Lifetime Modeling of Sub 2 Micron Dielectric Thickness BME MLCC

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Abstract

Multilayer ceramic capacitor (MLCC) design is driven toward increased capacitance per unit volume, achieved via increased active layer count combined with decreased dielectric thickness. Current state of the art MLCC technology combines <2.0 um dielectric thickness with >350 active layers in an 0805X5R106 design, having >6 cm^2 active area. In order to insure adequate service life at rated temperature and voltage, it is imperative that the relationship between highly accelerated life test (HALT) data and life data under use conditions be understood.

This paper examines accelerated life performance of 0805X5R106 6.3V base metal electrode (BME) MLCC and correlates HALT performance with time-to-failure (TTF) data under life test conditions using product from four different manufacturers. The models generated are used to predict TTFs under use conditions.

While the model activation energies (E_a) do not vary significantly between manufacturers, the calculated voltage stress exponents do, indicating the importance of establishing individual model parameters for each MLCC system evaluated. The models also serve as a reminder that the combination of voltage and temperature model parameters, as well as the actual HALT TTF data and distribution thereof, are necessary in accurately estimating TTFs under use conditions. The model is extended to devices having different active areas and an active area correction factor is introduced.

Introduction

Typically, one of the most important performance factors in electronic device development is reliability of in field service. One very important component of reliability is TTF. With the introduction of BME MLCC in the early 1990s, the ability to predict field failure rates due to dielectric wear out became even more important and adoption of HALT test variants as a predictive method of TTF in the field.

In most types of HALT testing, device leakage current or insulation resistance is observed over time as the devices are subjected to high temperatures and high multiples of rated voltage. Device failures are indicated when insulation resistance degrades significantly (typically >1 order of magnitude from the leakage current measured at time zero). The distribution of device failure times is then plotted as a function of time and the failure behavior modeled to predict median time to failure (MTTF). Figures 1 and 2 illustrate a typical insulation resistance vs. time chart, or monitored IR curve, and a typical TTF curve respectively. Figure 3 shows a typical failure rate curve for a HALT test (i.e., the "bathtub" curve). This is helpful in understanding the different regimes of failure in a typical sampling of devices. More information on HALT testing is available in numerous other publications.[1-6]

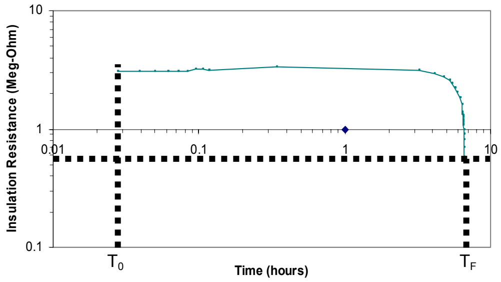

Figure 1. Typical HALT monitored IR curve indicating time zero (T_0), time to failure (T_F).

Once the HALT characteristics for an MLCC system are characterized, it is important to be able to use the TTF data as a predictor of time to failure in the field (i.e., under non-accelerated conditions). Calculated time-to-failure data at maximum rated use temperature and voltage can then be used to predict TTF field performance under maximum use conditions.

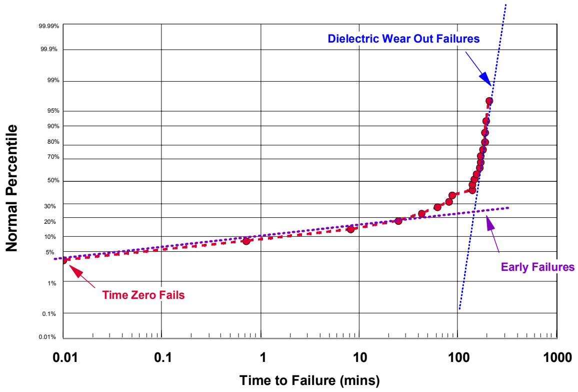

Figure 2. Typical HALT TTF curve indicating 3 failure modes (time zero, early time and dielectric wear out)

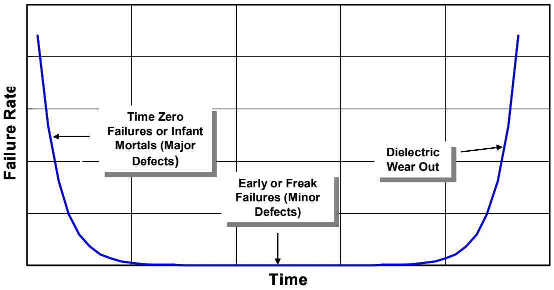

Figure 3. Illustration of the "bathtub curve" typically observed in failure rate during HALT testing.

