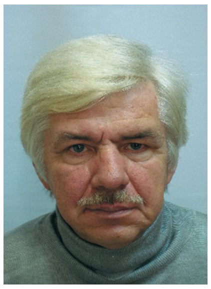


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FORECASTING DEPENDABILITY INDICATORS OF SPACECRAFT ONBOARD EQUIPMENT UNDER LOW-INTENSITY IONIZING RADIATION

The article deals with forecasting the dependability indicators of state-of-the-art spacecraft onboard equipment. The authors demonstrate the applicability of the results of equipment and components testing for resistance to ionizing radiation in forecasting dependability indicators. They prove the applicability of Alfa distribution of time to failure in forecasting CMOS IC reliability and longevity. The paper presents design ratios for probability evaluation of fail-safe operation, mean time to failure and minimum operation time. Ways are shown to improve the resistance of state-of-the-art spacecraft onboard equipment through the use of specialized means of protection against the effects of ionizing radiation of the outer space. This research (No. 14-05-0038) was conducted with the support of the Higher School of Economics Academic Fund Program in 2014.

Keywords: *dependability, resistance, electronic devices, integrated circuit, spacecraft, ionizing radiation.*

The widespread application of foreign electronic components in Russian-made equipment, on the one hand, allows designing and manufacturing state-of-the-art hardware, and, on the other hand, creates a number of difficulties in the design process, namely the engineering estimate of dependability indicators. That is especially relevant when it comes to spacecraft onboard equipment that widely uses commercial semiconductor components with relatively low radiation hardness. Therefore, forecasting the dependability indicators of such equipment requires taking into consideration the probability of their failure due to ionizing radiation of the outer space.

Dependability indicators of spacecraft onboard equipment are calculated during the design stage in order to confirm the feasibility of ensuring the required parameters and is a mandatory activity as per GOST RV 20.39.302 [1]. Equipment components dependability calculation (first level electronic units) shall be performed according to the method given in OST 4G 0.012.242 [2] and based on the method of “λ-characteristics”. In particular, the fail-safe operation probability (P_1) is determined from the following formula:

$$P_1\left(t_{CAC}\right) = e^{-\Lambda \cdot t_{CAC}},$$

where: Λ is the operational failure rate; t_{al} is the active life (AL) of the spacecraft.где:

$$\Lambda = \sum_{n=1}^{N} \lambda_n,$$

where: λ_n is the operational failure rate of electronic components (ECs); N is the number of the ECs.

In order to support the application of this method for the purpose of ECs failure rate calculation (λ-characteristics), official guidelines [3, 4] must be used, which ensures compliance with GOST 27.301 [5] in terms repeatability of results.

In order to take into consideration the special features of spacecraft onboard equipment, the above standards introduces two coefficients in the mathematical models λ_n:

C_o, coefficient of operation that takes into consideration the severity of the operational environment onboard the spacecraft;

C_{IR}, coefficient of ionizing radiation (IR) effect allowing for the severity of external IR.

At the same time, RD 134-0139 [6] briefly mentions that if the technical specification does not set forth any radiation hardness requirements, the probability of fault-free operation of equipment must be calculated using the following formula:

$$P(t_{CAC}) = P_1(t_{CAC}) \cdot P_2(t_{CAC}) \cdot P_3,$$

$P_2(t_{al})$ is the probability of fault-free operation under low-intensity IR OS (dose effect); P_3 is the probability of fault-free operation in case of penetration of a single high-energy charged particle (single effect).

The P_3 calculation methods are given in RD 134-0139 [6] and will not be considered in this paper.

Calculation of $P_2(t_{al})$ based on the methods set forth in OST 134-1034 [7] is performed element by element and consists in comparing the resistance of each type of ECs (maximum permissible dose, D_{MPD}) specified in standard technical documentation (STD) with the level of radiation exposure (absorbed dose of electrons, protons and the total dose) defined by means of calculation $D_{ND}(t_{al})$. The level of EC radiation exposure depends both of the SC orbit characteristics and their location within the SC of which the classification is given in GOST RV 20.39.305 [8].

In case of SC with long active life operating on geostationary orbit it is commonly believed that the intensity of EC radiation exposure is constant, i.e. dose build-up can be approximated with a line function as follows:

$$D_{НД}(t) = D_{ПД} \cdot t, \qquad (1)$$

where: $D_{ND}(t)$ is the dose absorbed by EC; D_{PD} is the rate of the dose absorbed per unit time; t is time.

