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Research of Mathematical Models for Assessing the Pumping Flashtubes Failure Rate

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***Abstract*—The research provides a review and analysis of the existing mathematical model of the pumping flashtubes operational failure rate. They are used in various spheres of human activity, such as: industry (laser welding, balancing devices), medicine (laser devices, endoscopes, blood analyzers), photography (high-speed cameras). A computational assessment was carried out using a decision support system, which makes it possible to numerically determine the importance of the factors considered in the work in assessing the operational failure rate. As a result of the study, the main parameters have been determined that have the greatest impact on the pumping flashtubes dependability. Mathematical models considering these parameters have been identified. Reliable mathematical model is proposed, suitable for evaluating the dependability characteristics of pulsed pump lamps.**

***Keywords*—dependability, reliability, operational failure rate, pulse lamp.**

I. INTRODUCTION

The need to create pumping flashtubes (PFT) appeared due to photographing devices, since a bright light was needed at the time of displaying a picture of an object on a photosensitive element. However, the initial models had significant drawbacks (a dense cloud of white smoke appeared, which made photography difficult), which demonstrated in [1]. Over time, PFT became electronic, which completely replaced disposable flash lamps. The function of the PFT is to supply light depending on the task of a particular lamp. For example, when used in flashing beacons on special vehicles, the light intensity and response frequency have the same parameters, but in professional cameras, the same characteristics have different values. PFT also works in the range of visible light and ultraviolet radiation.

Depending on the field of application, PFT has different dependability characteristics. According to [2] The study of the official reference book of the Russian Federation on the Dependability of electrical devices made it possible to understand that the existing mathematical model (MM) of dependability calculations has significant drawbacks in terms of considering factors, that has a direct impact on the obtained theoretical result of evaluating the PFT dependability, in particular, the operational failure rate (OFR).

Therefore, the purpose of the work is to increase the veracity of a PFT simple dependability measure – reliability. Thus, the objects of research are the mathematical models of the PFT OFR, given in the specialized literature on the device of flash lamps and on the assessment of the dependability of electrical radio devices. Such lamps are described in their work by Mandrikov and Tagatov [3].

II. OVERVIEW OF THE EXISTING PFT OFR CALCULATION MODEL

According [2] the mathematical model of the operational failure rate λ_o is (1):

$$\lambda_o = \lambda_b\left(\lambda_{bfr.}\right) \cdot K_o, \tag{1}$$

where $\lambda_b(\lambda_{bfr})$ stands for basic failure rate (basic group failure rate), the value of which is determined from the table (1/ pulse); K_o stands for operating factor, considering the severity of the operating conditions and shows how many times the failure rate of a product in equipment of a particular class is higher, all other things being equal, than in ground-based stationary equipment, which demonstrated in [4].

In turn, the base failure rate for xenon-filled, liquid-cooled flashlights with a pulse repetition rate $f > 1$ Hz is calculated by the following formula (2):

$$\lambda_b = 0.323 \cdot 10^{-8} \cdot \left(\frac{W_{all}}{l \cdot d \cdot \sqrt{\tau}}\right)^{0.838}, \tag{2}$$

where W_{all} stands for maximum allowable discharge energy (J); d stands for lamp inner diameter (cm); τ stands for luminous intensity pulse duration (μs); l stands for length of the discharge gap of the lamp (cm).

The model of a pulsed pumping lamp INP-2/25 was considered as examples. The obtained calculation results are listed in Table 1. It should be noted that the reference data is obtained as a result of the experiments.

TABLE I. Comparison of calculated and reference baseline failure rates

PFT model	**$\lambda_b \cdot 10^{-6}$, 1/pulse Reference**	**$\lambda_b \cdot 10^{-6}$, 1/pulse Calculated**	**Percentage error, %**
INP-2/25	0.017	0.005	71

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According to the data obtained, it is concluded that the above formula (2) does not allow obtaining correct data with regard to the basic failure rate. The calculation results give an estimate with a large percentage error relative to the experiment, which leads to the need to correct formula (2).

III. PARAMETERS AFFECTING THE PFT DEPENDABILITY

Flash lamps are a non-refillable electronic product, so it is important to consider their lifetime. For this, there is such an indicator of reliability as the operating time to failure. This time is determined by design features and depends on the following parameters:

- [2] show that there are flash energy (maximum allowable charge energy), the length of the discharge gap of the lamp, the inner diameter of the lamp, the duration of the luminous intensity pulse;
- Sviridov et al [5] sure that discharges capacitor, cooling systems, sealing method, peak currents influence on PFT.