Perhaps the most widely accepted TTF predictive model is that proposed long ago by Prokopowicz and Vaskas.[2] The P-V model involves two acceleration factors as indicated in the equation:

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\left(Ea/k\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right)$$

Where:

t_i= time to failure under conditions i
V_i = voltage under condition i
n = the voltage stress exponential
E_a = the activation energy for dielectric wear out
k = Boltzmann's constant (8.62E-5 eV/K)
T_i = absolute temperature for condition i

The P-V equation has been used in numerous studies on MLCC reliability.[2-6] In most of the studies, the activation energy values for barium titanate based dielectric (BME and PME) agree and are typically from 0.9 to 1.7 eV.[6] However, in several instances, the value for the voltage stress exponential (**n**) has varied widely from values of close to 1 to as high as ~9.[3,6] Obviously, since this value is used as the power for voltage acceleration in the P-V equation to predict TTF, the variation noted in **n** can lead to dramatically different TTF projections. Thus, it is important to carefully characterize each system in order to accurately determine n on a case by case basis.

In earlier studies, it has been hypothesized that the variation in n observed may be due to varying dielectric thickness. It has been hypothesized that n tends to increase as dielectric thickness is reduced.[7]

The goal of the present study is to evaluate TTF characteristics for very high volumetric efficiency BME MLCC and to determine if E_a and n are consistent using MLCC produced by different manufacturers, as well as to determine how well P-V calculations predict Life Test performance for high volumetric efficiency BME MLCC. The part type evaluated was 0805 X5R 10 µF, 6.3 V-rated (V_r) configuration. MLCC from four different manufacturers were evaluated.

Experimental

Capacitors of the above type, made by four different manufacturers were obtained. The general characteristics of each manufacturer's MLCC were determined (see Table I).

Table I. Characteristics of 0805 X5R 106, 6.3V BME MLCC

MFG	A	B	C	D
Cap. (µF)	11.1	10.8	9.3	9.1
Df (%)	7.3	8.0	4.6	4.6
Breakdown Voltage (V)	65	96	144	114
IR at 25C (M-Ohm)	148	105	174	216
IR at 125C (M-Ohm)	112	13	46	94
Dielectric Thickness (µm)	1.38	1.55	1.74	1.78
Electrode Thickness (µm)	1.27	1.67	1.57	1.44
Active Layers	395	323	371	333
Margins (mm)	0.11	0.12	0.13	0.14
LxWxT (mm)	2.05x1.30x1.30	2.13x1.37x1.37	2.01x1.37x1.37	2.11x1.35x1.35
Active Area (cm^2)	6.5	5.9	5.0	5.4
K (calculated)	2690	3176	2817	3434
Grain Size (µm)	0.24	0.49	0.35	0.36
Notes: All values are averages				

Each set of MLCC was evaluated using a MicroInstruments model PE 9051 HALT system. The parts were mounted in mechanical test fixtures and 20 pieces were evaluated per HALT test to generate TTF curves. TTF was defined as the time when insulation resistance (IR) degraded to a value of 500 K-Ohm (the lower limit of the test equipment). Parts were tested at temperatures ranging from 125C to 140C and at voltages from 2 to 8 times V_r (12.6 to 50.4 V). Since only two temperatures were evaluated in this part of the study, an average of MTTF vs. inverse temperature, for at least four different voltages was used to calculate E_a for each set of MLCC.

Median time to failure values from the TTF curves were then used to calculate **n** and E_a using the P-V relation. These data were used to estimate MTTF under Life Test conditions (2 x V_r and 85C). MLCC (100 pc each) from each manufacturer were evaluated under those conditions. Life test data were then compared with the data predicted from the P-V equation.

