RELIABILITY EVALUATION OF ELECTRONIC COMPONENT IN MILITARY VEHICLES UNDER THERMAL EXPOSURE AND THERMAL CYCLING BY ACCELERATED TEST METHOD

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Abstract. *The majority of electronic components are susceptible to damage at high temperatures (overheating) and their reliability is affected by its operating temperature. The temperature can basically dictate the effective performance as well as the lifetime or life cycle of the electronic components. In addition, the reliability of electronic components is not only affected temperatures but also by changes in temperature over a period of time (thermal cycles). This article describes the methodology how to prepare, perform and evaluate the accelerated reliability compliance test of electronic components in military vehicles under thermal exposure and thermal cycling.*

1 Introduction

At present, the number of electronic components in military vehicles has greatly increased, combat vehicles achieve the parameters of the major military characteristics (tactical-technical parameters) through a high proportion of electronic components with digital control. These electronic components contribute significantly to the achievement of the reliability of vehicles. The military vehicle is considered a system of the overall defence system, in which crew members can receive and transmit orders (by voice, text, video, etc.), data exchange (point locations, area boundaries, logistic state, etc.) with partners. Therefore, combat vehicles are equipped with sophisticated communications systems including Battle Management Systems (BMS), Tactical Radio, Navigation Systems, Headsets, etc. At the same time, electronic and electromechanical technologies are replacing mechanical and hydraulic solutions in combat vehicles. For example, the electric turret motor has become popular, electro-mechanical transmissions are increasingly used to replace mechanical transmissions. The new operational systems are integrated into combat vehicles such as electrochemical or electromagnetic energy propelled ammunitions, active electromagnetic protections, active suspensions [1].

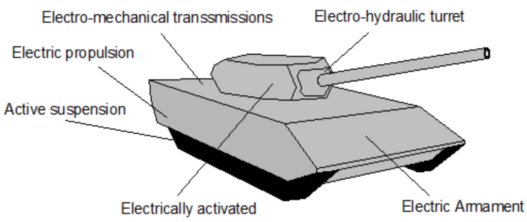

Fig. 1. *Electronic system in modern combat vehicles [1]*

Due to the increasing number of electronic systems in military vehicles, it can be said that this is the process of digitizing military technology. The reliability of the electronic components characterizes the resulting values of the reliability of the entire electronic system in military vehicles. Electronic component failure can lead to catastrophic effects in combat operations. For this reason, it is necessary to study and develop methods for predicting the reliability of electronic components used in military vehicles. At present, reliability of electronic components is estimated by using the standard handbook, statistical analysis of operation & maintenance data (reliability database) or performing reliability testing [2]. In general, the use of standard handbooks (e.g. MIL-HDBK-217, RIAC-217, PRISM), and reliability database (e.g. EPRD-2G14, FMD-2G16), have some inherent limitations such as these methods are based on assumptions about a constant failure rate that may incorrectly reflect the failure trend in the product life cycle; the methods cannot indicate basic failure mechanisms and do not provide the root cause of failure; the methods are not effective in predicting the reliability of new electronic components, etc. Hence, in order to obtain failures data of electronic components for analysing their failure modes and understanding life characteristics in a short period of time, another approach is developed, i.e. accelerated test method. This method has become increasingly important because of the need to develop newer, higher technology product, the shorter period between product design and release while improving productivity, quality, and reliability.

2 Effect of temperature and thermal cycling

There are many factors that influence on the reliability of electronic components, such as temperature, thermal cycling, heat shock, humidity, voltage, current, mechanical stress (vibration, shock) or combination of stresses. In this study, we conducted an accelerated reliability test (ART) with the combined temperature and thermal cycling stress to evaluate their influence on the product reliability.

2.1. Temperature

Most electronic components are susceptible to damage at high temperatures (overheating) and their reliability is influenced by its operating temperature [3]. It can be said that temperature is the enemy of reliability of all electronic components. Therefore, when analysing system errors of electronic components, it usually involves examining evidence or signs of overheating. Studies have also shown that there is a relationship between the performance, lifetime or life cycle of an electronic component with its specific operating temperature range. The temperature can basically dictate the effective performance as well as the lifetime or life cycle of the electronic components.

