Temperature and Humidity Acceleration Factors on MLV Lifetime

With and Without DC Bias

Greg Caswell

Introduction

This white paper assesses the temperature and humidity acceleration factors both with and without DC bias. The influence of these factors on MLV lifetime will be addressed, especially as it relates to the operating environment seen by MLVs.

Additionally, technical explanations of the different failure modes and failure mechanisms are provided, specifically with regards to temperature and humidity exposure.

Over 50 years ago, typical life tests simulated the operational conditions of a product. However, these tests became useless due to the rapid improvement of electronic component reliability. The solution was to develop a testing methodology utilizing the same types of stress, but at higher levels than typical operating conditions. The purpose of these accelerated tests was to shorten the timeframe necessary to obtain relevant results through an aging deterioration of the device in order to induce normal failures.

A fundamental principal of accelerated testing is that the failures modes encountered must be the same as those anticipated for normal operating conditions. The model describing the acceleration obtained by a given stress is useful and valid *only* for a population affected by the same failure mode. As such, any statistical analysis can only be effective if the failed items have been carefully analyzed so that they can be separated into groups having the same failure modes and mechanisms.

Following this approach is imperative as it assures that a failure mode that may occur in operation is not missed in accelerated testing.

Acceleration Factor Background

Reliability projections based on failure data from high stress tests assume we know the correct acceleration model for the failure mechanism under investigation and we have also chosen the correct life distribution model for the product in question. This is because we are extrapolating "backwards" - trying to describe failure behavior in the early tail of the life distribution, where we have little or no actual data.

However, it is frequently necessary to test at high stress (to obtain any failures at all!) and project backwards to the use environment. Thus, the field of reliability physics must be approached at the most fundamental level when evaluating and predicting product field performance over the lifetime of the product.

Reliability testing is required in order to characterize the lifetime of the MLV part using acceleration factors for proper lifetime prediction. Reliability testing at accelerated conditions is critical to generating lifetime data in a much shorter time span. Stresses, such as elevated temperature, temperature cycling, applied voltage, and relative humidity, that are typically experienced in the use environment are "accelerated", or increased to a level to hasten the time to failure of an individual failure mechanism. The key is to create the same failure mechanisms as those that occur in normal operating conditions. Development of an acceleration model is performed through knowledge of the physics of failure. An acceleration factor is calculated as a function of the use conditions.

To be able to derive viable models and acceleration factors, it is useful to have an understanding of MLV failure modes and mechanisms as they relate to the environmental conditions and operating characteristics of their MLVs.

Typical MLVs

The typical MLVs assessed are High Surge SMD Varistors ranging in size from 0402 to 2220 in size. The MLVs have a working temperature from -40 to +85°C. The maximum working voltage depends on the varistor and is defined as the maximum steady-state DC operating voltage the MLV can maintain at 25C and have leakage current levels less than 50 microamps.
Figure 1 shows the typical SMD MLV device.

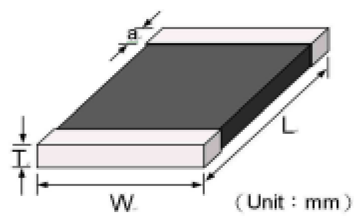

Figure 1 – Typical SMD MLV Device

Standard test conditions for the MLVs are 5C to 35C temperature range and 45 to 85% relative humidity. These characteristics are summarized in Table 1.

BASIC TEST

Characteristics	Test Method/Description
Standard Test Condition	Environmental condition under which every measuring is done without doubt on the measuring results. Unless specially specified, temperature, relative humidity are 5 to 35℃, 45 to 85％RH.
Max. Working Voltage	Maximum steady-state DC operating voltage the device can maintain and typical leakage current at 25℃ not exceed 50 μA.
Varistor Voltage	With the specified measuring current of 1mA DC applied.
Max. Clamping Voltage	Maximum peak voltage across the varistor measured at a specified pulse current (A) and waveform 8/20μs.
Surge Current	Maximum peak current which may be applied with the specified waveform 8/20μs without device failure.
Surge Shift ΔV/V	The shift of varistor voltage after suffering the specified surge current.
Energy Absorption	Maximum energy which may be dissipated with a specified waveform 10/1000μs.without device failure.
Typical Capacitance	Device Capacitance measured with zero voltage bias 0.5VRMS and 1KHZ
Leakage Current	Typical leakage current at 25℃＜50μA

Table 1 – MLV Basic Test Conditions.

