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Highly Accelerated Life Stress Testing (HALST) and Mixed Failure Modes in Multilayer Ceramic Capacitors with Base-Metal Electrodes

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ABSTRACT

An improved highly accelerated life stress testing (HALST) procedure and modeling method was developed to evaluate the reliability of ceramic capacitors with base-metal electrodes (BME). A combination of leakage current and time-to-failure (TTF) measurements under accelerated life stress conditions have been used to distinguish and separate the TTF data into two failure modes: slow degradation and catastrophic. The slow degradation failures, characterized by a near-linear leakage current increase against stress time, fit well to an exponential law form. A characteristic exponential growth time, τ_{SD}, is defined to describe the reliability life of this failure mode. The recorded TTF data at a given stress level were fitted to the 2-parameter Weibull model with three different modeling scenarios: (1) single set: all TTF data points will be used for the modeling and a state of failure will be assigned to all data points; (2) catastrophic: the TTF data points that were revealed to be catastrophic will be assigned a state of failure, while those data points revealed to be slow degradations will be treated as suspensions; and (3) slow degradation: in a reversal of the catastrophic scenario, the TTF data points revealed to be catastrophic will be treated as suspensions. The initial TTF data for slow degradation failures appear to follow an exponential acceleration function over the applied field, while those for catastrophic failures follow the conventional power-law. The reliability model developed with respect to mixed failure modes and acceleration functions for BME capacitors agrees well with the HALST results -- not only with the calculated reliability lifetime, but also with the assumed failure mode.

I. INTRODUCTION

The highly accelerated life testing method has been widely used to evaluate the reliability of multilayer ceramic capacitors (MLCCs).[1-7] The testing involves determining the time to failure (TTF) data of a group of capacitor samples under accelerated life stress conditions (usually external applied voltage V and temperature T) that are higher than the regular operating conditions (rated voltage and room temperature, typically). However, highly accelerated life testing results for many MLCCs with base-metal electrodes (BME), particularly those with thin dielectric layers, have been found to give inaccurate predictions of use-level lifetimes.[6-8] In many cases, the calculated lifetime is much longer than that actually achieved through life testing. Several factors may account for this problem:

(1) Higher accelerated life stresses are often required to generate failures, which results in the introduction of new failure modes. The microstructure of BME MLCCs will require much higher life stresses to cause a failure in a "reasonable" period of time ("reasonable" is defined for the purposes of this paper as a period of time typically in the tens to thousands of minutes), as compared to ceramic capacitors with precious-metal electrodes (PME). (2) The failure modes characterized by the Weibull slope parameter β are very likely to change when extrapolating the TTF data at high life stress levels down to the use-level, which is normally more than 100°C lower in temperature and several times less in voltage. (3) A statistical method that could handle multiple failure modes and multiple acceleration functions needed to be developed. Some studies have indicated that the acceleration function of BME MLCCs does not always follow the conventional power-law relationship over applied voltage; rather, it likely follows an exponential relationship (E-model).[1, 8]

II. EXPERIMENTAL PROCEDURE

Traditional accelerated life testing requires the collection of a number of TTF data under various V and T levels to fit a selected statistical model based on a single failure mode. The complexity in calculating the reliability of BME MLCCs, such as the existence of mixed failure modes, requires additional test results to be used in order to build up a reliability model. Since leakage current was previously reported to differentiate the failure modes of ceramic capacitors,[1] the leakage current as a function of stress time has been monitored in-situ and recorded for each

BME capacitor until the capacitor has reached the failure criterion, which was set at 100 μA for all BME capacitors in this study. A series resistor is also connected to each BME capacitor under test, for the purpose of current limiting. The values of the resistors were selected so that at least 95% of the applied voltage was loaded on the BME capacitors during a highly accelerated life stress testing (HALST) process.

A 20-position printed circuit board (PCB) testing card was used for the characterization of BME capacitors throughout this study. The PCB card was made from polyimide material and was used for high-temperature accelerated life testing up to 175°C. All capacitors were reflow attached on the testing card. The soldering reflow condition was in compliance with MIL-PRF-55681. Each PCB test card with 20 capacitors was assembled in a single reflow cycle using no-clean solder paste with RMA (Rosin mildly activated) flux.

After assembly, all capacitors were subjected to an electrical test for capacitance and dielectric loss at 1 kHz, to make sure all units were electrically in specification. One board was used to determine the failure rate at elevated voltages and temperatures, by testing all parts to destruction. Data was used to define a test window for which all parts would reach the failure criterion in a reasonable period of time and at external stress levels as low as possible.

III. RESULTS AND DISCUSSION

A. A HALST example for BME capacitors with traditional method

A typical HALST process involves measuring TTF data for a group of BME capacitors under various stress conditions, so that most units under test can reveal failures within a reasonable period of stress time. The insert data in FIG. 1 show actual TTF data at 165ºC and 72V for a BME capacitor of 4.7 μF, 16V, 0805 (EIA chip size), made by manufacturer C. A simplified part number of C08X47516 has been assigned to this BME capacitor product. Corresponding cumulative failure percentage plots of the TTF data are generated using a 2-parameter Weibull model, which can be expressed as:

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}} \tag{1}$$

where *R(t)* is the reliability at time *t*, *e* is the base for natural logarithms, slope β is the dimensionless shape parameter whose value is often characteristic of the particular failure mode

under study, and η is the scale parameter that represents the point at which 63.2% of the population has failed. When the values of β and η are known, another important characteristic, reliability lifetime mean-time-to-failure (MTTF), can be calculated by:

$$MTTF = \eta\Gamma(1 + 1/\beta), \tag{2}$$

where $\Gamma(x)$ is the gamma function of x (Note that $\Gamma\ (1+1/\beta)$ ranges from 0.887 to 0.900 as β ranges from 2.5 to 3.5.).