The temperature on electronic component includes the temperature of the environment (generated by the direct influence of solar radiation and heat exchange) and the temperature generated when the device is in operation. For example, the heat source is generated by the engine, by the action of friction and it is transmitted from mechanical energy to heat, the conductors emit heat when the current passes through, the heat dissipation from the semiconductor device, etc. High and low temperatures can make electronic components unsafe or unsuitable for use because they change the properties of materials used in the construction of electronic components. Failure mechanisms of electronic components due to high temperature are oxidation, physical expansion, softening/melting, chemical decomposition, etc., while due to low temperature are physical contraction, ice formation, embrittlement [4].

2.2 Thermal cycling

The reliability of electronic components is not only affected by low and high temperatures, but also by changes in temperature over a period of time (thermal cycles). These temperature variations depend on operating cycles of the electronic components (on/off) and variations in its environment (e.g. day/night). The thermal cycling particularly stresses on the solder joints, die attachments, wire bonds which can lead to catastrophic failure of the electronic components (e.g. breaking of solder joints, loss of conductive contact, deformation of the processor plate). The most common failure mode due to thermal cycling is fatigue. The lifetime of an item under thermal cycling stress depends on the thermal cycling profile, the coefficients of thermal expansion, and other material properties that determine crack initiation and propagation rates [5].

A thermal cycle is characterized by high temperature (T_{max}), low temperature (T_{min}), dwell time at high temperature (τ_{dw_high}), dwell time at low temperature (τ_{dw_low}), and rate of temperature change. Reliability testing with thermal cycling is specified in many different technical standards as an integral part of environmental stress testing. For example, standard JESD22-A104E recommends thirteen thermal cycling test conditions for electronic components and solder interconnects [6]; standard MIL-STD-883F recommends six thermal cycling profiles for microcircuits [7].

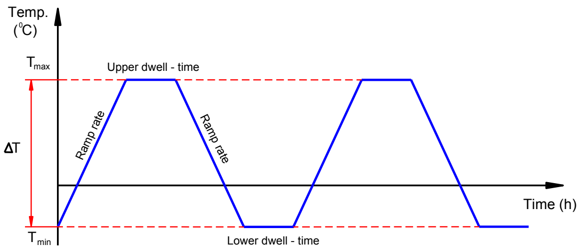

Fig. 2. *Schematic of temperature cycle profile [5]*

3 Design of accelerated reliability testing

3.1 Test conditions and stress levels

To successfully design an ART, it is necessary to have a good knowledge of the intended use environment, the environment profile and operating conditions of the product as well as product design capabilities [8]. In this case study, electronic components are designed for use in combat vehicles with the following operating and environmental conditions.

Table 1. *Operating conditions of electronic components*

Parameter	Symbol	Value
Required life	τ_r	15 years = 131400 h
Time - ON	τ_{ON}	4h/day = 21900 h
Temperature - ON	T_{ON}	60 °C
Time - OFF	τ_{OFF}	109500 h
Temperature – OFF	T_{OFF}	25 °C
Temperature change	ΔT_{use}	45 °C
Rate of temperature change	ξ_{use}	1.5 °C/min
Number of thermal cycles per day	N_{cy}	2
Total cycles	N_o	10950

In ART, to simulate a lifetime of actual stresses that the product will be exposed to, all of the test units are subject to each of the stresses in the entire test sequence. The failure data of the test units is required to estimate the reliability in the field and in order to obtain this information quickly, electronic components need to be operated at elevated stress conditions. The nominal time of testing for these stresses is determined based on the cumulative damage model, in which the equivalent test damage occurs by increasing the amplitudes of each individual stresses but ensuring within the maximum design limit of products.

In this paper, we focus on the effect of temperature, thermal cycle to reliability of electronic components. The characteristics of the thermal cycle in ART include the high temperature (T_{max}) of 100 °C, low temperature (T_{min}) of -40 °C, rate of temperature change in test (ξ_{test}) of 3.0 °C/min. The temperature change of ART is:

$$\Delta T = T_{max} - T_{min} = 140\ ^{o}C$$

With the test stress is thermal cycle, according to Coffin-Manson model [8], the acceleration factor is:

$$A_{TC} = \left(\frac{\Delta T_{use}}{\Delta T_{test}}\right)^{-2} \cdot \left(\frac{\xi_{use}}{\xi_{test}}\right)^{-1/3} = 12.2$$