Failure Modes and Mechanisms for MLVs

Multilayer Varistors behave similarly to ceramic capacitors with regard to failure modes and mechanisms due to their similarities in construction. Figure 2 illustrates a typical cross section of an MLV showing the electrodes, ceramic material, termination metallizations, and outer layer of a solderable surface.

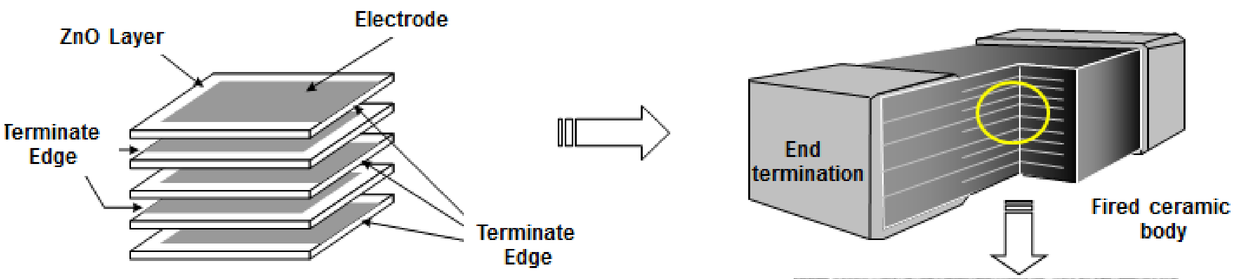

Figure 2 – Typical MLV Cross Section (1)

Zinc oxide varistors are semi-conductive in nature. This property allows them to “turn on” and divert a damaging transient away from sensitive electronic circuitry safely to ground.

There are three primary failure modes of ZnO Varistors (2); thermal runaway, rupture and cracking. It is important from the operational point of view for any user of ZnO MLVs to know the fundamental mechanisms of these failure modes. Thermal runaway occurs when a continuous operating voltage is apparent after a surge. The MLV isn’t cooled down well and the temperature of the device is increased due to its larger leakage current as an effect of the degradation of the ZnO. Rupture is when a hole occurs in the center of the ZnO varistor. This is induced by a relatively large continuous current which also has a concurrent temperature increase. Therefore, rupture results from the non-uniform distributions of temperature and current which are caused by the higher temperature and the larger current which are occurring at the center of the MLV. Cracking can occur due to large surge current because higher thermal tensile stresses result from the temperature.

In addition, SMD MLVs can be affected by mechanical stresses occurring either during manufacturing or operation in the field. Figure 3, although photos of capacitors, are illustrative of the cracking due to mechanical stresses.

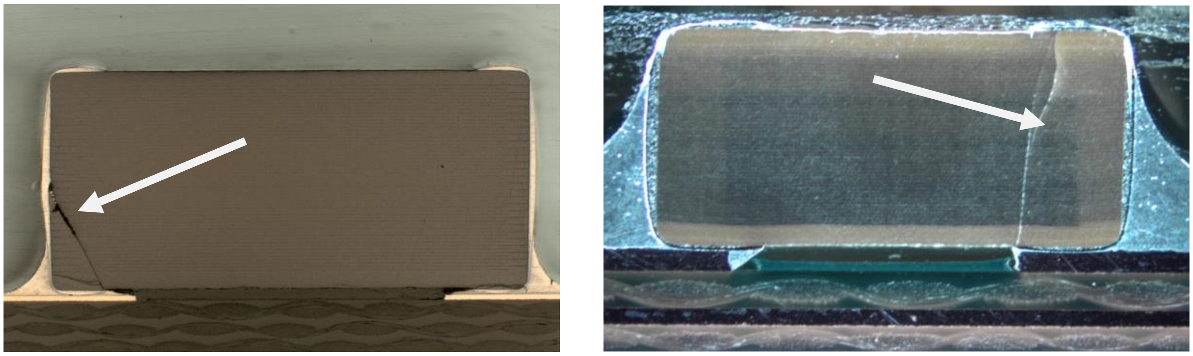

Figure 3 – Cross Sections Depicting Cracks Due to Mechanical Stress

Cracks caused by thermal effects have a uniquely different appearance as shown in Figure 4.