The testing procedure illustrated in FIG. 1 can be repeated many times when different stress conditions are used (three voltages and three temperatures are typical). A group of TTF data under various stress conditions can thus be obtained (FIG. 2). Corresponding mean-time-to-failure (MTTF), as well as Weibull parameters β and η, can be calculated. The results are summarized in Table I.

All TTF data were taken with accelerated voltage several times the rated voltage, and temperature between 155°C and175°C. Table II includes a data set obtained at 135°C and 72V, which is used for model verification purposes only, and will not be used in statistical modeling to determine the acceleration factors. It will be used to compare the calculated MTTF results from different modeling approaches.

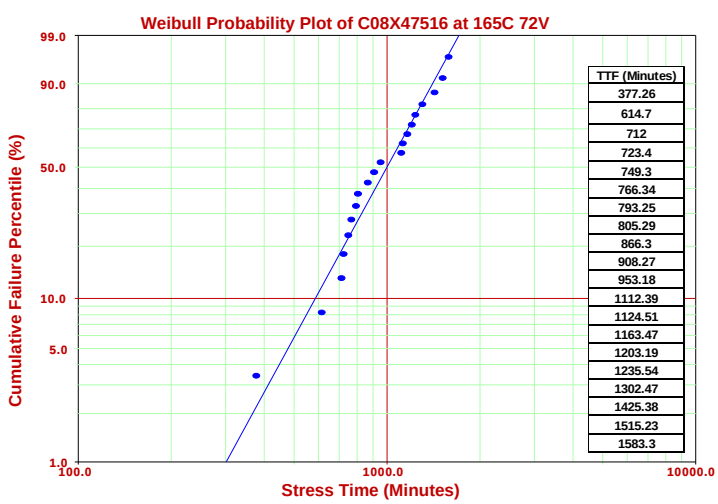


FIG. 1. 2-parameter Weibull plot of TTF data for BME capacitor C08X47516, measured at 165°C and 72V. From this plot, the Weibull parameters β and η, as well as MTTF, can be determined.

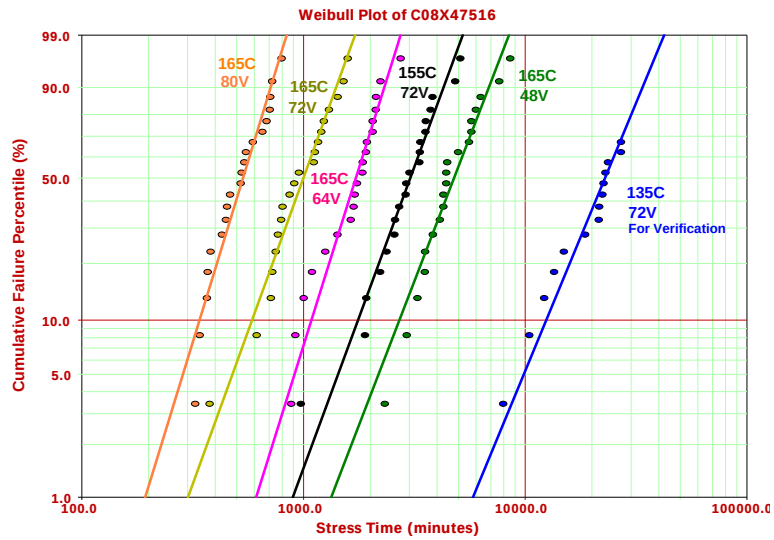


FIG. 2. Weibull plots of a number of TTF data under various stress conditions. The MTTF, β, and η values are also included for information. This data set that was obtained at 135°C and 72V is for verification of the model only and was not used for reliability modeling, as discussed later.

Up to this point, all measured TTF data were processed with a 2-parameter Weibull model only; no acceleration function has been involved. In order to determine the reliability lifetime as a function of external stresses, an acceleration function form that is widely known in the ceramic capacitor industry as the Prokopowicz and Vaskas equation [*P-V* Equation, Eq. (3)] is used to process the TTF data shown in FIG. 2 and to determine the acceleration factors E_a and n, shown in Eq. (3)[9], where k is the Boltzmann constant.

Table I. HALST conditions and corresponding Weibull modeling results for BME capacitor C08X47516 at 165°C

HALST conditions	MTTF (min)	β	η
165°C 48V ($3\times V_r$)[a]	4787.46	3.32	5335.48
165°C 54V ($3.4\times V_r$)	3087.29	2.95	3459.73
165°C 64V ($4\times V_r$)	1710.94	4.08	1885.37
165°C 72V ($4.5\times V_r$)	998.04	3.53	1108.74
165°C 80V ($5\times V_r$)	529.27	4.17	582.54
175°C 72V ($4.5\times V_r$)	111.84	2.21	126.28
155°C 72V ($4.5\times V_r$)	3029.82	3.47	3368.76
135°C 72V ($4.5\times V_r$)[b]	19097.00	3.82	21124.00

[a] V_r=16V is the rated voltage.
[b] TTF data at this stress condition are measured for model verification only.

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \qquad (P\text{-}V \text{ Equation}) \qquad (3)$$

Table II summarizes the calculated acceleration factors and the MTTF comparison to that obtained at 135ºC and 72V. It is clear that the calculated lifetime of 2111.17 hours is much longer than the 318.28 hours actually measured. Indeed, the inconsistency between the calculated MTTF using a single Weibull model and *P-V* equation and the actual measured MTTF has been consistently found to be longer than the measured lifetime for many BME capacitors.[6, 8]

Table II. Calculated reliability lifetime and determined acceleration factors for BME capacitor C08X47516 at 135ºC and 72V

Model parameters	β	η (min.)	E_a (eV)	n	MTTF (hrs.)
Calculated data	2.755	3.587×10^{07}	2.60	4.524	2111.17
Verification data	3.822	2.112×10^{04}	N/A	N/A	318.28

B. TTF data and leakage current characterization in BME capacitors

The Weibull modeling results shown in Table II that use the measured TTF data suggest that a traditional single failure mode method is not adequate to reveal the failure mechanism and to predict the reliability life of BME capacitors. In order to reveal failure characteristic details while performing HALST evaluation, the leakage current as a function of applied stress time was recorded for every BME capacitor sample.