The result of evaluation is the EC radiation hardness safety margin (M_s). If $M_s \geq 3$, then $P_2(t_{al}) = 1$, if $Ms \leq 1$, then $P_2(t_{al}) = 0$, if $1 < Ms < 3$, then the evaluation of $P_2(t_{al})$ requires resistance testing of EC. First, test must be performed to dose design value that equals to $D_{ND}(t_{al})$, then, preferably, to failure, which would help specify the value of resistance of the particular type of EC.

The above clearly shows that the OST 134-1034 [7] method implies the use of radiation-resistant EC in SC, while the use of ECs with $M_s < 3$ and their testing shall be performed in exceptional cases. However, the use in Russian SC of equipment that contains foreign electronic components, mostly commercial CMOS IC with low IR OS resistance, has already caused the situation when IC testing is rather a rule that an exception. The tests are performed to failure, as data sheets do not specify radiation resistance, and if they do, the information is extremely scarce [9].

On completion of testing, the value of $P_2(t_{al})$ is identified as follows:

$$P_2(t_{CAC}) \approx 1 - Q^*$$

Q* is the IC failure rate due to low-intensity IR exposure.

$$Q = \frac{k(D_{НД})}{K}, \qquad (2)$$

where: $k(D_{ND})$ is the number of failed ICs that have $D_{MPD} \leq D_{ND}(t_{al})$; K is the total number of ICs submitted to testing.

Taking into consideration the fact that the electronic components market provides a wide selection of CMOS ICs by various manufacturers that are similar in terms of function and performance, it is obvious that one of the key criteria of specific IC selection must be their dependability and resistance, which imposes one more task: evaluation of the dependability in low-intensity IR environment at early design stages.

The application of OST 134-1034 [7] methods is possible, but hardly economically viable, as tests do not always yield positive results. At the same time, at early stages of SC equipment design when the list of used electronic components is defined and the IC part types are chosen, the positive outcome of their certification testing must be assured.

One of the possible ways of solving this task is using the results of previously conducted radiation resistance tests of foreign ICs in order to forecast the dependability indicators of CMOS ICs similar in functionality and design.

Thus, the test results of CMOS IC of a 0.15 MCM non-volatile storage device manufactured by Xilinx, Texas Instruments, Cypress Semiconductor, Atmel, Analog Devices, etc. have shown that for d_{MPD} a truncated Gaussian distribution can be accepted:

$$f(d_{ПНД}) = \frac{C}{\sigma(d_{ПНД}) \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{\left[\frac{d_{ПНД} - m(d_{ПНД})}{\sigma(d_{ПНД})}\right]^2}{2}}, \qquad (3)$$

where: $f(d_{MPD})$ is the probability density; $m(d_{MPD})$ is the mathematical expectation; $\sigma(d_{MPD})$ is the mean square deviation; C is the normalizing factor.

C is determined from the formula:

$$C = \frac{1}{F(D_{ПНД_{MAX}}) - F(D_{ПНД_{MIN}})},$$

where: $F(D_{MPDmax})$, $F(D_{MPDmin})$ are Gaussian distribution functions.

It should be noted that model (3) also allows calculating $P_2(t_{al})$ IC if $m(d_{MPD})$, $\sigma(d_{MPD})$ and $D_{ND}(t_{al})$ are known:

$$P_2(t_{CAC}) = 1 - F\left[D_{НД}(t_{CAC})\right] = = 1 - \int_{D_{ПНД_{MIN}}}^{D_{НД}(t_{CAC})} f(d_{ПНД}) d_{ПНД}, \quad (4)$$

where: $F(d_{MPD})$ is the Gaussian distribution value if $d_{MPD} = D_{DPU}(t_{al})$.

The generic formula for function $F(d_{MPD})$ is given in Fig. 1.

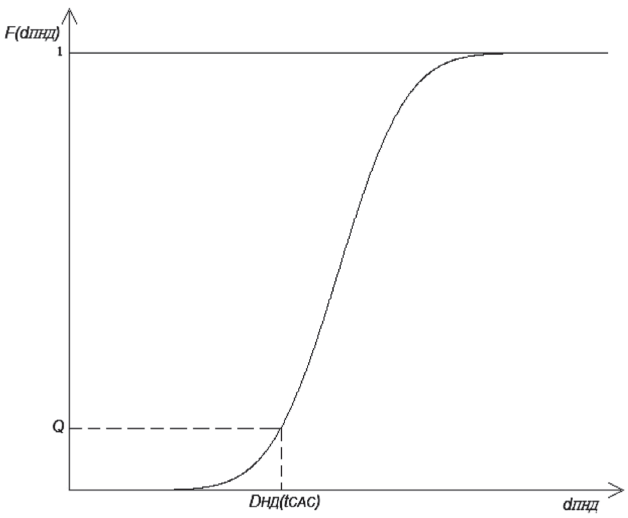

Fig. 1. Threshold accumulated dose distribution function

Fig. 2 shows the probability density function generation procedure d_{MPD} according to test results.

