Failure Prediction Models for Accelerated Life Tests

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Abstract: The aim of this paper is to introduce the reliability methods in connection with lifetime determination and to design testing method for the prediction of the life of the micro switches. These products are subjected to complex stressing, for example, humidity, temperature, current load and so on. Therefore, the most important failure prediction methods, acceleration life testing methods with one, two or more variables have been introduced, as these methods are essential and necessary for reliability prediction.

Key-Words: Accelerated Life Testing, Lifetime, Bathtub Curve, Failure Prediction, Reliability Prediction, Arrhenius Relationship

1 Introduction

We shall understand the reliability that a product maintains its initial quality and performance at a certain period of time, cycle, distance etc. under given conditions without failure. The operating conditions could be environmental conditions and working conditions. Environmental conditions include the humidity, vibration and temperature. The working condition means an artificial environment such as voltage, current load, place for installment and hours of use, which occurs during the life of the product [1].

It has already been pointed out in our previous papers that unfortunately the micro switches used in gardening machines have several malfunctions. During the last few years it was practiced, that certain types of micro switches have not provided a desirable life. Among others, due to high temperatures, deformation of internal components, loss of function, switching and breaking of button switches have experienced. In addition, the material surface can be burned and the contacting surfaces can be charred. For all of these reasons, the switch will not work properly [7-9]. Therefore, it is necessary to develop different test methods to predict the life expectancy of products.

The aim our investigations is to carry out pre-planned measurements and testing micro switches applied in several types of garden tools. To obtain objective conclusions, we need an effective method for designing and analyzing the experiments.

2 Failure prediction

The reliability prediction is to predict failure rate and average life span associated with reliability by taking operation, working environment and conditions associated with systems and parts into account.

The prediction will eventually be used mainly in design and product development stage of parts and system. Also, the prediction enables the operators to secure customer safety by building preventive maintenance plan in advance.

Predicting the life span of parts and applying it to maintenance or conducting activities to promote longer life span by reflecting operation data feedback to a design are not yet a common practice and it is quite challenging [1, 4-6].

2.1 The Bathtub Curve

We have already described in detail in our previous articles the bathtub curve's features and the bathtub shape's three phases of life for components, which was predicted by physics of failures (see Fig.1., [3, 7-9]).

2.1.1   Early, infant failures (I.)

In this is early life that is mortality, which is characterized by decreasing failure rate.

2.1.2   Middle, random phase (II.)

In this phase useful life, which has relatively constant failure rate.

2.1.3. Usage, wear out phase (III.)

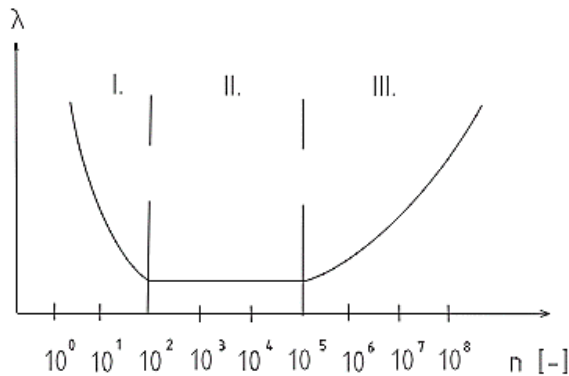The last phase is the long-term wear–out segment, which increases rapidly with increasing failure rate [3, 4].

Figure 1. The bathtub curve

2.2 Failure-Time Distribution Functions

The probability distribution for failure time *T* can be characterized by a cumulative distribution function, probability density function, a survival or hazard function. These functions are described below and illustrated for typical failure-time distributions. These functions are exhibited in the diagrams. The choice of function to use depends on convenience of model specification, interpretation, or technical development; all these functions are important for one or another purpose. On Figs. 2-4, we show the cumulative distribution function, the probability density function and the hazard function [2].
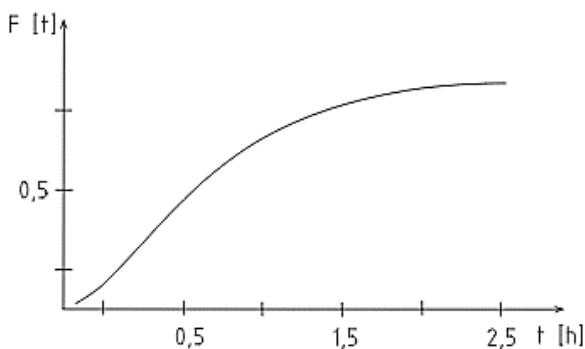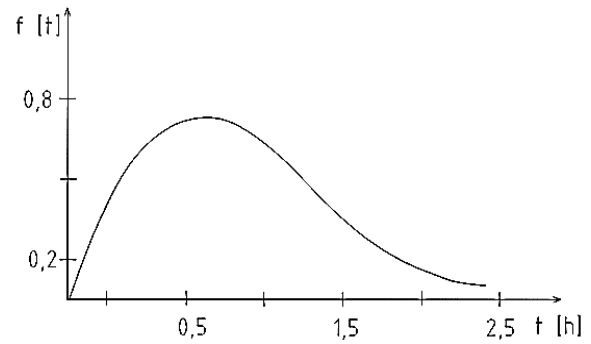