A. *Flash energy*

According to [6], the flash energy (J) is calculated by the formula (3):

$$E_{st} = C(V^2)/2, \tag{3}$$

where *C* stands for storage capacity (F), *V* stands for voltage at the lamp electrodes (V).

At high pump energies, the lamp life is mainly determined by the mechanical strength of the quartz bulb and the destruction of the bulb due to the evaporation of quartz. While at low flash energies, the lamp life is mainly determined by the electrode effects, namely, the evaporation of the cathode material.

The load factor is used for calculations (4):

$$K_n = \frac{E_0}{E_x}, \tag{4}$$

$$E_x = K_x \cdot (T)^{0.5}, \tag{5}$$

where E_0 stands for flash energy (J), E_x stands for the energy at which the lamps fail (J), K_x stands for lamp explosion pulse constant, *T* is 1/3 pulse width (s).

At low flash energies, the lamp lifetime is mainly determined by the electrode effects, mainly by the evaporation of the cathode material. The vaporized metal is deposited on the inner surface of the flask, reducing the transparency of the flask, which in turn leads to an increase in losses. High peak currents significantly reduce the lamp life.

There is no reliable way to predict the life of a lamp. At high pump energies, the lamp life is mainly determined by the mechanical strength of the quartz bulb and the destruction of the bulb due to the evaporation of quartz.

The dependence of the number of lamp pulses before failure on the load factor is shown in Fig. 1.

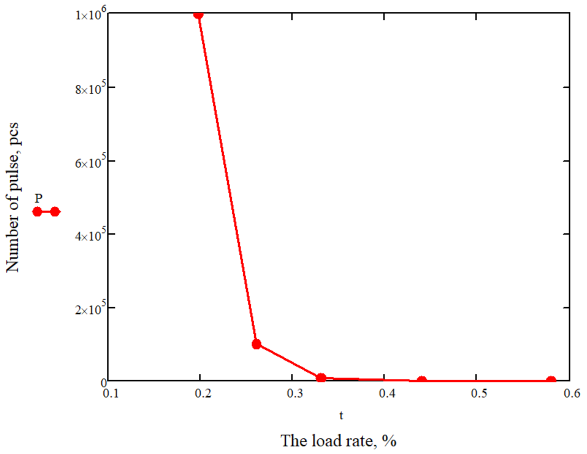

Fig. 1. Dependence of the number of lamp pulses before failure on the load factor.

According to the graph above, we can conclude that the reliability indicators are inversely related to the load factor: the higher the load factor, the fewer pulses the lamp will create before it fails.

B. *Discharge capacitor*

According [5], [6] the discharge capacitor has such parameters as the storage capacity (F) (6), the voltage across the storage capacity (V) (7), the inductance of the discharge battery (H) (8); discharge time (µs), current amplitude in the discharge circuit (kA).

Discharge battery storage capacity values (6)

$$C = \frac{(2 \cdot E_0 \cdot a^4 \cdot T^2)^{0.33}}{K_0^4}, \tag{6}$$

$$V_0 = \left(\frac{2 \cdot E_0}{C}\right)^{0.5}, \tag{7}$$

$$L = \frac{T^2}{C}, \tag{8}$$

where K_0 stands for lamp impedance (Ω /A$^{0.5}$), *a* stands for attenuation coefficient (taken equal to 0.8 for critical attenuation). These parameters are affected by the flash energy, respectively, they depend on its value.

C. *Cooling system*

Koromislov and Brendel [6] claim that there are 3 types of PFT cooling: convection air, forced air, water.

For correct lamp operation, the type of cooling required must be determined. For this purpose, the average released power (W) (9) and the power density in the bulb material (W/cm^2) are calculated (10).

$$P_{ave} = E_0 \cdot f, \tag{9}$$

$$\rho_{ave} = \frac{P_{ave}}{l \cdot d}, \tag{10}$$

where *f* stands for pulse repetition rate (Hz).

Further, depending on the obtained power density in the material of the flask, the type of cooling is selected (Table 2).

