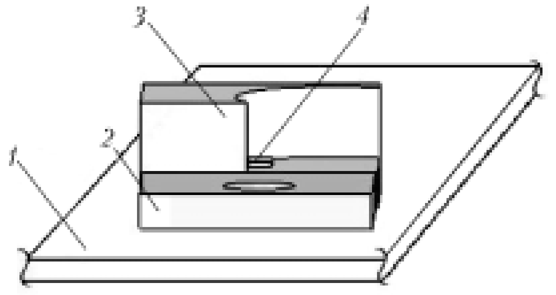

Fig. 2. Heat source (transistor): 1) printed-circuit board; 2) heat removing surface; 3) transistor case; 4) source of local heat release (crystal).

TABLE 1. Thermophysical Characteristics of the Model Elements

Region number	ρ	C	λ
1	2500	1088	2
2	2700	900	210
3	2900	1100	0.8
4	3000	733	2.17

For mathematical modeling of the aging process of polymer materials we chose a typical REE assembly consisting of a printed-circuit board and six local heat sources.

The object being modelled is a glass-fiber-based laminate board bounded by the sizes on the axes x, y, and z and, accordingly, L_x, L_y, and L_z. For heat sources, we chose silicon transistors used in power amplifiers and switches as the most typical devices in the wide class of radioengineering devices. The transistor cases are made of plastic with a heat-removing surface and rigid terminals. The contact between the transistors and the printed-circuit board was considered to be perfect. At boundaries with different thermophysical characteristics (TPC), the boundary condition of the IV kind was fulfilled, and at boundaries with the environment, the boundary condition of the III kind with radiation was met.

The geometry of the solution domain is given in Fig. 1. Inside the case of each transistor a local heat source operates (Fig. 2). The thermophysical characteristics of the model elements are given in Table 1. In such a formulation, the problem is reduced to the solution of the nonstationary heat conduction equation

$$C(x, y, z)\,\rho(x, y, z)\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x, y, z)\,\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(x, y, z)\,\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda(x, y, z)\,\frac{\partial T}{\partial z}\right) + Q(t, x, y, z) \qquad (2)$$

with the corresponding initial

$$t \in [0; t_{\max}]\,, \quad x \in [0; L_x]\,, \quad y \in [0; L_y]\,, \quad z \in [0; L_z]\,, \quad T\big|_{t=0} = T_0\,(x, y, z)$$

and boundary conditions

$$x = 0\,, \quad y \in [0; L_y]\,, \quad z \in [0; L_z]: \quad -\lambda \frac{\partial T}{\partial x} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right),$$

$$x = L_x\,, \quad y \in [0; L_y]\,, \quad z \in [0; L_z]: \quad \lambda \frac{\partial T}{\partial x} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right),$$

$$y = 0\,, \quad x \in [0; L_x]\,, \quad z \in [0; L_z]: \quad -\lambda \frac{\partial T}{\partial y} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right),$$

$$y = L_y\,, \quad x \in [0; L_x]\,, \quad z \in [0; L_z]: \quad \lambda \frac{\partial T}{\partial y} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right),$$

$$z = 0\,, \quad x \in [0; L_x]\,, \quad y \in [0; L_y]: \quad -\lambda \frac{\partial T}{\partial z} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right),$$

$$z = L_z\,, \quad x \in [0; L_x]\,, \quad y \in [0; L_y]: \quad \lambda \frac{\partial T}{\partial z} = \alpha\,(T)\,(T_{\text{amb}} - T) + \varepsilon_{\text{r}}\sigma\left(T_{\text{amb}}^4 - T^4\right).$$

The convective heat transfer coefficient depends on the temperature and is determined for each point of the model surface [5]:

$$\alpha\,(T) = \left(1.42 - 1.4 \cdot 10^{-3}\,T_{\text{m}}\right) N \left(\frac{T - T_{\text{amb}}}{L}\right)^{1/4}.$$