Figure 2. Cumulative distribution function

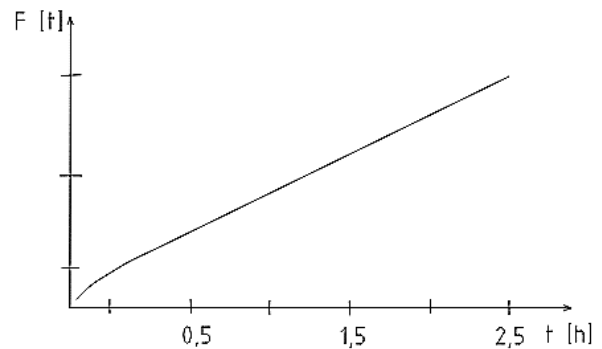*Figure 3. Probability Density function*

Figure 4. Hazard Function

Applying the general three-parameter form of the Weibull distribution, the distribution function can be formulated as a follow [7-9]:

$$F(t) = \begin{cases} 1 - exp\left[-\dfrac{(t-\gamma)^{\beta}}{\alpha}\right], & if\ t \geq \gamma, \\ 0 & ,if\ t < \gamma. \end{cases} \quad (1)$$

Function *F(t)* gives the failure probability during the actual operating time. In formula (1) the statistical variable is time *t* in hours or number of operations, the parameters involved in (1) are the following:

α> 0 is the scalar parameter,
β> 0 is the shape parameter,
γ≥ 0 is the location parameter.

The characteristic lifetime is denoted by η. Let us introduce the substitution $\eta = \alpha^{1/\beta}$ into expression (1). Thus, the distribution function can be written as follows:

$$F(t) = \begin{cases} 1 - exp\left[-\left(\dfrac{t-\gamma}{\eta}\right)^{\beta}\right], & if\ t \geq \gamma, \\ 0, & if\ t < \gamma. \end{cases} \quad (1a)$$

The position parameter γ can be taken to 0 for a few practical applications, the sampling plans are designed for case *γ=0*. The shape parameter *β* determines the figure of the density function. The density function *f(t)* for the Weibull distribution with *γ=0* can be determined by differentiation from the formula (1a) (see Fig. 2).

$$f(t) = F'(t)$$
$$= \begin{cases} \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], if \ t \geq 0, \\ 0, \qquad\qquad\qquad if \ t < 0. \end{cases} \quad (2)$$

If *β<1*, then *f(t)* is a monotone decreasing function, this is the phase of early failures.

If *β=1*, then we get the exponential distribution, which is the phase of random failures.

If *β>1*, then density function has a maximum, this characterize the phase-related failure phase [7-9].
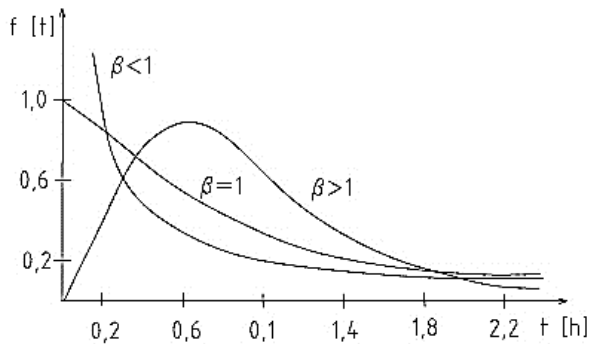

Figure 5. The density function of the Weibull distribution for different values of *β*

2.3 Electronic Parts Failure Prediction

The reliability test can be qualified by single component, but as more and more components are integrated altogether to form a desired electronic module, the individual components can be reduced due to interaction with overall system design [3].

There are several type of failure predictions which can be used in the industrial development. Figure 6. represents some of these methods, which are further classified into different groups based on several technologies.