It should be noted this probability density function generation procedure d_{MPD} according to test results also allows specifying value $\sigma(d_{MPD})$ or the IC part type of the given technology group if its D_{MPD} is known. Normally, D_{MPD} represents the bottom "3σ boundary" (see fig. 2). Then on the assumption of constant $m(d_{MPD})$ and coefficient of variation (ν), the value of σ can be deducted from the equation:

$$D^*_{ПНД} = \frac{\sigma(d^*_{ПНД})}{\nu} - 3 \cdot \sigma(d^*_{ПНД}),$$

where: D^*_{MPD} is the maximum allowable dose for this IC part type; $\nu = \sigma(d_{MPD})/m(d_{MPD})$; $\sigma(d^*_{MPD})$ is the mean square deviation d^*_{MPD} of this IC part type.

As shown in fig. 2, tests are conducted under condition of D_{PD}=const over time t_I. Nevertheless, based on (1) we can find such values of D_{PDk} for each (k^{th}) IC that each of their failure happen at the same value of $D_{PDk}/d_{MPDk} = 1$:

$$D_{ПД_k} = \frac{d_{ПНД_k}}{t_{O_k}}, \quad (5)$$

where: d_{MPDk} is the maximum allowed dose of the k^{th} IC; t_{Fk} is the time to failure of the k^{th} IC due to low-intensity IR exposure.

Fig. 3 shows IC time dependences $D_{DPUk}(t_I)/d_{MPDk}$ obtained using (5).

As shown in fig. 3, the change process $D_{DPUk}(t_I)/d_{MPDk}$ is a "fan type" stochastic process as per GOST 27.005 [10]. Given the above and in accordance with the recommendations of GOST 27.005 [10], the failure model shall be an α-distribution as follows:

$$f(t) = \frac{C \cdot \beta}{t^2 \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{1}{2}\left(\frac{\beta}{t} - \alpha\right)^2}, \quad (6)$$

where α, β are distribution parameters.

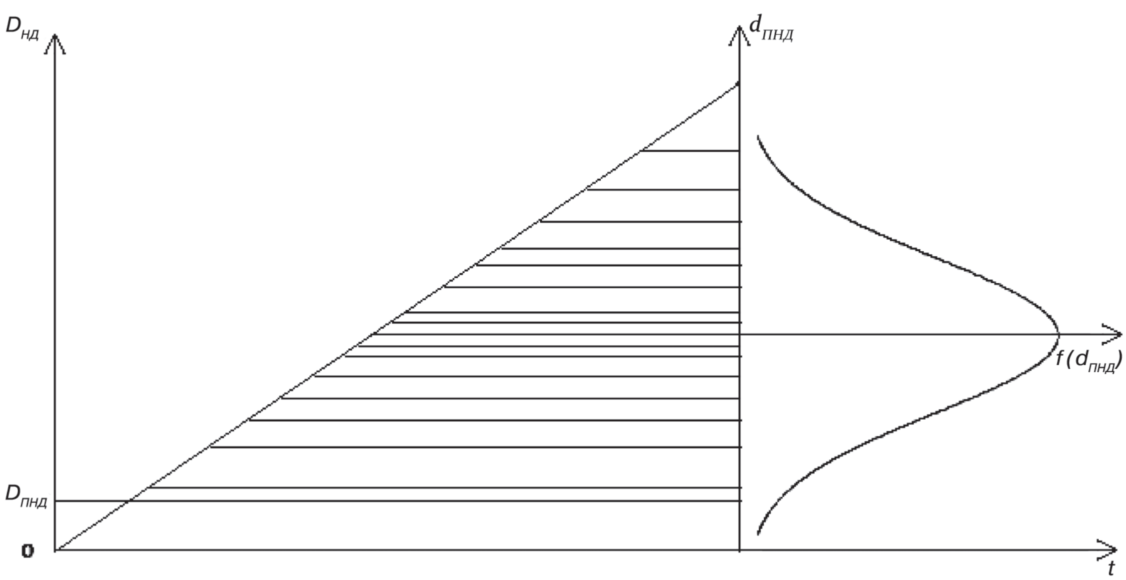

Fig. 2. Probability density function generation procedure dMPD according to test results