FIG. 3 shows the measured leakage current as a function of stress time for BME capacitor C08X47516 at 165ºC and 72V (the same stress levels shown in FIG. 1). Similar leakage current slope was seen for most BME capacitors in this study, with some continuing to failure, while other experience abrupt catastrophic failures characterized by rapid increase in leakage current.

Two failure modes can clearly be distinguished in the leakage current measurement results shown in FIG. 3: catastrophic and slow degradation. Catastrophic failures are characterized by a time-accelerated increase of leakage current that may lead to catastrophic damage to the capacitor (either avalanche or thermal runaway). Slow degradation failures are characterized by a gradual, near-linear increase of leakage current against stress time until the failure criterion (100 μA throughout this study) is reached. This slow degradation failure has been attributed to

the electromigration of ionized oxygen vacancies that gradually reduced the barrier height at the grain boundary regime and caused a gradual leakage current increase, a failure mechanism that is dominant and unique for BME capacitors.

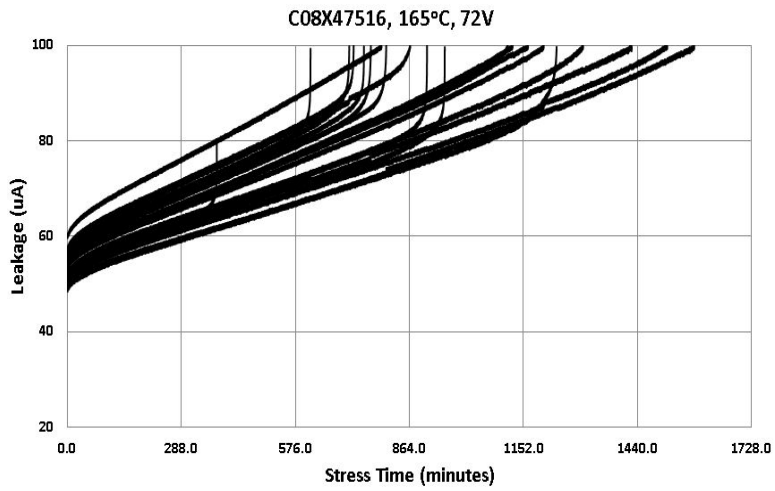


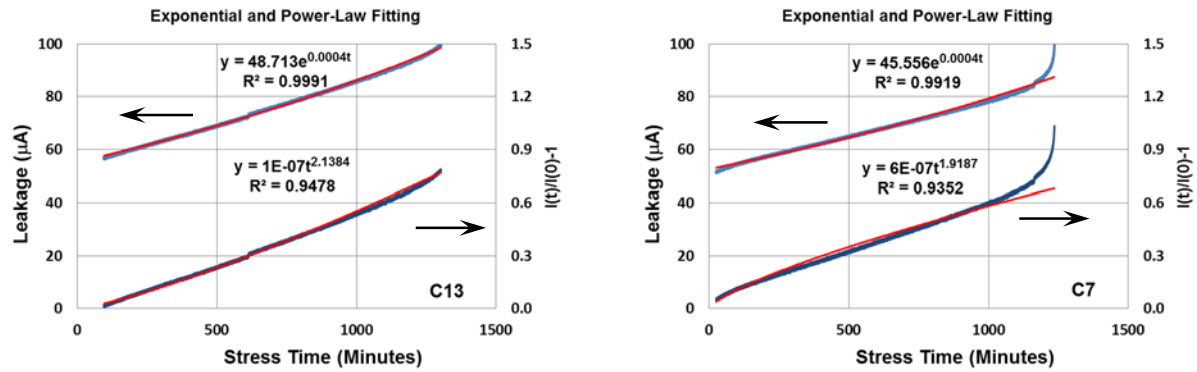
FIG. 3. Leakage current of 20 BME capacitors as a function of stress time for BME capacitor C08X47516, tested at 165°C and 72V.

In order to understand the leakage current patterns and their relation to the failure mechanism that was revealed in FIG. 3, four different empirical degradation formulas, i.e., linear, power-law, exponential, and logarithmic, have been practiced for curve-fitting the leakage current data. Both linear and logarithmic were found to not work well so that only power-law and exponential curve-fitting results were shown in FIG. 4. The curve-fitting coefficient of determination, R^2, has been used to quantitatively determine the validity of the formula that was used.

Although the leakage data shown in FIG. 3 appear to be linear for most of the stress time measured, the curve-fitting results show that the exponential form:

$$I_{SD} = I_{SD}(t_0)e^{\left(\frac{t}{\tau_{SD}}\right)} \tag{4}$$

actually fits most of the leakage data better than a linear form, given the relatively higher values of R^2 obtained and the broad range of data that is covered. In Eq. (4), I_{SD} is the measured leakage current and t_0 is the time at which all data points taken after t_0 will be used for the curve fitting. A larger value of τ_{SD} indicates a longer, slower degradation failure. Logarithms do not fit any data well among the four formulas.



(a) (b)

FIG. 4. Exponential and power-law curve-fitting of leakage data: (a) for capacitor sample C13 of Table II as a slow degradation failure example, and (b) for C7 as a catastrophic failure example.