It can be deducted from the Fig. 6. that there are many types of methods. We shall introduce some of them in more detail, which are most likely to be applied for micro switches at the current stage of the research.
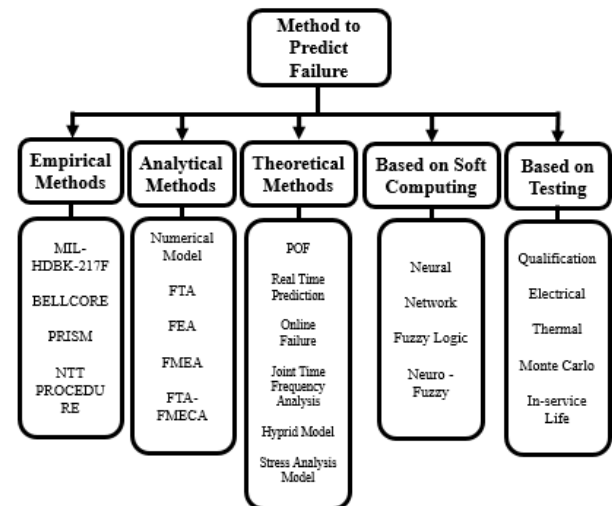

Figure 6. Failure prediction methods [3]

2.3.1 Empirical methods
The type of these methods based on models to predict the failure developed from historical data collected from filed, manufacturer or test data, is called empirical methods. These types of evaluations are widely used in military, automotive and commercial use. Also, it is easy to use, it provides relatively good performance and approximation of field failure rates, but the data used is not device specific, so approximation cannot be perfect [10, 11]

2.3.2 Analytical methods
To predict the failure, the analytical methods provide better approximation. Various numerical models are used to predict the failure. Finite Element Method (FEM) is an accurate technique for fault prediction, as it deals with both normal and faulty characteristics of the device. Fault tree analysis (FTA) is a numerical approach to detect fault based on the simulation. Failure mode, mechanisms and effect analysis (FMMEA) is a systematic and anticipatory method that deals with step by step approach to identify the faults during design or in service. A modified approach was discussed, which is a hybrid of FTA and FMECA and identifies and estimates the effects of failure (see [3]).

2.3.3 Theoretical methods
Physics of failure understands the failure mechanism and different models of physics can be applied for the data. For accurate prediction of wear out failure of components, analysis is costly, complex and detailed manufacturing characteristics

of component are needed. Physics of failure can be used both at design stage and at the production stage.

2.3.4 Methods based on soft computing techniques

Some authors have also applied a soft computing approach (neuro-fuzzy model) for intelligent online performance monitoring of electronic circuits and devices and classifies the stressors broadly into three main groups: electrical stressors, mechanical stressors and thermal environment of the component.

2.3.5 Failure prediction method based on testing

In life data analysis or Weibull analysis, under normal operating conditions reliability is measured using a test which is conducted on large sample of units, time-to-failure are analyzed using statistical distribution. Due to design or manufacturing, the components are not independent, but physics of failure and empirical method assumes that there is no interaction between failures, so for realistic prediction at system level, life testing method is preferred over physics of failure or empirical method.

3 Acceleration life testing with one variable factor

Today's manufacturers face strong pressure to develop new products with higher technological content in record time while improving productivity, product field reliability and overall quality. This has motivated the development of such methods like concurrent engineering and has encouraged us to design experiments for product and process improvement. The requirements for higher reliability have increased the need of testing the materials, the components and the systems. To achieve high reliability, it is necessary to improve the design and manufacturing processes.

In the literature we can find three different methods of accelerated reliability tests [3]:

> *i.)*   *Increase the use-rate of the product.*

Useful reliability information could be obtained in a matter of days instead of months.

> *ii.)*   *Increase the aging-rate of the product.*

Increasing the level of experimental variables like temperature or humidity we can accelerate the chemical processes of certain failure mechanisms.

> *iii.)*   *Increase the level of stress.*

In the last type we increase the level of stress, the temperature, the voltage, or the pressure during the tests comparing with the levels that units operate. A unit will fail when its strength drops below applied stress. Thus, a unit at a high stress will generally fail more rapidly than it would have failed at low stress.

Combination of these methods of acceleration are also employed. Variable like voltage and temperature cycling can both rate of an electrochemical reaction and increase stress relative to strength. In those situations, when the effect of an accelerating variable is complicated, there may not be enough, physical model for acceleration [3].

Combination of these methods will be used further of the research, because the micros witches will also be subjected to complex stresses.