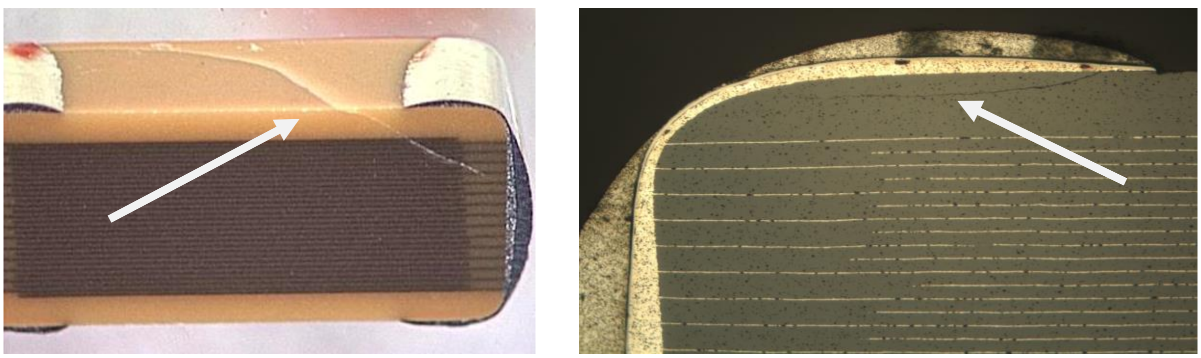

Figure 4 – Cracks Induced by Thermal Effects

Increases in leakage current are typically the first indicator of an issue, but cracks may not translate into a complete failure without accelerated stress levels during test. Using these tests to ascertain the best acceleration factors is the best approach. There are two primary ways to induce acceleration:

Increase the aging-rate of the product. Increasing the level of experimental variables such as temperature or humidity can accelerate certain failure mechanisms such as chemical degradation (resulting in eventual weakening and failure) of an adhesive mechanical bond or the growth of a conducting filament across an insulator (eventually causing a short circuit).

Increase the level of stress. (e.g., amplitude in temperature cycling, voltage, or pressure) under which test units operate. A unit will fail when its strength drops below applied stress. Thus, a unit at high stress will generally fail more rapidly than it would have failed at low stress. (3)

This white paper will assess the combined stresses of temperature and humidity on MLVs.

Acceleration Factors

Acceleration Factor (AF) is defined as a constant derived from experimental data which relates the times to failure at two different stresses by allowing extrapolation of failure rates from accelerated test conditions to use conditions

Temperature Acceleration Factor

The IEEE definition for Acceleration Factor is "The ratio between the times necessary to obtain a stated proportion of failures for two different sets of stress conditions involving the same failure modes and/or mechanisms."

The acceleration factor due to changes in temperature most often referenced is the Arrhenius equation for reliability. It is commonly used to calculate the acceleration factor that applies to the acceleration of time-to-failure distributions for microcircuits and other semiconductor devices:

$$A_T = \lambda_{T1} / \lambda_{T2} = \exp[(-E_a/k)(1/T_1 - 1/T_2)]$$

where

E_a is the activation energy (eV);
k is Boltzmann's constant (8.62×10^{-5} eV/K);
T_1 is the absolute temperature of test 1 (K);
T_2 is the absolute temperature of test 2 (K);
λ_{T1} is the observed failure rate at test temperature T_1 (h^{-1});
λ_{T2} is the observed failure rate at the test temperature $T_{2\,n}$(h^{-1}).

Additional acceleration factors can be calculated for electrical, mechanical, environmental, and other stresses that can affect the reliability of a device. Acceleration factors can be a combination of one or more of the basic stresses.

Humidity Acceleration Factor

In his paper entitled "Comprehensive Model for Humidity Testing Correlation", Stewart Peck (4) developed an acceleration formula that provides direct correlation from autoclave test results up to 140C to low humidity down to 30% RH. Classically, the standard test for determining the effect of humidity has been the electrically biased test of the devices in 85C temperature with 85% RH. It was felt that a requirement of 10% failures at 1000 hours for the test would indicate reliability in standard operational conditions. His model allows the changing of temperature and humidity to ascertain the acceleration factor for Temperature-Humidity-Bias testing.