The following general power-law relationship has also been used for curve-fitting the leakage data:

$$I_{SD} = I_{SD}(t_0)[1 + A_0(t)^m],$$

and a linear regression line form was used:[17]

$$\left(\frac{I_{SD}}{I_{SD}(t_0)} - 1\right) = A_0(t)^m \tag{5}$$

where m is the power-law exponent and A_0 is fitting constant. Table III compares the curve-fitting results for both exponential and power-law relationships over the leakage current data shown in FIG. 3.

An example of determination of the fitting parameters is shown in FIG. 4(a) for a BME capacitor, C13, which revealed a slow degradation failure characteristic. The leakage current data for slow degradation failures were found to fit almost perfectly to the exponential equation [Eq. (4)], with R^2 very close to 1.

As shown in Table III, R^2 values slightly decrease when the exponential form of Eq. (4) is used to fit the TTF data with a catastrophic failure characteristic. The catastrophic failure example shown in FIG. 4(b) for C7 indicates that the formula only fits leakage data well prior to the beginning of a catastrophic failure.

Table III. Exponential and power-law curve-fitting results of leakage current data in FIG. 3

C08X47516, 165ºC, 72V			Exponential Form Eq. (4)			Power-Law Form Eq. (5)		
Capacitor ID	TTF (min.)	Failure Mode	τ (Hrs.)	I(0)	R^2	Slope *m*	A_0	R^2
C15	377.26	Catastrophic	27.778	25.68	0.979	7.528	3.0E-25	0.849
C12	614.70	Catastrophic	27.778	33.80	0.992	4.832	2.0E-16	0.875
C16	712.00	Catastrophic	27.778	35.08	0.995	5.197	1.0E-17	0.905
C19	723.40	Catastrophic	33.333	37.88	0.996	4.375	6.0E-15	0.888
C14	749.30	Catastrophic	33.333	37.56	0.996	4.679	7.0E-16	0.888
C10	766.34	Catastrophic	33.333	37.48	0.993	3.953	2.0E-13	0.894
C18	793.25[a]	Slow Degradation	27.778	41.48	0.998	4.250	2.0E-14	0.887
C4	805.29	Catastrophic	33.333	38.83	0.994	3.511	4.0E-12	0.898
C17	866.30	Catastrophic	33.333	40.85	0.997	3.476	6.0E-12	0.896
C3	908.27	Catastrophic	41.667	41.72	0.993	3.481	4.0E-12	0.902
C9	953.18	Catastrophic	33.333	39.97	0.994	2.865	5.0E-10	0.908
C2	1112.39	Slow Degradation	33.333	46.82	0.999	2.791	9.0E-10	0.915
C8	1124.51	Slow Degradation	33.333	46.82	0.999	2.865	6.0E-10	0.920
C6	1163.47	Slow Degradation	33.333	47.77	0.999	2.368	2.0E-08	0.924
C0	1203.19	Slow Degradation	33.333	48.51	0.999	2.417	2.0E-08	0.931
C7	1235.54	Catastrophic	41.667	45.56	0.992	1.919	6.0E-07	0.935
C13	1302.47	Slow Degradation	41.667	48.71	0.999	2.138	1.0E-07	0.948
C11	1425.38	Slow Degradation	41.667	51.88	0.999	1.884	8.0E-07	0.951
C1	1515.23	Slow Degradation	41.667	53.51	0.999	1.576	8.0E-06	0.968
C5	1583.30	Slow Degradation	41.667	52.95	0.999	1.293	6.0E-05	0.988

[a] Background shading is used to highlight the TTF data points that were slow degradation failures.

The described curve-fitting process was performed for all of the leakage current data measured at different stress levels and for different BME capacitors. This practice gave rise to the following conclusions:

(1) Slow degradation failures appear to fit well to the exponential form [Eq. (4)]. (2) Although the power-law form [Eq. (5)] appears to fit slow degradation failures, with comparable, but always lower R^2 values than those of the exponential form [Eq. (4)], the power-law relationship appears to not fit well the slow degradation failures. (3) Neither the exponential form nor the power-law form fits catastrophic data well, indicating that a different failure mechanism must be associated with the catastrophic failures.

The physical meaning of τ_{SD} can be illustrated by the following example: Let I_1 and I_2 be the leakages at times t_1 and t_2, respectively, for a slow degradation failure. If one assumes $\frac{I_2}{I_1} = 2$, then Eq. (4) can be rewritten as:

$$\frac{I_2}{I_1} = e^{\left(\frac{t_2 - t_1}{\tau_{SD}}\right)} = e^{\left(\frac{\Delta t}{\tau_{SD}}\right)} = 2, \text{and } \tau_{SD} = \frac{\Delta t}{ln(2)} \approx 1.4427 \cdot \Delta t$$

where Δt is the time at which the leakage current doubles its value. The greater the τ_{SD}, the longer the time span of a slow degradation failure. τ_{SD} has been found to decrease with

increasing stress levels. A physical model that relates τ_{SD} to the microstructure of $BaTiO_3$ dielectrics is being developed.

C. An improved Weibull model with a combination of leakage current data

The leakage current testing data shown in Table III revealed two distinct failure modes. When combined with corresponding TTF data, each capacitor can be assigned to one of the two identifiable failure modes. According to Weibull modeling theory, if mixed failure modes are present in a group of TTF data and if the failures can be distinguished from each other, then the Weibull modeling process can be performed as follows:

When TTF data of failure mode A are taken into account, the TTF data for failure mode B in the group can be treated as "censored" or "suspensions," meaning that the capacitors may fail by a different failure mode but cannot be ignored even though the suspensions were never plotted. The TTF data on suspended units must also be included in the Weibull analysis. Therefore, when mixed failure modes are present, the Weibull plots will include TTF data and also the state of failure (F) or suspension (S).