The reduced emissivity of the model surface and environment is defined by the relation [5]

$$\varepsilon_{\text{r}} = \left(\frac{1}{\varepsilon_{\text{s}}} + \frac{1}{\varepsilon_{\text{env}}} - 1\right)^{-1}.$$

Method of Solution. The heat conduction equation (2) with the corresponding initial and boundary conditions was solved by the finite difference method [6]. To solve the difference analogs of the three-dimensional equation, the coordinate-splitting scheme [7] was used. In the solution, the following assumptions were used:

1. The elements of the printed-circuit assembly are modelled by parallelepipeds. This fact will introduce some error into the calculation accuracy; however, taking into account that almost all significant elements are close in shape to parallelepipeds, the error introduced must be insignificant.
2. The thermophysical characteristics of the materials of parallelepipeds (elements) are assumed to be isotropic. This assumption is justified, since the thermophysical properties of the majority of materials are characterized by isotropy.
3. The TPCs of the materials of parallelepipeds (elements) are assumed to be temperature-independent. This assumption is justified by the fact that the temperature dependence of the TPCs of the materials is very weak.
4. It is assumed that at the boundaries between elements a perfect thermal contact exists. The heat resistance between the heat removing surface and the printed-circuit board is decreased by using heat conductive pastes.

Results of Numerical Experiments. Modeling of the temperature fields was carried out on a 110 × 100 × 18 computational mesh for a long-term realization (t = $1.56 \cdot 10^8$ sec) of the real temperature conditions. The power of the heat sources was the same, 1.2 W. Figure 3 shows the temperature field of the modeled printed-circuit assembly at time t = 1800 sec. It should be noted that it is essentially inhomogeneous. The temperature gradients on the z-axis reach 20° and higher. The typical field isotherms of the modelled REE assembly are given in Fig. 4.

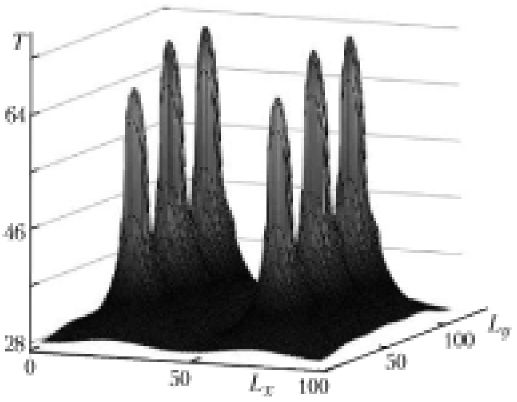

Fig. 3. Temperature field of the modelled printed-circuit assembly. T, °C; L_x, L_y, mm.

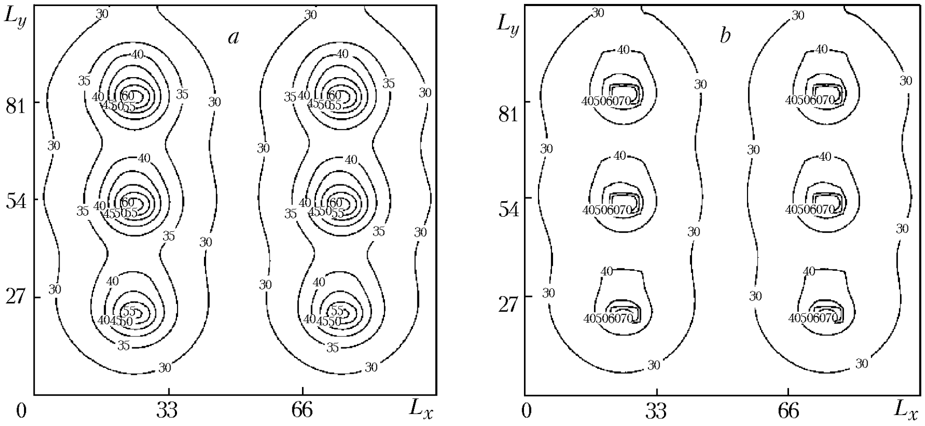

Fig. 4. Isotherms of the field of the printed-circuit board: $Z = 0$ (a), $Z = 4$ mm (b). T, °C; L_x, L_y, mm.