TABLE II. Selecting the type of PFT cooling

ρ_{ave} , W/cm2	The cooling type
0-15	Convection air
15-30	Air-forced
30-320	Water

Table 2 shows that the water type of cooling is predominantly used, since the power density range in the bulb material has a wider spectrum.

D. *Method of sealing*

The PFT should be provided with a hermetic seal so that the gas inside the flask does not escape outside as shown in [7], [8]. This seal is not easy to achieve, given the different nature of the bulb material, the metal electrodes, as these elements expand and contract at different rates under the same thermal conditions. There are 3 main types of flash tube encapsulation:

- Ribbon Seal.
- Solder Seal.
- “Rod Seal”.

In case of ribbon seal, quartz is bonded directly to a thin strip of molybdenum foil. The PFT, sealed in this way, has a very strong bond between metal electrodes and quartz. This sealing method allows the designer to minimize "dead volume" (that is, the interior space between the electrode tip and the seal). However, this seal cannot withstand the enormous current supplied to the electrodes.

The solder seal allows to create a bond between the Invar round tape and the quartz tube. The seal is made using lead-indium solder with a melting point of 350 °C. This method reduces "dead volumes", provides a rigid attachment of the electrodes to the quartz tube, is highly durable and has the best current control of any sealing method. Unfortunately, the solder seal has a low operating temperature of less than 100 °C and has a questionable shelf life.

The term “rod seal” is used to describe the sealing method in which quartz is immediately fused to metal electrodes in a tight bond. This can be achieved by using extremely high temperature and / or pressure. This compaction method has high dependability, high peak and RMS current conductivity, can handle relatively high temperatures, and has a high potential for silica heat treatment capabilities.

E. *Peak currents*

According to [4] the PFT dependability is greatly influenced by the value of the peak currents at the cathode. At high current values, the cathode overheats, which leads to a significant decrease in the lamp life (cathode erosion occurs). The peak current value should not exceed 1000 A, so this principle is also used in this work.

IV. DEVELOPMENT OF AN APPROACH FOR DETERMINING COEFFICIENTS FOR A MODEL OF INTENSIVE FAILURES RATE

For each parameter related to the PFT design and described in Chapter 3, it is necessary to determine the coefficients that will indicate their importance in the calculation of dependability. It is also necessary to determine the quality factors for the alternatives of these parameters (sub-parameters).

This paper will consider the importance of design parameters such as cooling systems and sealing method. When evaluating the sub-parameters, their degree of impact on OFR will be considered. The higher the given number, the higher the dependability. Cooling methods will be evaluated for the cooling system. For sealing methods - the degree of influence of the 3 described sealing methods.

To solve this problem, according method Vyunenko [9] a decision support system (DSS) is used. For this, estimates of parameters from 5 experts were drawn up and the results were analyzed. The results are shown in Tables 3 to 5 for parameters and sub-parameters, respectively.

TABLE III. Calculation of the parameter importance factor

Parameters	Expert assessments					K_v, Importance factor
	Q1	*Q2*	*Q3*	*Q4*	*Q5*	
Cooling system	8	7	9	5	8	0.74
Sealing method	9	9	9	8	8	0.86

TABLE IV. Calculation of the coefficient of influence of the cooling system sub-parameters

Parameters	Expert assessments					Y_o, Influence factor
	Q1	*Q2*	*Q 3*	*Q 4*	*Q 5*	
Convection air	4	3	6	2	3	0.36
Air-forced	5	5	4	6	6	0.52
Water	9	8	9	7	8	0.82

TABLE V. Calculation of the coefficient of influence of the connection method sub-parameters

Parameters	Expert assessments					Y_u, Influence factor
	Q1	*Q2*	*Q3*	*Q4*	*Q5*	
Ribbon Seal	2	5	3	5	5	0.4
Solder Seal	3	2	3	4	4	0.32
“Rod Seal”	7	6	8	9	8	0.76

The calculation of the coefficients is carried out according to the formula (11):

$$K_y(Y_y) = \frac{\sum_{i=1}^{n} P_i}{n}, \tag{11}$$

$$P_i = \frac{Q_i}{z}, \tag{12}$$

where n stands for number of experts, P_i stands for weight of the i-th expert, z stands for the expert's maximum score (in this case 10), Q_i stands for expert number.