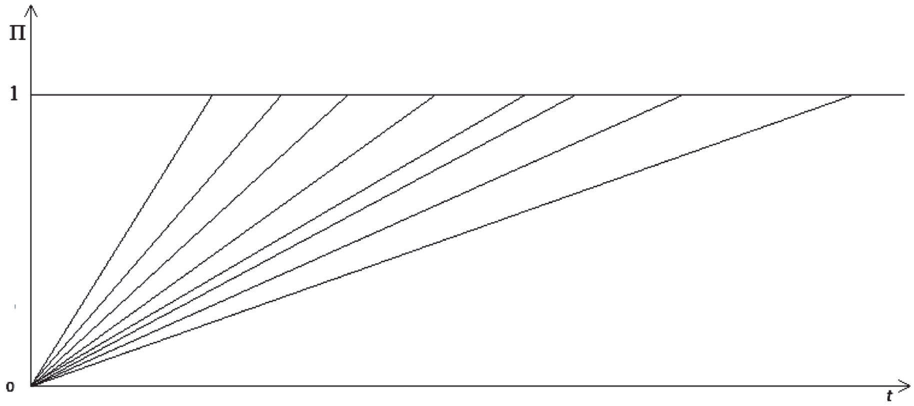

Fig. 3. Implementation of the change process $D_{DPUk}(t_I)/d_{MPDk}$ IC

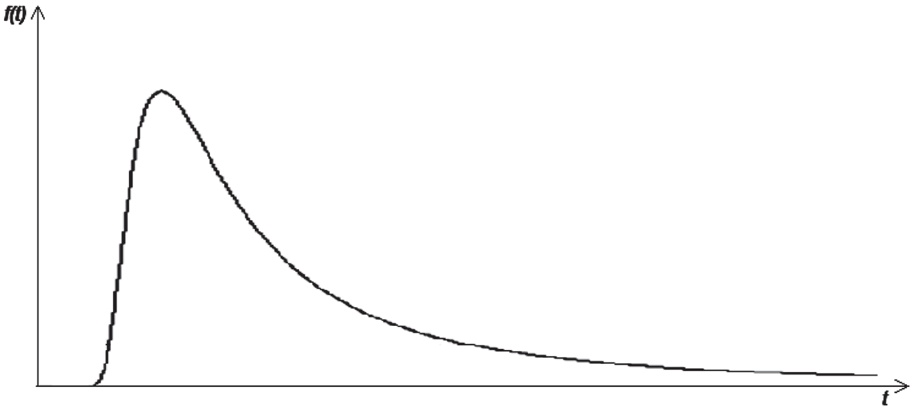

Fig. 4. Probability density of IC time to failure

Parameter α is the relative rate of change of the governing parameter (coefficient of uniformity of the rate of change of the governing parameter).

Parameter β is the relative margin of longevity.

The graph of the probability-density function of α-distribution is shown in Fig. 4.

The values of α and β parameters can be identified using the correlations given in GOST 27.005 [10]:

$$\alpha = \frac{m(V_П)}{\sigma(V_П)};\ \beta = \frac{П_{Пр} \cdot t_{САС}}{\sigma(V_П)}$$

where $m(V_{GP})$ is the average rate of change of the governing parameter; $\sigma(V_{GP})$ is the mean square deviation of the rate of change of the governing parameter; P_{GP} is the limit value of the governing parameter.

The values of $m(V_{GP})$, $\sigma(V_{GP})$ and $\sigma(V_{GP})$ can be identified using the known values of $m(d_{MPD})$, $\sigma(d_{MPD})$ and $D_{DPU}(t_{al})$. However, the following aspects should be taken in consideration. Unlike in the case of the "classic" α-distribution model generation procedure where the limit value of the governing parameter P_{GP} is deterministic, while its rate of change is stochastic (see fig. 2), in this case the dose build-up rate (D_{DPU}) according to (1) is a deterministic value, while the maximum allowed accumulated dose (d_{MPD}) is