3.1 Use Rate

Increasing use-rate will, for some components, accelerate failure causing wear and degradation. The increased use rate attempts to simulate actual use. Therefore, other environmental factors should be controlled to mimic actual use environments.
For example:

- Running automobile engines, appliances, and similar products and continuously or with higher than usual-rates.
- Higher than usual cycling rates for relays and switches.
- Increasing the cycling rate (frequency) in fatigue testing.

There is a basic assumption underlying simple use-rate acceleration models. Useful life must be adequately modeled by cycles of operation and cycling rate or frequency should not impact on the cycles-to-failure distribution. This is reasonable if cycling return to steady state after each cycle [2, 12].

3.2 Temperature Acceleration

Increasing temperature is one of the most commonly used methods to accelerate a failure mechanism.

The Arrhenius relationship is a widely used model describing the effect that temperature has on the rate of a simple chemical reaction. This relationship can be written as

$$\mathcal{R}(temp) = \left(\frac{-E_a}{k_b \text{ x } temp \, K}\right)$$
$$= \gamma_0 exp\left(\frac{-E_a \text{ x } 11605}{temp \, K}\right), \qquad (3)$$

where $\mathcal{R}$ is the reaction rate at $temp \, K = temp \,°C + 273{,}15$ is temperature in the absolute Kelvin scale, $k_b = 8{,}6171 \text{ x } 10^{-5} \, 1/11605$ is Boltzmann's constant [electron volts per $°C$], and E_a is the activation energy in electron volts [eV]. The parameters E_a and γ_0 are product or material characteristics. The Arrhenius acceleration factor for the use temperature $temp_U$ is

$$\mathcal{AF}(\,temp, \, temp_U, E_a) = \frac{\mathcal{R}(temp)}{\mathcal{R}(temp_U)} =$$
$$exp\left[E_a\left(\frac{11605}{temp_U \, K} - \frac{11605}{temp \, K}\right)\right] \qquad (4)$$

When $temp > temp_U$, then $\mathcal{AF}(\,temp, \, temp_U, E_a) > 1$. When $temp_U$ and E_a are understood to be, respectively, product use temperature and reaction – specific activation energy $\mathcal{AF}(temp) = \mathcal{AF}(\,temp, \, temp_U, E_a)$ will be used to denote a time-acceleration factor

$$\mathcal{AF}(\,temp_{High}, temp_{Low}, E_a)$$
$$= exp(\,E_a \text{ x } TDF) \qquad (5)$$

as a function of E_a and the temperature differential factor (TDF) values (see [2])

$$TDF = \left(\frac{11605}{temp_{Low} \, K} - \frac{11605}{temp_{High} \, K}\right). \qquad (6)$$

The Arrhenius relationship does not apply to all temperature-acceleration problems and will be adequate over only limited temperature range (depending on the particular application). Even dough, it is satisfactorily and widely used in many applications [12].

3.3 Pressure Acceleration

Increasing voltage or voltage stress (electric field) is another commonly used method to accelerate failure of electrical materials and components like light bulbs, capacitors, transformers, heaters, and insulation. Voltage is defined as the difference in electrical potential between two points. Physically it can be thought of as the amount of pressure behind an electrical current. Voltage stress across a dielectric is measured in units of volts/thickness.

3.3.1. Inverse-power acceleration

The most commonly used model for voltage acceleration is the inverse power relationship. Let $T(volt)$ and $T(volt_U)$ denote the failure times that would result for a particular unit tested at increased voltage and use voltage conditions, respectively. The inverse power relationship is the following:

$$T(volt) = \frac{T(volt_U)}{\mathcal{AF}(volt)} = \left(\frac{volt}{volt_U}\right)^{\beta_1} T(volt_U), \quad (7)$$

which is the scale-accelerated failure-time (SAFT) model. The relationship in the formula (7) is known as the inverse power relationship, since generally $\beta_1 < 0$.

The inverse power relationship voltage-acceleration factor can be expressed as

$$\mathcal{AF}(volt) = \mathcal{AF}(\,temp, \, temp_U, \beta_1) = \frac{T(volt_U)}{T(volt)}$$
$$= \left(\frac{volt}{volt_U}\right)^{-\beta_1}. \qquad (8)$$

When $volt > volt_U$ and $\beta_1 < 0$, $\mathcal{AF}(\,temp, \, temp_U, \beta_1) > 1$. When $volt_U$ and β_1 are understood to be, respectively, product use voltage and the material-specific exponent, $\mathcal{AF}(\,temp, \, temp_U, \beta_1)$ denotes the acceleration factor. $\mathcal{AF}$ as a function of stress ratio and β_1 [12].