The acceleration factor for elevated humidity is empirically derived to be:

$$t_f = A_0 RH^{-n} f(v) \exp(-\Delta H/kT)$$

where t_f is time to failure, A_0 is a material dependent constant, RH is relative humidity, n is an empirically determined constant, ΔH is activation energy, k is Boltzmann's constant, T is temperature, and f(v)is an undetermined function of voltage. Peck's model is based on the Eyring equation, with stress terms for relative humidity and voltage. (5)

A variation of the Peck Equation was created by Nihal Sinnadurai while inventing the **highly accelerated stress test** (HAST) method in order to perform highly accelerated reliability testing of electronics components that are likely to encounter humid environments during normal (ambient) operation. The acceleration factor for elevated humidity is empirically derived to be:

$$AF = e(Constant * RH_s^n - RH_0^n)$$

Where RH_s is the stressed humidity, RH_o is the operating environment humidity and n is an empirically derived constant (usually $1<n<5$)

The acceleration factor for elevated temperature is derived to be:

$$AF_T = e(E_a/k)*(1/T_0-1/T_s)$$

Where E_a is the activation energy for the temperature induced failure (most often 0.7eV for electronics), k is Boltzmann's Constant, T_o is the operating temperature in Kelvin, and T_s is the stressed temperature.

Therefore the total acceleration factor for unbiased HAST testing is:

$$AF_{HAST} = AF_H * AF_T = e(Constant * RH_s^n - RH_0^n)*e(Ea/k)*1/T_0-1/T_s)$$

Voltage Acceleration

Voltage acceleration is given by substituting n = 1 and voltage S = V to the general life formula.

$$\tau = A\exp(-V*\beta)$$

If the constants A and β are known, the relationship between the voltage V and life t can be ascertained. As such, these constants can be calculated by experimentally obtaining the life at multiple voltages. Taking the natural logarithm ln, the above formula can be transformed as follows.

$$\ln\tau = \ln A - \beta*V$$

β can be obtained from the slope when plotting this formula with the voltage V as the horizontal axis and the life τ as the vertical axis as shown in Figure 5.

The life also contains variance which is not due to stress. This variance follows a Weibull or logarithmic normal distribution, but in consideration of the distribution with respect to individual stresses, η and μ are used in place of t for the Weibull and logarithmic normal plots, respectively.

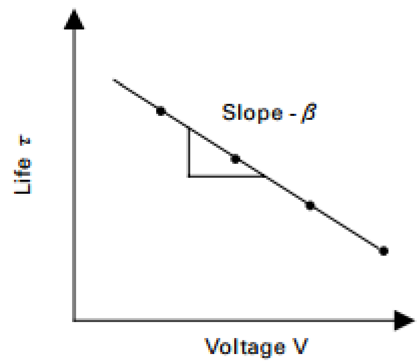

Figure 5 – Relationship Between Voltage and Life τ (6)

MLV Lifetime (Selection of Failure Distribution Approach)

Once the modeling approach has been defined and implemented, the failure distribution that best approximates the rate of observed failures with time from the accelerated test data should be selected. The lognormal and Weibull distributions are most often used to represent reliability failure mechanisms for electronic components. The exponential distribution, which produces a constant failure rate, is a special case of the Weibull distribution. (7)

Before getting into the different distribution models, it is useful to understand the "bathtub curve."

The life of a population of units can be divided into three distinct periods. Figure 6 shows the reliability "bathtub curve" which depicts the cradle to grave instantaneous failure rates versus time. If we follow the slope from the start to where it begins to flatten out, this can be considered the infant mortality period which is characterized by a decreasing failure rate. The next period is the flat portion of the graph, which is called the normal/useful life period as failures occur more in a random sequence during this time. It is difficult to predict which failure modes will occur, but the rate of failures is predictable. Notice the constant slope. The third period begins at the point where the slope begins to increase and extends to the end of the graph. This is what happens when units become old and begin to fail at an increasing rate. This is the wearout phase of the diagram and is indicative of the end of life period for a product.