Results and Discussion

A representative plot of MTTF vs. inverse temperature is illustrated in Figure 4. Plots of this type were used to calculate E_a for each set of MLCC. Figure 5 illustrates a representative plot used to calculate the voltage exponential of each set of parts.

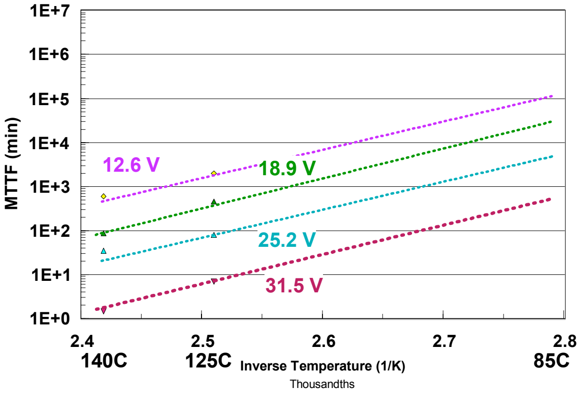

Figure 4. Representative plot of MTTF vs. inverse absolute temperature used to calculate E_a.

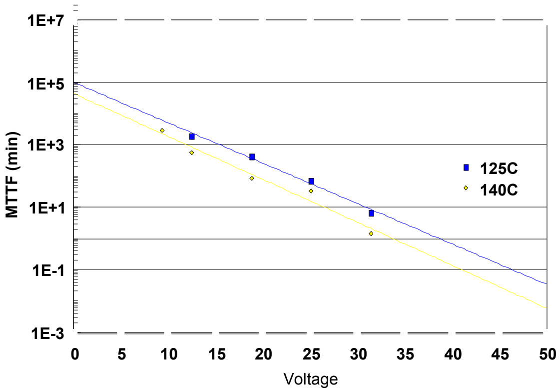

Figure 5. Representative plot of MTTF vs. HALT voltage used to calculate **n**.

Table II depicts a summary of the HALT study performed. Values of n were calculated for 125C and 140C. The **n** values at 125C and 140C agree to within 15% for each manufacturer's product.

Table II. E_a and n summary from HALT study

MFG	E_a (eV)	n (125C)	n (140C)
A	1.34	1.56	1.81
B	1.38	6.27	6.67
C	1.50	2.70	3.10
D	1.49	3.27	3.10

Table II E_a data indicate relatively similar activation energies between all sample sets evaluated. These activation energy data also agree well with data from previous HALT studies.[5] However, the calculated voltage stress exponential data vary widely between manufacturers, from a maximum in excess of 6 to a minimum of about 1.5, even though the dielectric thicknesses are relatively similar for all products tested (see Table I).

This variation in n values has a tremendous effect on predictions resulting from the P-V equation and denotes the importance of calculating the value of n for each type of MLCC evaluated. For example, using MFG A's HALT MTTF data with MFG B's n value would result in a difference in predicted MTTF under Life Test conditions at 85C and 1.5 x V_r of >15,000 hours which is more than 8 times higher than the correctly calculated TTF of ~1900 hours.

Predictions of MTTF based upon the P-V model using estimated values of **n** and E_a for each manufacturer are depicted in Figures 6-9. The effect of large n is apparent upon MFG B's TTF performance at or near maximum use conditions (85C/6.3V). Interestingly this larger n value also yields the longest predicted MTTF for MFG B's product when used at relatively low temperatures and voltages, while MFG A's product, which had the longest MTTFs (predicted and tested) would be projected to have shorter MTTFs when used at relatively low temperatures and voltages. This predicted observation was not verified experimentally as the TTFs at low temperatures and voltages would be very long, and the test duration required would not be practical.