4 Acceleration models with two accelerating factors

In some accelerated tests more than one accelerating variable are used. Such tests might be suggested when it is known that two or more potential accelerating variables exist.

For example, the two variable accelerated lifetime test (ALT) model, for long-location-scale distribution, the two-variable model is applied. The linear function μ of two experimental variables:

$$\mu = \mu(x_1, x_2) = \beta_0 + \beta_1 x_1 + \beta_2 x_2, \qquad (9)$$

where x_1 and x_2 are the possibly transformed levels of the accelerating or other experimental variables and $\beta_0, \beta_1, \beta_2$ are unknown coefficients to be estimated from test data. In some under underlying failure processes, it is possible for the underlying accelerating variables to interact. For example, in the model

$$\mu = \mu(x_1, x_2) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \quad (10)$$

the transformed variables are x_1 and x_2 interact in the sense that the effect of changing x_1 depends on the level of x_2 and vice versa [12]. Parameters β_i are unknown that are characteristics of the material or product being tested and they are to be estimated from the available ALT.

4.1 Temperature–(voltage) Stress Acceleration

The terms with x_1 and x_2 correspond, respectively, to the Arrhenius and the power relationship acceleration models. The term with x_3, a function of both temperature and voltage, is an interaction suggesting that the temperature – acceleration factor depends on the level of voltage. Similarly, a voltage-temperature interaction suggests that the voltage-acceleration factor depends on the level of temperature [2, 12].

$$\mathcal{R}(temp, volt)$$
$$= \gamma_0 \; x \; (temp\,K)^m \; x \exp\left(\frac{-E_a}{k_B \,x\, temp\,K}\right)$$

$$x \exp\left(\gamma_2 \log(volt) + \frac{\gamma_3 \log(volt)}{k_B \; x \; temp\,K}\right), \quad (11)$$

where the $x_1 = 11605/tempK$, $x_2 = \log(volt)$, $x_3 = x_1 x_2$.
The failure time T gives [12]

$$T(temp, volt) = \frac{1}{\mathcal{R}(temp, volt)}\left(\frac{volt}{\delta_0}\right)^{\gamma_1}. \quad (12)$$

Then, the ratio of failure times at $(temp_U, volt_U)$ versus $(temp, volt)$ is the acceleration factor

$$\mathcal{AF}(temp, volt) = \frac{T(temp_U, volt_U)}{T(temp, volt)}$$
$$= exp[E_a(x_{1U}$$
$$- x_1)] \; x \; (\frac{volt}{volt_U})^{\gamma_2 - \gamma_1} x \; \{exp[x_1 log(volt)$$
$$- x_{1U} \log(volt_U)]\}^{\gamma_3}, \quad (13)$$

where $x_{1U} = 11605/(temp_U K)$ and $x_1 = 11605/tempK$. For the special case when $\gamma_3 = 0$ (no interaction), $\mathcal{AF}(temp, volt)$ is composed of separate factors for temperature and voltage acceleration. The voltage-acceleration factor (holding temperature constant) does not depend on the temperature level used in the acceleration.

4.2 Temperature – Humidity Acceleration

Humidity is commonly used accelerating variable, particularly for failure mechanisms involving corrosion and certain kinds of chemical degradation [2, 12].
A variety of humidity models, mostly empirical but few with some physical basis have been suggested for different kinds of failure mechanisms. humidity is also an important factor in the service-life in distribution. In most test applications, where humidity is used as an accelerated variable, it used in conjunction with temperature.

5 Acceleration Life Testing More Than Two Experimental Variables

For more different units to be tested, we may need the acceleration life testing with more than two experimental variables, and prediction processes to summarize the influences.
In the applications it is often necessary or useful to conduct an accelerated test with more than two experimental variables. In such situations the ideas presented in this chapter can be extended and combined with traditional experimental design concepts [2, 12].
When the number of nonaccelerating variables is more than two or three, complete factorial designs may lead to an unreasonably large number of variable-level combinations. In this case, a reasonable strategy would be to use a standard fraction of a factorial design for the nonaccelerating variables and to run a single-variables ALT compromise plan at each of the combinations in the fraction.

6 Conclusion

In this paper the most important type of failure prediction methods has been considered. These methods are important and useful to apply in the prediction of lifetime with accelerated lifetime test. Here, the acceleration models with one, two or more variables factors are presented, the determination of the accelerating factors are provided.

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