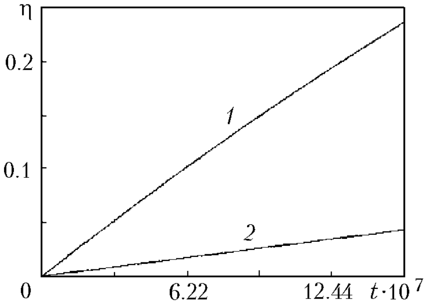

Fig. 5. Aging indices: 1) of the real thermal conditions; 2) at a temperature of 300 K. t, sec.

For a realization time equal to five years, the ratio between the aging indices at a temperature of 300 K was five times smaller than for the conditions under which the thermal regime is realized. Thus, if for the diagnostic variable in the estimations of the reliability indices the aging index of polymer materials is chosen, then it may be stated that the reliability of the modelled assembly will also be five times lower when nonnormalized temperature conditions are realized.

Conclusions. The results obtained permit concluding that in analyzing the reliability indices of REE assemblies and units, it is necessary to take into account the real picture of the change with time in the temperatures of these functional assemblies. In problems on the determination of reliability indices, it is also necessary to take into account the degradation intensity of the polymer materials used in radioengineering devices of different purposes at all stages of the "life" cycle of these products. In so doing, the choice of a particular dependence of the time variation in temperatures should be accompanied by the analysis of the real processes of heat release of REE assemblies and units and the conditions of heat exchange both inside the REE and with the environment.

NOTATION

C, specific heat capacity, J/(kg·K); E, activation energy; k, pre-exponential factor; L, determining size of the surface, m; L_x, L_y, L_z, geometric dimensions of the assembly, mm; N, coefficient depending on the spatial orientation of the surface; Q, heat release of the source, W; R, molar gas constant, J/(K·mole); t, time, sec; T, temperature, K; T_{amb}, ambient temperature, K; T_0, initial temperature, K; T_{m}, arithmetical mean of the model surface and ambient temperatures, K; x, y, z, coordinates; $\alpha(T)$, heat transfer coefficient, W/(m^2·K); ε_{r}, reduced emissivity of the model surface; ε_{s}, emissivity of the model surface; ε_{env}, emissivity of the environment; η, aging index; λ, heat conductivity coefficient, W/(m·K); ρ, density, kg/m^3; σ, Stefan–Boltzmann constant, W/(m^2·K^4). Subscripts: amb, ambient; 0, initial; m, mean; r, reduced; s, surface; env, environment; max, maximum.

REFERENCES

1. N. P. Pavlov and A. I. Krotov, Atmospheric resistance of polymer materials, *Plastic Masses*, No. 2, 59–60 (1976).
2. P. M. Émmanuél', Structural-kinetic aspects of the aging and stabilization of polymers, *Vysokomolek. Soed.*, No. 12, 2653–2665 (1978).
3. N. N. Goryunov, *Properties of Semiconducting Devices in Long Operation and Storage* [in Russian], Énergiya, Moscow (1970
4. D. V. Gaskarov, *Prediction of the Technical State and Reliability of REA* [in Russian], Sov. Radio, Moscow (1974).
5. G. N. Dul'nev, *Heat- and Mass Transfer in Radioelectronic Equipment* [in Russian], Vysshaya Shkola, Moscow (1984).
6. A. A. Samarskii, *Theory of Difference Schemes* [in Russian], Nauka, Moscow (1983).
7. V. M. Paskonov, V. I. Polezhaev, and L. A. Chudov, *Numerical Simulation of Heat- and Mass Transfer Processes* [in Russian], Nauka, Moscow (1984).