The total number of cycles of ART is then:

$$N_{test} = \frac{N_o}{A_{TC}} = \frac{10950}{12.2} = 897 \text{ cycles}$$

To determine the test time in ART under thermal stress, the time at the off- state (time – OFF) is normalized to the equivalent time at the on- state (time – ON).

$$\tau_{ON-N} = \tau_{ON} + \tau_{OFF} e^{\frac{E_a}{k_B}\left(\frac{1}{273+T_{OFF}} - \frac{1}{273+T_{ON}}\right)}$$

where E_a is the activation energy (eV); k_B is the Boltzmann's constant, k_B = 8,617385.10^{-5} (eV/K). The values of the activation energy for electronic component can be found in [9] ranging from 0.3 to 0.8 eV (see Table 2). In this case study, E_a = 0.8 eV is selected, then the equivalent time is:

$$\tau_{ON-N} = 21900 + \frac{109500}{26.4} = 26047 \text{ h}$$

Table 2. *Activation energies in different standards [9]*

Electronic components	MIL-HDBK-217F	RDF 2000 (2000)	RIAC-217 plus (2007)	FIDES (2009)
Bipolar logic	0.4 eV	0.4 eV	0.8 eV	0.7 eV
CMOS logic	0.35 eV	0.3 eV	0.8 eV	0.7 eV
BICmos logic	0.5 eV	0.4 eV	0.8 eV	0.7 eV
Linear	0.65 eV		0.8 eV	0.7 eV
Memories	0.6 eV		0.8 eV	0.7 eV
VHSIC	0.4 eV		0.8 eV	0.7 eV

With the test stress is temperature, Arrhenius model is used to calculate the acceleration factor [8].

$$A_T = e^{\frac{E_a}{k_B}\left(\frac{1}{273+T_{ON}} - \frac{1}{273+T_{test}}\right)} = 19.8$$

The necessary test duration of ART is:

$$\tau_{test} = \frac{\tau_{ON-N}}{A_T} = \frac{26047}{19.8} = 1315 \text{ h}$$

When conducting tests with a combination of thermal exposure and thermal cycling, thermal exposure over the high temperature of the thermal cycling is used to determine the dwell time at high temperature. Thus, dwell times at high temperature is:

$$\tau_{dw-high} = \frac{\tau_{test}}{N_{test}} = \frac{1315}{897} = 1.45 \text{ h} = 87 \text{ min}$$

The dwell time at low temperature of 45 min is selected to ensure the homogeneous temperature in the chamber was provided when reaching a maximum or a minimum temperature. The test duration of a temperature cycle is:

$$\tau_{TC} = 2\frac{\Delta T_{test}}{60\xi_{test}} + \tau_{dwell\_high} + t_{dwell\_low} = 225 \text{ min}$$

Table 3. *Test conditions*

Thermal Cycles	Number of Cycles	Current (mA)
-40 °C /45 min +100 °C /87 min 3 °C /min	897	1050
		525
		210

3.2 Experimental setup

The experiment has been conducted on Light Emitting Diodes (LEDs) in combat vehicles. The electrical and optical characteristics of the high-power LED at ambient temperature of 25 °C are described in Table 4.

Table 4. *Electrical-optical characteristics of LED*

Parameter	Min	Typ	Max	Unit
Luminous Flux	700	~	800	lm
Correlated Color Temperature/ Wavelength	2900	~	3200	K/nm
Color Rendering Index (CRI)	60	~	90	~
Forward Voltage	9	~	11	V
Power Dissipation	~	9.45	~	W
View Angle	~	90	~	deg.
Thermal Resistance	~	12	~	°C/W

The LEDs were placed in the climate chamber Votsch VC3 7034. The LEDs are then connected to the DC power supply (Keysight E3634A) and measure unit (Keysight 34980A Multifunction Switch/Measure Unit). The LEDs are supplied constant currents, and voltage in each LED are measured every 10 minutes. The measured values were continuously recorded using a PC with BenchLink Data Logger Pro software. The experimental setup for the ART of the high-power LEDs is shown in Fig.3.