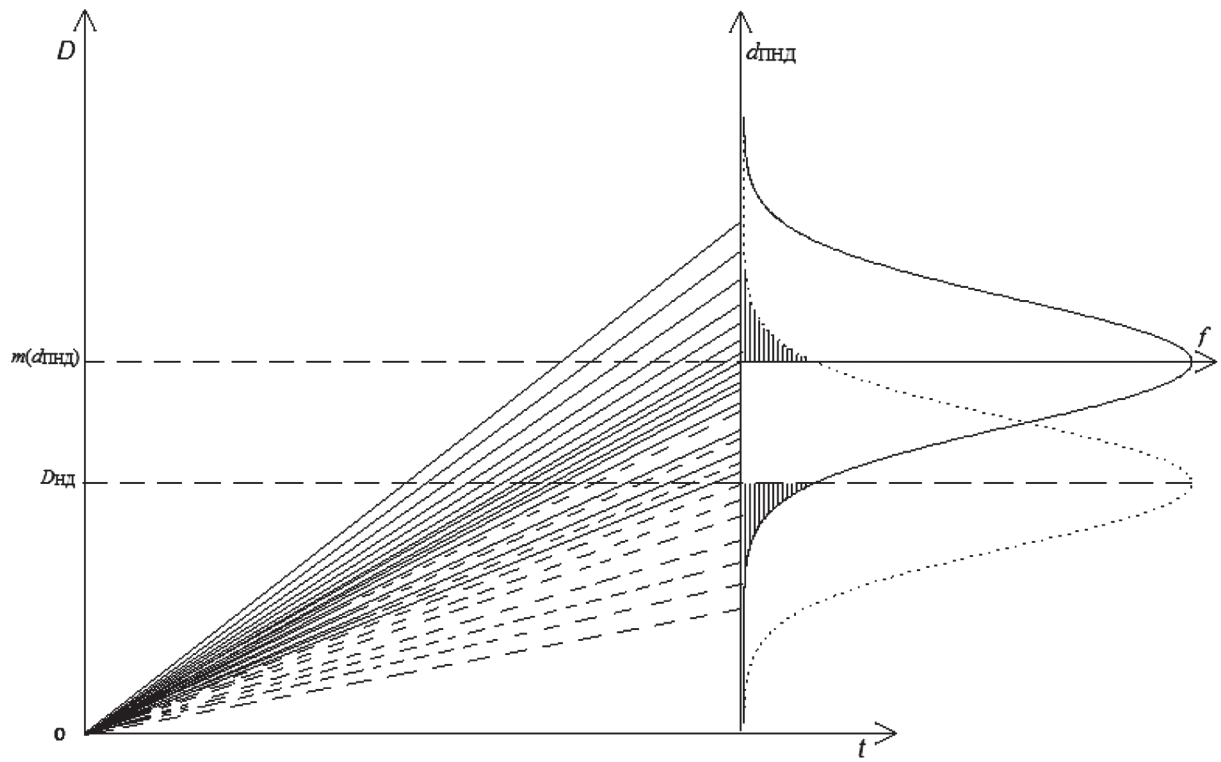

Fig. 5. IC failure probability densities if $m(V_{GP}) = m(d_{MPD})$ and $m(V_{GP}) = D_{DPU}$

stochastic (see fig. 1). That leads to the situation where if the limit value of the governing parameter is taken as $D_{DPU}(t_{al})$ (deterministic value) then if it increases $P_2(t_{al})$ will rise as well, which goes against the common sense (i.e. the higher the dose accumulated over time t_{al} the less is the probability of IC failure during that time).

Therefore, in order to avoid this contradiction we shall accept that:

$m(V_{ОП}) = _{ДИД}$ and $П_{ОП} = m(d_{ПНД})$.

Then the values of parameters α and β will respectively be:

$$\alpha = \frac{D_{НД}}{\sigma\left(d_{ПНД}\right)}; \ \beta = \frac{m\left(d_{ПНД}\right)\cdot t_{CAC}}{\sigma\left(d_{ПНД}\right)}. \qquad (7)$$

Fig. 5 shows the sufficiency of the justification given above.

As shown in Fig. 5 the probabilities (dashed areas) of failure if $P_{GP} = D_{DPU}$ and fault-free operation if $P_{GP} = m(d_{MPD})$ are equal.