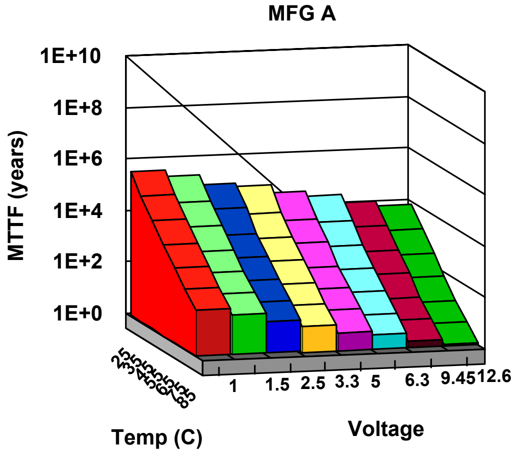

Figure 6. MTTF predictions for MFG A under various conditions using the P-V equation.

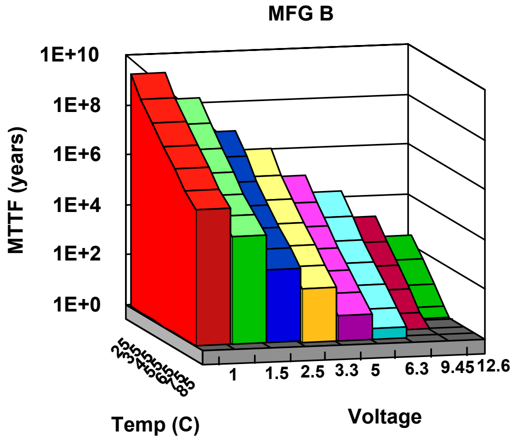

Figure 7. MTTF predictions for MFG B under various conditions using the P-V equation.

Based upon the above analyses, the MTTFs for each manufacturer's product under 3 different Life Test conditions were predicted (see Table III). These predicted MTTFs were then compared with actual test data (see Figures 10-12).

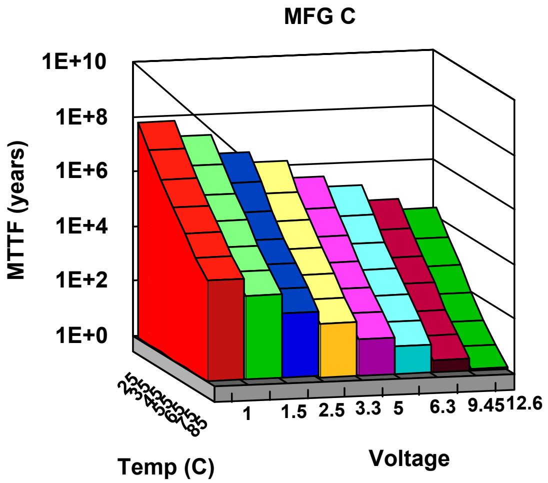

Figure 8. MTTF predictions for MFG C under various conditions using the P-V equation.

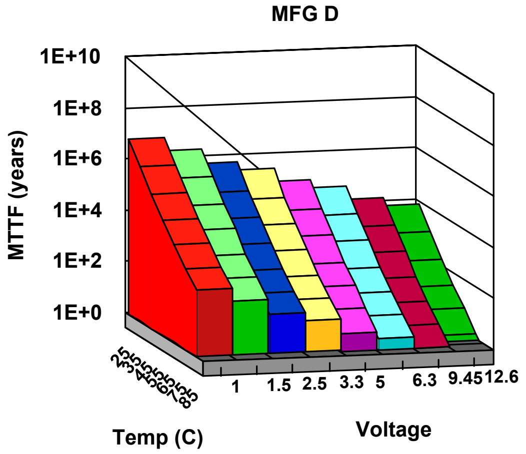

Figure 9. MTTF predictions for MFG D under various conditions using the P-V equation.

Table III. MTTF Predictions

MFG/ Est. TTF (h)	A	B	C	D
85 C, 1.5 x V_r	17,939	1,919	26,741	8,307
85C, 2 x V_r	11,448	316	10,439	3,820
125C, 2 x V_r	147	4	80	29

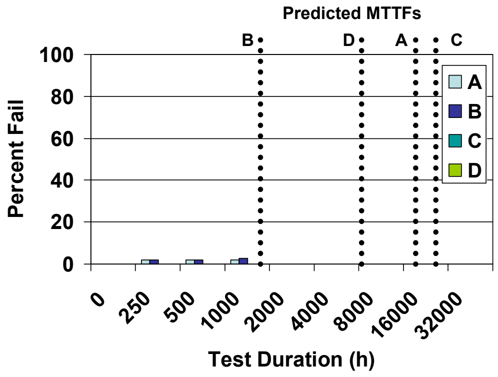

Figure 10. Predicted vs. actual Life data for 85C@1.5 x V_r Life test.