This Weibull modeling method for dealing with mixed failure modes is shown in Table IV. The original TTF data shown in FIG. 1 have been extended to three groups for Weibull modeling. The single set column uses all TTF data, with all data points labeled "failure" (F). The catastrophic column labels all capacitors that failed with a catastrophic characteristic as failures (F), whereas the capacitors that failed with a slow degradation failure mode will be labeled as suspensions (S). The slow degradation column labels all capacitors that failed with a catastrophic characteristic as suspensions (S), whereas the capacitors that failed with a slow degradation failure mode will be labeled as failures (F).

The 2-parameter Weibull plot shown in FIG. 1, combined with the corresponding measured leakage current data, is re-plotted in FIG. 5(a), where arrows indicate the TTF data points in FIG. 5(b) that failed catastrophically.

Furthermore, two Weibull plots with catastrophic and slow degradation failures can be generated using the same TTF data in Table IV, with different columns labeled "catastrophic" and "slow degradation." Corresponding results are shown in FIG. 6(a).

Table IV. TTF, failure modes, and three different approaches for Weibull modeling of C08X47516 at 165°C and 72V

TTF (min.)	Failure Mode	Single Set (traditional)	Catastrophic	Slow Degradation
377.26	Catastrophic	F	F	S
614.70	Catastrophic	F	F	S
712.00	Catastrophic	F	F	S
723.40	Catastrophic	F	F	S
749.30	Catastrophic	F	F	S
766.34	Catastrophic	F	F	S
793.25[a]	Slow Degradation	F	S	F
805.29	Catastrophic	F	F	S
866.30	Catastrophic	F	F	S
908.27	Catastrophic	F	F	S
953.18	Catastrophic	F	F	S
1112.39	Slow Degradation	F	S	F
1124.51	Slow Degradation	F	S	F
1163.47	Slow Degradation	F	S	F
1203.19	Slow Degradation	F	S	F
1235.54	Catastrophic	F	F	S
1302.47	Slow Degradation	F	S	F
1425.38	Slow Degradation	F	S	F
1515.23	Slow Degradation	F	S	F
1583.30	Slow Degradation	F	S	F

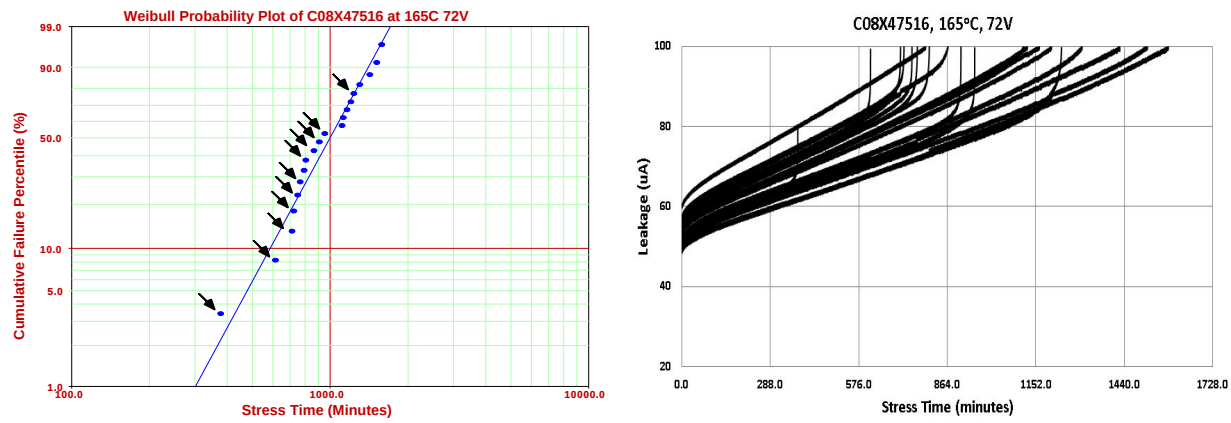
[a] Background shading is used to highlight the TTF data points that were slow degradation failures.

It is clear that the two plots have different values of slope parameter β. This difference can be further revealed using a contour plot technique. As shown in FIG. 6(b), a contour plot gives rise to a visual picture of confidence bounds on β and η for a 2-parameter Weibull distribution at a certain confidence level (typically 95%). The plot defines the statistical boundary of a data set with respect to the possible values of β and η. This technique is often applied to compare different data sets to determine if they have statistically different failure modes.

It is important to note that in the contour plots shown in FIG. 6(b), the two data sets do not show any overlap with respect to the β values (y-axis), indicating that the two data sets statistically represent two different failure modes.

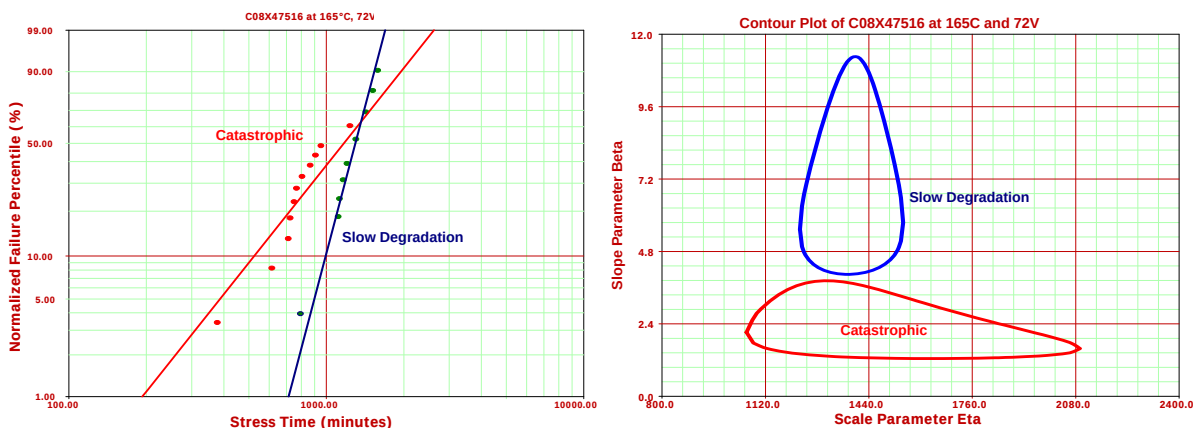
A comparison of FIG. 5 and FIG. 6 leads to an interesting observation: if only the TTF data are taken into account for Weibull modeling, the result appears to fit a single failure mode fairly well [FIG. 5(a)]. However, when the leakage current data are used to separate the TTF data based on different failure modes, the same TTF data can be statistically divided into two subgroups with