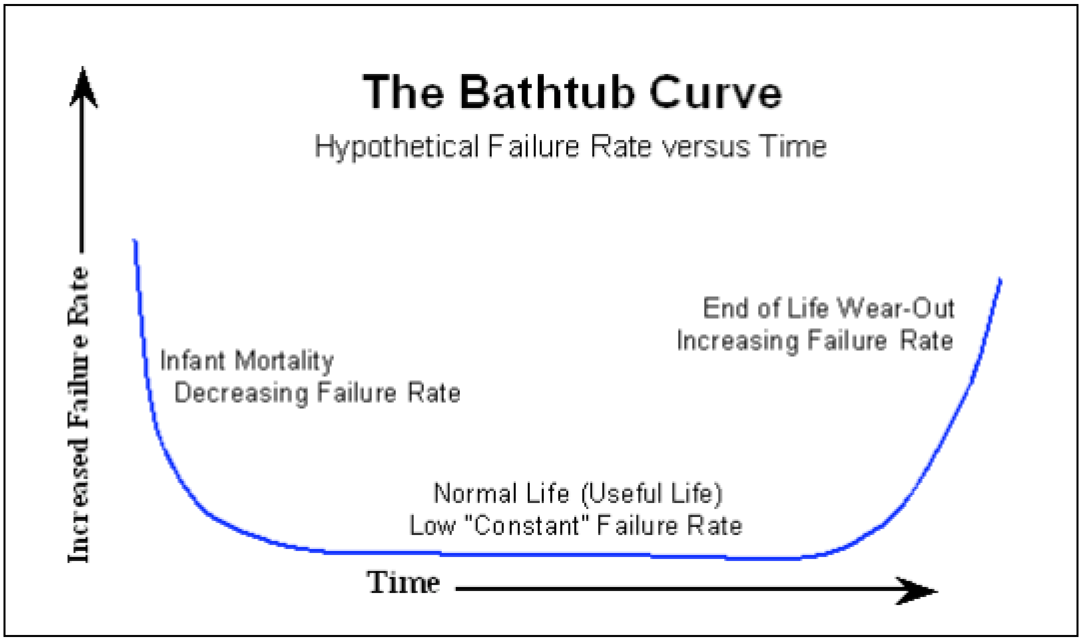

Figure 6 – BathTub Curve

Weibull Distribution Analysis

Weibull Analysis can be used as a method of determining where a population of MLVs is on the bathtub curve. The Weibull distribution is a 3-parameter distribution, β, η, and time. The Weibull distribution is given by:

$$f(T) = \left[\frac{\beta}{n}\right]\left[\frac{T}{n}\right]^{(\beta-1)} e^{\left(\frac{T}{n}\right)\beta}$$

The Weibull parameter β (beta) is the slope. It signifies the rate of failure. When $\beta < 1$, the Weibull distribution models infant mortality failures of parts. When $\beta = 1$, the Weibull distribution models the exponential distribution or the random failure portion of the curve. When $\beta = >3$, the Weibull distribution models the early wearout time. When $\beta > 10$, rapid wearout is occurring. (8)

Lognormal Distribution

The lognormal life distribution, like the Weibull, is a very flexible model that can empirically fit many types of failure data. The two-parameter form has parameters σ is the shape parameter and T_{50} is the median (a scale parameter).

If time to failure, t_f, has a lognormal distribution, then the (natural) logarithm of time to failure has a normal distribution with mean $\mu = \ln T_{50}$ and standard deviation σ. This makes lognormal data convenient to work with; just take natural logarithms of all the failure times and censoring times and analyze the resulting normal data. Later on, convert back to real time and lognormal parameters using σ as the lognormal shape and $T_{50} = e^{\mu}$ as the (median) scale parameter.

The lognormal (also called the Gaussian) distribution is:

$$f(t) = \frac{1}{\sigma t \sqrt{2\pi}} e^{\left(-\frac{\left(\ln(t)-\ln(T_{50})\right)^2}{2\sigma^2}\right)}$$

Exponential Distribution

The exponential distribution is well understood and as valid as any for life tests with large sample sizes and few failures. No actual distribution can be implied as there is seldom enough data to determine one. The exponential distribution, characterized by a constant failure rate, is a special case of the Weibull. The exponential distribution is the only one for which a MTTF (mean time to failure) value may easily be estimated as it is simply the reciprocal of the failure rate (λ). In addition it is the only one for which a confidence level may be readily assigned to the failure rate calculation. (9)

The conventional expression for the failure rate, λ, is:

$$\lambda = \chi^2 (2n+2,1-\alpha)*10^9/(2*ss*t*AF)$$

where:

λ is the failure rate in FITs(failures per billion unit-hours),
$\chi^2 (2n+2,1-\alpha)/2$ is the upper confidence value for "n" failures and upper confidence limit,
α (expressed as a decimal value),
ss is the sample size,
t is the test duration in hours,
AF is the acceleration factor relating the life test junction temperature to an assumed field junction temperature.

Summary

This white paper has endeavored to provide into the tools to assess acceleration factors from tests performed and implement them into failure distributions so that lifetimes can be projected for MLVs at operating temperatures. Once appropriate tests are established, then the actual failure data can be fit into the life models noted herein for establishing the MLVs ability to survive the intended applications.

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