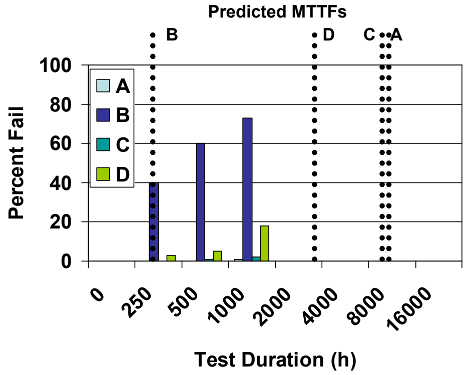

Figure 11. Predicted vs. actual Life data for 85C@2 x V_r Life test.

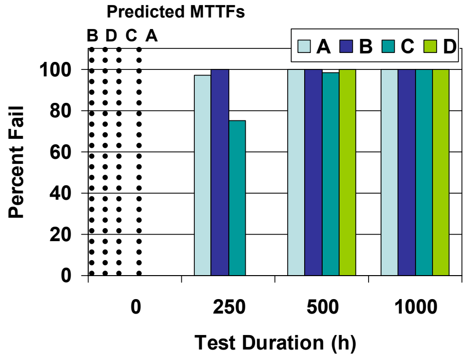

Figure 12. Predicted vs. actual Life data for 125C@2 x V_r Life test.

With the exception of two instances, the predicted MTTFs agree well with the Life Test data. The first discrepancy is illustrated in Figure 10. While the failure rate for MFG B was highest for the 85C, 1.5xV_r conditions, the failure rate is lower than would be predicted unless the distribution of failures vs. time is relatively narrow. Figure 13 illustrates the insulation resistance (IR) distribution for MFG B under these conditions. The figure indicates that, by 250 h, there is significant degradation in the IR values for ~1/2 of the MLCC tested, but that the parts had not degraded to the point of failure. The second discrepancy is depicted in Figure 12. The relative rate of failure for MFG C at 250 hours is slightly lower than it probably should be based upon the predicted MTTF, and is likely due to the wide TTF distribution in this situation.

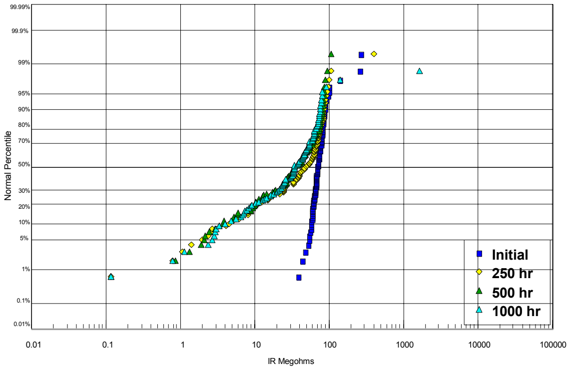

Figure 13. IR distribution for MFG B at Life test conditions of 85C and 2 x V_r, indicating ~50% of the parts exhibiting IR degradation by 250h.

While MTTF is an important factor, the TTF distribution is also important as it gives an indication of how reliable MTTF predictions will be for all parts within the population. Figure 14 illustrates that, excluding early failures ("infant mortality"), the TTF distributions span ~2 orders of magnitude in time. The verticality of this distribution should be considered as a figure of merit, along with MTTF during product development.

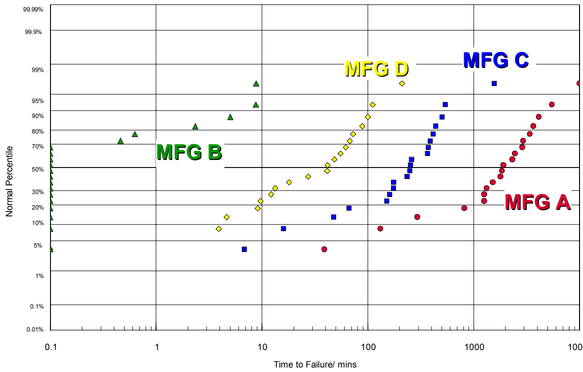

Figure 14. HALT TTF distributions for MFGs A-D, 125C, 6 x V_r.