V. PROPOSED MATHEMATICAL MODEL OF PFT OFR

To solve this problem, a modular approach is proposed, that is, the influence of design parameters that are not taken into account in formula (1) is considered. To compile a mathematical model of OFR, it is necessary to modernize formula (2) to reduce the error between calculations by the formula and the results of experiments. For this, formula (13) is proposed instead of (2).

$$\lambda_b = 0.323 \cdot 10^{-8} \cdot \left(\frac{W_{all} \cdot \sqrt[3]{I_{max}}}{l \cdot d \cdot \sqrt{\tau}}\right)^{0.838}, \tag{13}$$

where I_{max} stands for peak current.

TABLE VI. Calculations of the percentage error by formulas (2) and (13)

PFT model	$\lambda_b \cdot 10^{-6}$, **1/pulse Reference**	$\lambda_b \cdot 10^{-6}$, **1/pulse Calculated**	**Percentage error, %**	
			Formula (2)	***Formula (13)***
INP-2/25	0.017	0.014	71	29
INP-16/250A	0.080	0.031	94	32

According to the results obtained, it can be seen that the percentage calculation error has become much smaller.

As a result of the study, the final mathematical model of the PFT OFR is proposed (14):

$$\lambda_o = \lambda_b(\lambda_{bfr}) \cdot K_o \cdot (K_{vo} \cdot Y_p) \cdot (K_{vu} \cdot Y_u), \qquad (14)$$

where K_{vo} stands for cooling systems importance factor, Y_p stands for cooling type coefficient, K_{vu} stands for sealing importance factor, Y_u stands for seal type factor. λ_b in this case is considered from the formula (13).

For clarity, there are two graphs of dependences of OFR on the cooling type coefficient (Fig. 2) and on the seal type factor (Fig. 3)

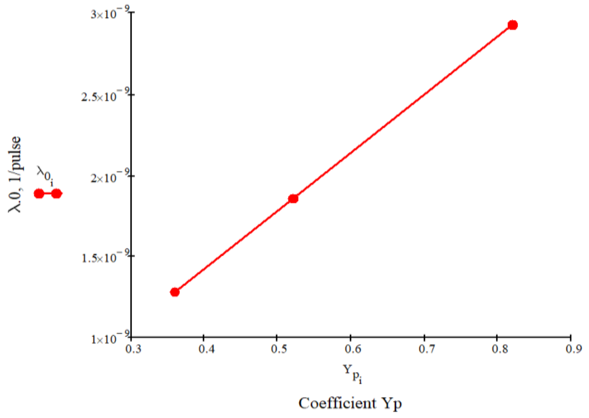

Fig. 2. Dependence of OFR on the cooling type coefficient.

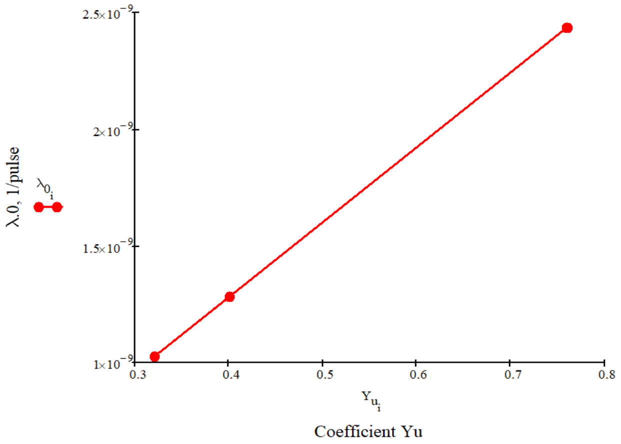

Fig. 3. Dependence of OFR on the seal type factor.

According to Figures 2 and 3, the worse the cooling and the weaker the sealing, the lower the OFR. However, the change in OFR does not exceed 2.5 times for each of the considered coefficients.

VI. CONCLUSION

As a result of the study, the most important parameters in assessing the dependability of the PFT were revealed: the flash energy, the parameters of the discharge capacitor, the cooling system, the sealing method, the values of the peak currents. According to this, two models of PFT are considered [2], [10] and for them calculations of the basic failure rate are made. Indeed, the calculations showed that formula (13) is more correct for calculations. However, calculations according to formula (14) must be carried out at the enterprise to determine the key parameters of the formula itself, which depend on the purpose of the PFT.

In this regard, the derived formula is exclusively theoretical in nature, since at the time of writing the work there is no confirmation of it at the enterprise.

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