When using model (5), the calculation of $K_2(t_{al})$ of IC if α, β and C are known is performed using formula:

$$P_2\left(t_{CAC}\right) = 1 - \int_0^{t_{CAC}} f\left(t\right)dt$$

It should also be noted that using failure model (5) unlike model (4) allows evaluating not only $R_2(t_{al})$, but also the mean time to failure (T_0) of IC exposed to low-intensity IR:

$$T_0 = \int_0^{\infty} P_2\left(t\right)dt.$$

Another significant aspect of model (5) is its capability to evaluate such IC longevity indicator as the minimum operation time (T_{MT}). That is especially important as in the practice of engineering the evaluation of this indicator of CMOS IC is affected by systematic errors due to the reasons that are considered in depth in [11, 12]. Please note that according to GOST RV 20.39.303 [13] CMOS IC are classified as general purpose products of the first type (highly dependable general use components) for continuous long term application, non-recoverable, maintenance-free, the transition of which into the limit state does not entail catastrophic consequences, wear-prone and ageing in storage. The limit state criterion of such products is the maximum allowable failure rate (λ_{emax}).

When using model (5) the value of T_{MT2} of CMOS IC exposed to low-intensity IR equals to operation time (t) of SC equipment whereby distribution density $f(t) \approx \lambda(t)$ first reaches critical value $f_{cr}(t = T_{MT2}) \approx \lambda_{max}$ [14]. Value λ_{max} can be identified based on the required value of λ_{emax} of CMOS IC. Fig. 6 shows the connection between the values λ_{max} and T_{MT2}.

Then value T_{MT} can be found using the following equation:

$$\lambda_{MAX} = \frac{\beta}{\left(T_{M.H_2}\right)^2 \cdot \sqrt{2\cdot\pi}} \cdot e^{-\frac{\left(\frac{\beta}{T_{M.H_2}} - \alpha\right)^2}{2}},$$

solving this for T_{MT2}.

Please note that the precise value of T_{MT2} can be found if $\lambda_{cr}(t = T_{MT2}) = \lambda_{max}$, solving equation (8) for T_{MT2}:

$$\lambda_{MAX} = \lambda_{кр} = \frac{f\left(T_{M.H_2}\right)}{1 - F\left(T_{M.H_2}\right)}, \qquad (8)$$

where: $F(T_{MT2})$ is the value of operation time distribution function.

The final value of minimal operation time of CMOS IC is deducted based on correlation given in OST 4.012.013 [16]:

$$T_{M.H_{ИС}} = \min\left(T_{M.H_1}, T_{M.H_2}\right),$$

where: T_{MT1} is the minimal operation time of CMOS IC not subject to the effects of low-intensity IR.

The information presented in this paper allows forecasting dependability and longevity indicators of spacecraft onboard equipment. At the same time, CMOS IC resistance and dependability depend not only on the characteristics of their maximum allowable dose distribution law, but also the accumulated dose. Therefore, if the prognostic evaluation of the dependability indicators does not comply with the requirements, the only way to ensure the required dependability and longevity indicators is the reduction of the

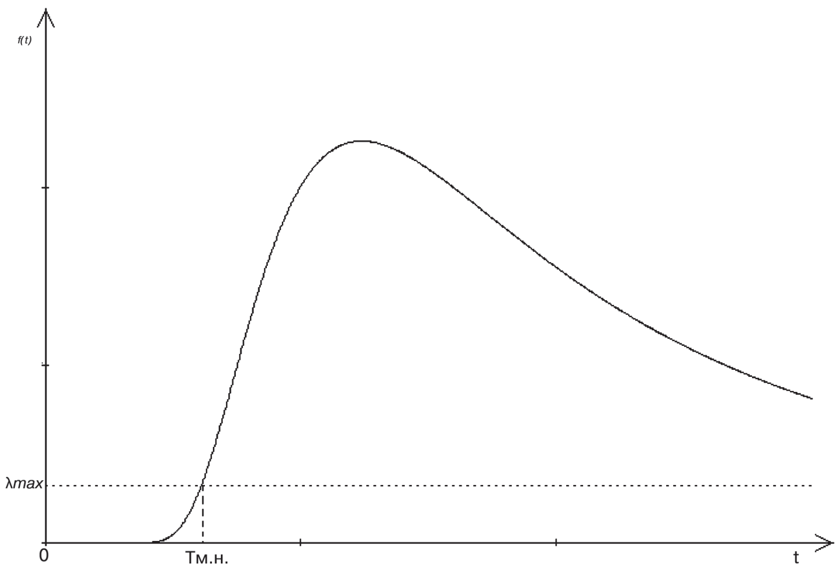

Fig. 6. Connection between values λ_{max} and T_{MN2}

accumulated dose. That can be achieved not only through conventional means of equipment protection that usually affects its weight and size characteristics, but also through special means (e.g. by using special printed boards [16]), as well as through rational placement of radiation-resistant ECs on printed board assemblies and their arrangement in equipment units [17, 18].

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