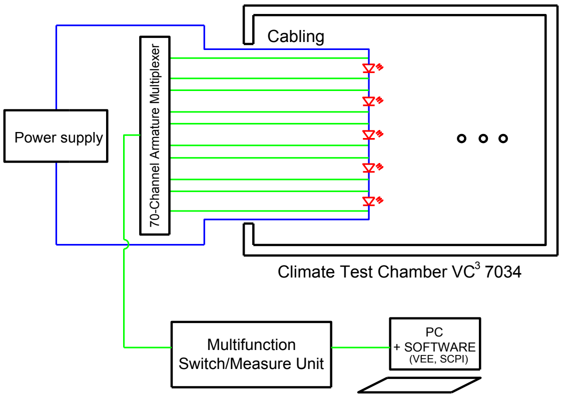

Fig. 3 *Experimental arrangements*

3.3 Experimental procedure

The thermal cycles were set so that after the test begins, the LEDs can be heated to +100 °C. When this temperature was reached, it was kept in the climate chamber for 87 minutes. The cooling cycle was then started, and LEDs were continually cooled to -40 °C. When this temperature was reached, the control program kept the temperature in the climate chamber for 45 minutes. After that, the heating cycle started again, and LEDs were continually heated to the maximum temperature (+100 °C). The speed of temperature change in test is 3 °C/min, and test duration of a thermal cycle is 225 minutes. The number of test samples includes 20 LEDs at current of 1050 mA (condition A), 25 LEDs at current of 525 mA (condition B), 30 LEDs at current of 210 mA (condition C). The test is terminated at test time of 897 cycles. The number of failures during the test is also a variable random. The failed units are not replaced by new ones during the test.

For LED reliability testing, there are two types of failure that are evaluated, i.e. catastrophic and degradation failure [10]. However, in the tests were performed above, all observed failures were catastrophic with open circuit failure. This failure is detected when the bias voltage drops to zero.

4 Evaluation of accelerated reliability testing data

The results of ART are evaluated using the principle of confidence limit and predicting the lower one-sided confidence of mean time to failure ($MTTF_L$). The formulas for establishing one-sided (i.e., lower limit) confidence limits on $MTTF_L$, respectively, are as follows [11]:

$$MTTF_L = \frac{2T_{OE}}{\chi^2_\alpha(\nu)}$$

where $\chi^2_\alpha(\nu)$ is the chi-squared distribution for number of degrees of freedom ν at confidence level α; T_{OE} is accumulated test time. The number of degrees of freedom is specified for each case related to the number of failures r recorded in the test. In case of test without replacement of failed units, the number of degrees of freedom is given by [11]:

$$\nu = 2r + 1$$

The accumulated test time depends on the test plan, number of samples and failures recorded in the test. Test is terminated at a pre-assigned test duration τ_o, without replacement of failed units, the accumulated test time is defined as follows [11]:

$$T_{OE} = \sum_{i=1}^{r} t_i + (n - r)\cdot\tau_o$$

where n is the sample size, t_i is the failure time of the i^{th} sample; τ_o is the test time.

The experiments are still in progress. In the test, with condition A, the number of samples is 20 LEDs (n = 20). For example, during the test, four failed samples are observed (r = 4). The first failure occurs at N_1 = 405 cycles, the second failure at N_2 = 535 cycles, the third failure at N_3 = 715 cycles, and the fourth failure at N_4 = 845 cycles. The accumulated test time in this case is:

$$T_{OE} = \sum_{i=1}^{4} N_i \square A_{TC} + (20 - 4)\cdot N_o = 211465 \text{ cycles}$$

With the confidence level for reliability evaluation of $\alpha = 0.95$ and $\nu = 2\times4 + 1 = 9$, the chi-squared distribution is:

$$\chi^2_{0.95}(7) = 16.9$$

$MTTF_L$ of LED is then:

$$MTTF_L = 24343 \text{ cycles}$$

This corresponds to approximately 33.4 years under given conditions (as shown in Table 1).

5 Conclusion

This paper presents the effect of temperature and thermal cycling on the reliability of electronic components, and methodology how to prepare, perform and evaluate the ART of electronic components in military vehicles under their influence. LEDs were selected for testing because they are not only widely in many important applications, but they are also used in military equipment, especially in military vehicles. Based on operating and environmental conditions of military vehicles, combination of temperature and thermal cycling was used to conduct experiments. A monitoring system was set up to detect catastrophic failures and degradation failures of test units during testing. The ART is still undergoing. The information from tests will be analyse based on the principle of confidence limits on MTTF.

Acknowledgment

This paper has been prepared with the support of the Ministry of Defence of the Czech Republic, Partial Project for Institutional Development, MOBAUT, University of Defence, Brno.

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