Summary and Conclusion

The predictions from the P-V equation indicate that it is relatively accurate in projecting Life Test TTF for very high active layer, X5R thin layer BME MLCC. As with all models, the projections appear to be less accurate as conditions are extrapolated further from the test conditions.

This study indicates the importance of defining individual voltage exponential (**n**) values for each different manufacturer or materials set. This is crucial for accurate TTF modeling, even though the devices were of similar value (10 µF), temperature class (X5R) and voltage rating (6.3V). It appears that there is significantly less variation in E_a between manufacturers in this category of MLCC.

When predicting TTFs it is important to consider the variation within the TTF distribution. The TTF distributions in this study and others[5] indicate that TTF range can easily span one or more order of magnitude in time, excluding "infant mortality" failures. It is logical that the width of the TTF distribution should increase as dielectric thickness is decreased, due to the greater variation in dielectric thickness, on a normalized basis, encountered when reducing dielectric thickness. It is also logical, from a defect density standpoint that the range of TTF should increase as active area is increased, similar to other measures that are effected by specimen size (such as mechanical properties, etc.).[8] This should be carefully considered during product development.

With proper use, the P-V equation accommodates the effect of dielectric thickness in the V terms (sometimes more accurately called the "E" or electric field term).[4] The P-V equation does not consider active area, however. This was not an issue for the current study, as the active areas of the devices evaluated were relatively similar (see Table I). However, when developing numerous capacitance value MLCC with similar dielectric thickness and chemistry, it would be advantageous to be able to predict TTF for the different capacitance values (active areas). Within a materials system, MTTF typically decreases as active area is increased (see Figure 16 for a typical example). In this case, two repetitions each of HALT were performed on two different MLCC designs made with the same materials set and dielectric thickness, but with different active areas. The active area in the 1206Y5V475 sample was ~47% that of the 1210Y5V106 design. It is clear that MTTF is significantly affected by the change in active area.

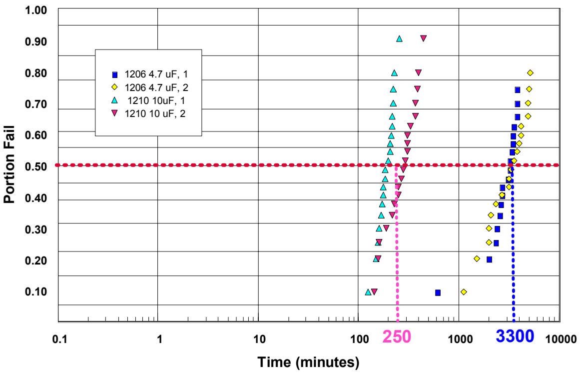

Figure 16. TTF distributions (2 repetitions of test for each active area), depicting the change in MTTF, within an MLCC system, with increasing active area (from ~3,300 minutes to ~250 minutes with a 2.12 fold increase in A in this case).

It is proposed that an appropriate modification to the P-V equation would be to add a term to compensate for active area. This modification would be in the form of:

$$\frac{t_1}{t_2} = \left(\frac{A_2}{A_1}\right)^r \left(\frac{V_2}{V_1}\right)^n \exp\left(Ea/k\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right)$$

Where:

A_i = the active area of MLCC design i
r = the area exponential
t_i= time to failure under conditions i
V_i = voltage under condition i
n = the voltage stress exponential
E_a = the activation energy for dielectric wear out
k = Boltzmann's constant (8.62E-5 eV/K)
T_i = absolute temperature for condition i

In the above case (Figure 16), the value for **r** is 3.4. It is likely that this value would vary between MLCC platform sets as with **n**. Thus, it would be prudent to determine **r** for each system as is recommended above for **n**. Based upon limited experience to date, **r** has been found to be in the range of 1 to 4. More experimentation is needed to determine refine the understanding of this proposed addition to the P-V equation.

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