two distinct failure modes [FIG. 6(b)]. This is indication that leakage current measurement is vital for revealing the mixed failure modes in BME MLCCs.



(a) (b)

FIG. 5. Weibull modeling results of TTF data from Table II for BME capacitor C08X47516, life tested at 165°C and 72V. (a) Weibull plot, with arrows indicating all catastrophic failures, (b) Leakage current plot over the stress time.



(a) (b)

FIG. 6. Weibull Plot (a) and corresponding contour plot (b) reveals the two slope parameters β for the two different failure modes, but the two subgroups share a similar scale parameter η.

In addition, the measured leakage current data with mixed failure modes have been found to be a common feature for all of BME capacitors studied from three different manufacturers. Characterization of the failure mechanisms in BME capacitors requires a combination of TTF and leakage current measurements to adequately reveal the complex, mixed-failure mode results.

D. Determination of acceleration functions of BME capacitors

An acceleration function describes how a capacitor's reliability life responds to external stresses such as V and T. All units in the testing group are subject to follow the same acceleration function if they share the same failure mode (independent of individual units).

For MLCCs, the Prokopowicz and Vaskas equation (P-V equation) [Eq. (3)] has proven to be a useful acceleration function in the capacitor industry for testing PME MLCCs under various highly accelerated testing conditions. An average of n ~3 has been found for the voltage acceleration factor, and an average value of $1 < E_a < 2$ eV is typical for the temperature acceleration factor.[10-12]

When Weibull distribution Eq. (1) and acceleration function Eq. (3) are used to model the TTF data, only a single failure mode is assumed. As a result of that, the value of β in Eq. (1) is not subject to change over the applied stresses. Only the Weibull distribution scale parameter η will change with external stresses. It can be expressed per Eq. (3) as

$$\eta(V,T) = \frac{C}{V^n} \cdot e^{\left(\frac{B}{T}\right)}, \tag{6}$$

where C and $B = E_a/k$ are constants.

As shown in Table II, the calculated reliability life (MTTF) using the P-V equation does not always agree with the actual testing results. One observation is that BME capacitors seem to not always follow the power-law over applied voltage. Deviations from the P-V equation were observed as early as 1984 for PME capacitors under highly accelerated stresses.[1] J. Scott also reported that the measured MTTF data for (Ba, Sr)TiO_3-based integrated ferroelectrics in memory applications appear to follow an exponential relationship over an electrical field rather than the traditional power-law relationship.[13, 14] Meanwhile, a general E-model was proposed by McPherson based on a thermo-chemical model that involves the migration of oxygen vacancies.[15-17] Although the E-model was proposed to explain and predict the reliability in SiO_2 gate-oxide, it has also been applied recently to predict the reliability life of BME capacitors due to the similar oxygen vacancy migration behavior involved.[8] This exponential relationship can be expressed as:

$$\frac{t_1}{t_2} = exp[-b(E_1 - E_2)]exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \qquad (E\text{-}Model) \qquad (7)$$

where b is a constant that presents the accelerating factor of external electric field E. It has been reported that Eq. (7) may give a more accurate reliability life than Eq. (3).[8]

Table V summarizes the two acceleration functions that have been used to predict the reliability life of BME capacitors under a given level of E and T, where $E \approx V/d$ is the external electrical field per dielectric layer.[17] To aid in understanding, the two acceleration functions are expressed with respect to both the Weibull scale parameter η and to TTF.

Table V. Summary of acceleration functions proposed for BME MLCCs

Type of acceleration function	Expression to scale parameter η	Expression to TTF
Exponential (E-Model)	$\eta(E,T) = Ce^{-bE} \cdot e^{(\frac{E_a}{kT})}$	$\frac{t_1}{t_2} = exp[-b(E_1 - E_2)]exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$
Power-law (P-V equation)	$\eta(V,T) = \frac{C}{V^n} \cdot e^{(\frac{E_a}{kT})}$	$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$

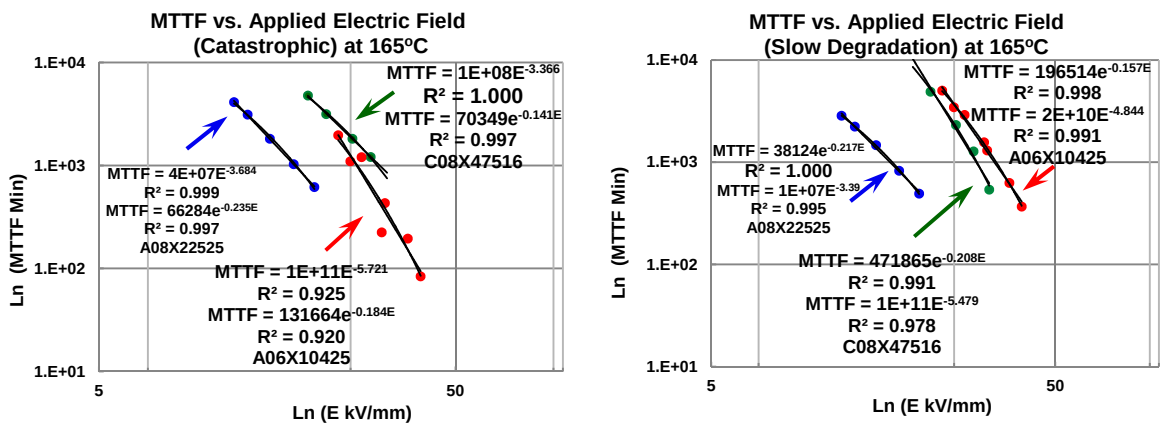
In order to find out which acceleration function in Table V is better for describing the reliability life, and to find the correlations between the failure modes and the acceleration functions, the Weibull modeling process of mixed failure modes described in Section C and in Table IV was repeated for all TTF data measured under various acceleration conditions at a constant temperature (165°C), and for a number of BME capacitor samples.

Corresponding calculated MTTF results are shown in Table VI, in which the average dielectric thickness of each capacitor sample was measured such that the applied voltage can be directly converted to the electric field. The MTTF data were also calculated for three different failure scenarios given in Table IV, i.e., traditional single set, catastrophic, and slow degradation.

FIG. 7 shows the MTTF data against external electric field at a constant temperature (165°C) for three representative BME capacitors, for which the MTTF data are summarized in Table VI. FIG. 7(a) uses only the MTTF data of Table VI with catastrophic failures. FIG. 7(b) uses those with slow degradation failures only.

Table VI. Calculated MTTF data (minutes) as a function of failure mode and testing voltage at 165°C for three BME capacitors

BME Capacitor ID	Voltage(V)	Dielectric Thickness (μm)	E (kV/mm)	MTTF (Single set)	MTTF (Catastrophic)	MTTF (Slow degradation)
C08X47516 4.7 μF, 0805, 16V by manufacturer C	48	2.49	19.2771	4787.46	4787.46	N/A
	54	2.49	21.6867	3087.29	3160.10	4902.66
	64	2.49	25.7028	1710.94	1822.15	2316.12
	72	2.49	28.9157	998.04	1211.75	1278.16
	80	2.49	32.1285	529.27	N/A	539.50
A06X10425 0.1 μF, 0603, 25V by manufacturer A	185	7.89	23.4474	3995.33	1966.56	5018.90
	200	7.89	25.3485	2847.73	1098.92	3452.53
	215	7.89	27.2497	2187.78	1206.88	2901.57
	245	7.89	31.0520	1198.81	224.51	1565.76
	250	7.89	31.6857	940.96	431.77	1303.54
	290	7.89	36.7554	452.59	195.19	627.52
	315	7.89	39.9240	182.86	83.75	368.42
A08X22525 2.2 μF, 0805, 25V by manufacturer A	47.6	3.98	11.9598	2761.43	4132.05	2854.68
	52	3.98	13.0653	2122.29	3129.37	2235.02
	60	3.98	15.0754	1461.26	1819.25	1472.27
	70	3.98	17.5879	818.44	1032.13	825.84
	80	3.98	20.1005	473.19	617.21	492.54



(a) (b)

FIG. 7. MTTF data as a function of applied electric field at 165°C for BME capacitors (a) with catastrophic failures, and (b) with slow degradation failures.

Each curve shown in FIG. 7 was curve-fitted using both power-law (*P-V* equation) and exponential *E*-model as the acceleration functions. Again, the curve-fitting coefficient of determination, R^2, was used to quantitatively determine which acceleration function fits the MTTF data better.

An analysis of the curve-fitting results in FIG. 7 finds that catastrophic failures fit better using the power-law [FIG. 7(a)], while slow degradation failures – with exponential [FIG. 7(b)]. This

difference in R^2 is not significant, but no exceptions to the observation were found. It is expected that the difference in R^2 for the two failure modes will become more distinct when more MTTF data points are available, particularly at lower electrical fields, although this may take years of testing to prove.[19]

E. Calculated reliability lifetime of BME capacitors with mixed failure modes

Up to this point, three different modeling scenarios and two acceleration functions have been developed for the reliability life of BME capacitors, giving rise to a total of six possible reliability models. Table VII summarizes the six possible Weibull modeling results for BME capacitor C08X47516. The results suggest that the calculated acceleration factors can be very different for the same group of TTF data, depending on which modeling scenario is used. The traditional modeling method that uses only TTF data and the *P-V* equation will give rise to acceleration factors of E_a= 2.60 eV and n= 4.52, which are higher than those that have been reported for most PME capacitors. However, when the mixed failure modes approach is applied, the acceleration factors obtained (E_a= 1.39 eV and n= 3.249 for the catastrophic failures) fit well to the classic acceleration factor values of PME capacitors. Indeed, a catastrophic failure with a power-law acceleration function is also the primary failure mode reported for PME capacitors. [1]

The MTTF can also be calculated using the obtained six different Weibull modeling results summarized in Table VII. Table VIII summarizes the calculated reliability life (MTTF) of BME capacitor C08X47516 using the six different Weibull models at a stress level of 135°C and 72V. The actual measured MTTF data at this stress level were also included for the purpose of comparison.

In general, a group of measured TTF data with a single failure mode should also follow a single acceleration function. Since the complete set has been shown to have mixed failure modes, the calculated MTTF for both acceleration functions must be taken into consideration. The TTF data for the slow degradation failure mode have been shown to follow an exponential acceleration function over an applied field [*E*-model, Eq. (7)], and those for catastrophic failures follow a power-law relationship [*P-V* equation, Eq. (3)]. Therefore, the calculated MTTF results shown in Table VIII using power-law for slow degradation and using *E*-model for catastrophic should be crossed out.

Table VII. Weibull modeling results for three different modeling scenarios and two different acceleration functions for BME capacitor C08X47516

Failure Modes	Weibull Modeling using power-law [Eq.(3)]				Weibull Modeling Using E-Model [Eq.(7)]			
	β	η	E_a (eV)	n	β	η	E_a (eV)	-b
Single Set (Traditional)	2.755	3.58E+07	2.60	4.524	2.795	1.70E+07	2.61	-0.181
Slow Degradation	3.326	1.32E+10	3.78	7.477	3.349	2.51E+09	3.86	-0.262
Catastrophic	3.288	8.05E+05	1.39	3.249	3.262	4.88E+05	1.39	-0.134

As shown in Table VIII, the single set scenario using the power-law acceleration function gives rise to a calculated lifetime of 2111.17 hours, which is much longer than the actually measured lifetime of 318.28 hours. However, the single set using the *E*-model acceleration gives rise to a calculated lifetime of 427.10 hours, which is still longer but a significant improvement. Recently, the exponential acceleration function Eq. (7) has been reported to calculate the MTTF for a number of BME capacitors. All of the calculated results were close to but still longer than those of measured MTTF data.[8]

Table VIII. Calculated MTTF (hrs.) data of C08X47516 at 135°C and 72V for Weibull modeling verification. Crossed out are acceleration functions that showed poor fit for given degradation type.

Failure Mode Scenarios	Acceleration Functions	
	Power-law [P-V Equation, Eq. (3)]	E-Model [Exponential, Eq. (7)]
Single Set (traditional)	2111.17	427.10
Slow Degradation	~~30835.00~~	9438.50
Catastrophic	318.67	~~79.86~~
Measured Verification Data	318. 28	

The best agreement between calculated and measured data in this study was for the catastrophic failures with the power-law acceleration function (*P-V* equation). Although the failure mode for BME capacitor C08X47516 at 135°C and 72V appears to follow a traditional dielectric wearout that has been revealed in most PME capacitors, this good agreement between the calculation and the measurement can only be achieved if a mixed failure mode method is used; it is not attainable for a traditional method such as single set with power-law acceleration (see Table VIII) without the incorporation of the capacitor's leakage current measurement.

If the calculated reliability life is accurate for BME capacitor C08X47516, then all of the capacitors that failed at 135°C and 72V should have revealed catastrophic failures. FIG. 8 shows the actual measured leakage current data over the applied voltage at 135°C and 72V. It is clear

that all capacitors exhibited catastrophic failures. The calculated MTTF results for other BME capacitors in this study show similar results to those summarized in Table VIII.

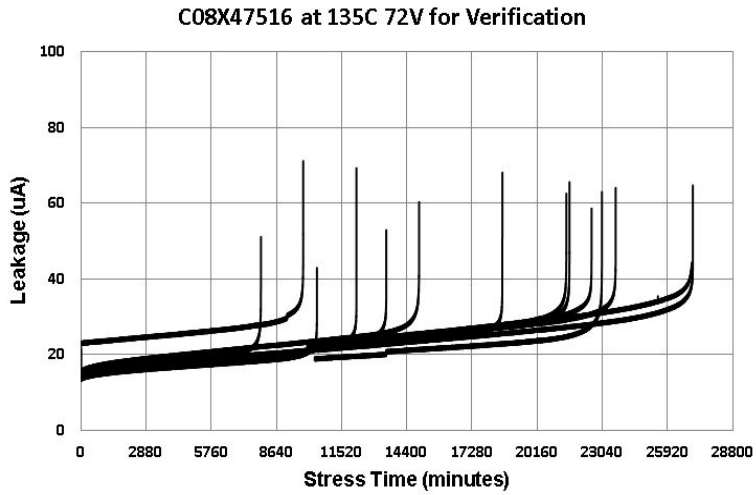


FIG. 8. Leakage current results at 135°C and 72V show that all capacitors failed catastrophically, which confirms the proposed reliability model for BME capacitors in this study.

IV. CONCLUSIONS

Traditional highly accelerated life testing, i.e., measuring TTF data and using the P-V equation Eq. (3) as an acceleration function, has been found to give rise to a longer calculated lifetime than actually measured. The problem has been attributed to the electromigration of oxygen vacancies in BME capacitors that may introduce a new failure mode. A highly accelerated life stress testing (HALST) method that combines the TTF data and leakage current measurement results was developed and used to evaluate and predict the reliability life of BME capacitors.

This improved HALST method combines in-situ leakage current and TTF data. The leakage current measurement data reveal two distinct failure modes: slow degradation and catastrophic. The slow degradation failures fit well to an exponential law [Eq. (4)] over the stress time. A characteristic exponential growth time τ_{SD} can be used to describe the reliability life of this failure mode. The larger the value of τ_{SD}, the longer the MTTF of a slow degradation process.

The measured TTF data at a given stress level were fitted to the 2-parameter Weibull model with three different scenarios: (1) single set: all TTF data points will be used for the modeling and a state of failure will be assigned to all data points; (2) catastrophic: the TTF data points that were

revealed to be catastrophic will be assigned a state of failure, while those data points revealed to be slow degradations will be treated as suspensions; and (3) slow degradation: in a reversal of the catastrophic scenario, the TTF data points revealed to be catastrophic will be treated as suspensions.

The two identified failure modes were found to follow different acceleration functions over the applied external field. Slow degradation failures appear to follow an exponential-law (*E*-model), while catastrophic failures appear to follow the traditional power-law (*P*-*V* equation). This makes calculations of MTTF data more complicated for BME capacitors than for PME capacitors. The determination of acceleration factors E_a and n is more difficult for BME MLCCs.

The developed reliability model for BME capacitors gives rise to the best agreement between the calculated MTTF and measured results. Good correlation was found not only for the reliability lifetime, but also the failure modes.

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