Reliability Evaluations of BME Capacitors for Space Applications

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Outline

- NEPP Funded Deliverables for Fiscal Year 2013
- Development of a Reliability Model for BME Capacitors
- Key Issues in Evaluating BME Capacitors for Space Applications
- Summary

NEPP Funded Deliverables for This Fiscal Year

- Engineering guidelines and drawings to be used as specifications for NASA procurement of BME capacitors for high-reliability applications
  - D. Liu, "Selection, Qualification, Inspection, and Derating of Multilayer Ceramic Capacitors with Base-Metal Electrodes," NASA NEPP FY Report, (2013). (https://nepp.nasa.gov/files/24351/Liu_2013_G11_BME_Guidelines.pdf)
  - Participating G11 BME Industrial Forum weekly meeting to establish a MIL standard for BME capacitors
- Possible reliability model that can become a practical standard for advanced MLCCs placed in demanding conditions
  - D. Liu, "Reliability of Multilayer Ceramic Capacitors with Base-Metal Electrodes," NASA EEE Parts Bulletin, Special Issue, Vol. 5[2], April/May, pp. 1-10, (2013). (https://nepp.nasa.gov/files/24396/EEE_Parts_Bulletin_Apr-May2013_final.pdf)
  - D. Liu, "Highly Accelerated Life Stress Testing (HALST) of Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, Houston, TX, pp. 235–248, (March 26–29, 2013). (https://nepp.nasa.gov/files/24300/CARTS2013_Liu_HALST.pdf)
  - R. Weachock and D. Liu, "Failure Analysis of Dielectric Breakdowns in Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, Houston, TX, pp. 151–165, (2013). (https://nepp.nasa.gov/files/24303/CARTS2013_Liu_FailureAnalysis.pdf)

A General Expression of Reliability for MLCCs

$$\boxed{R(t) = \varphi(N, d, \bar{r}, S) \times AF(V,T) \times \gamma(t)}$$

$\gamma(t)$: Statistical distribution that describes the *individual variation* of properties (Weibull, log normal, normal)

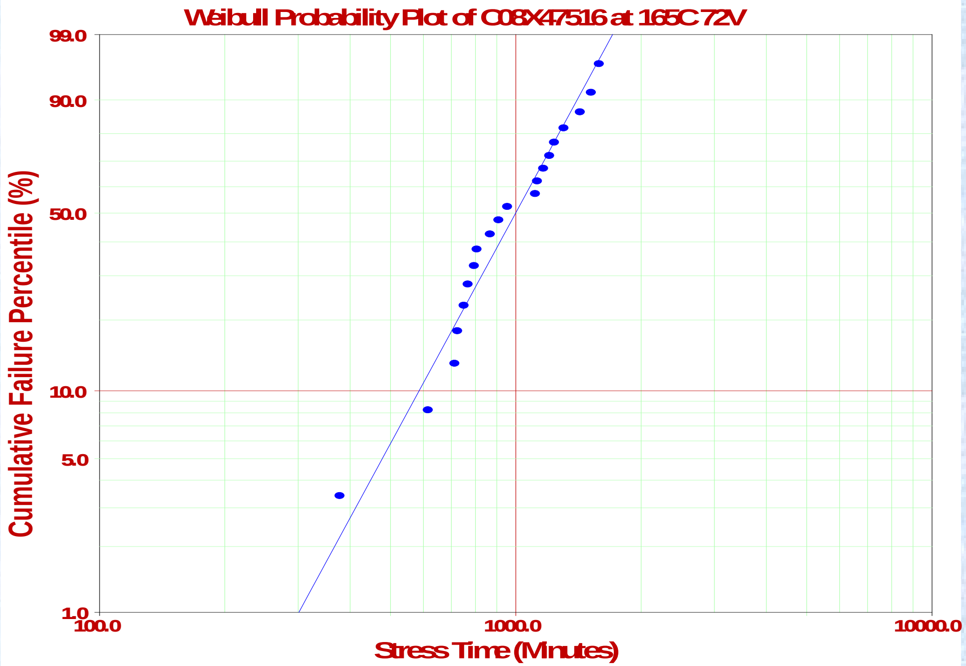
$AF(V,T)$: A function that describes lifetime of a device to respond to the external stresses (*independent of individual units*)

$\varphi(N, d, \bar{a}, S)$: Impacts due to the characteristics of a capacitor device (structure, construction, etc.)

- Statistical Distribution: $\gamma(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$
  - *2*-parameter Weibull:
  - A function of time, always decreases with time
  - The probability of a failure occurring: $\gamma(t) = [0,1]$
  - The durability of a MLCC that can function normally during wearout:
    - When β >3 and $t < \eta$, $R(t)$ ~1, a reliable life span before η
    - When β >3 and $t > \eta$, $R(t)$ ~0, part failed rapidly after η

Determination of Acceleration Functions

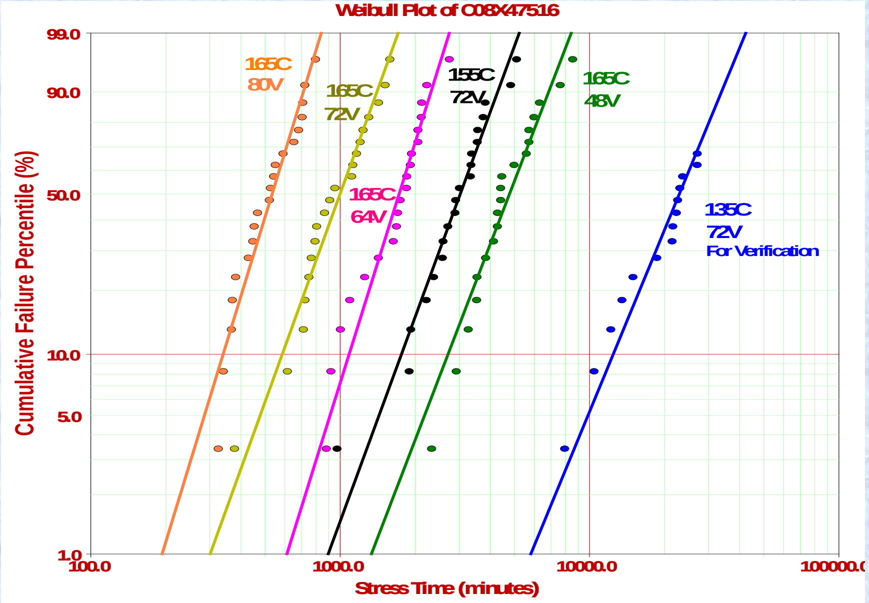
- Determination of *AF(V,T)* requires the performance of highly accelerated life testing (HALT)
- A typical HALT method involves the measurements of time-to-failure (TTF) data of a group of BME capacitors under certain stress conditions



TTF (minutes)
81.50
601.63
947.00
1019.27
1497.37
1565.63
1921.03
2187.37
2189.72
2525.67
2527.30
2564.23
2629.02
2827.58
3096.52
3141.35
3233.25
3290.27
3314.33
3404.85

Determination of Acceleration Functions (Cont'd)

- Repeat the testing procedure under different stress conditions (three voltages and three temperatures are normally required) and a group of TTF data under various stress conditions will be obtained.
- Data set at 135^{o}C, 72V is for verification purposes ***only***.



BME Info.	HALT Conditions	MTTF (min)	Beta (β)	Eta (η)
C08X47516 0805, 0.47uF, 16V From Mfr. C	165^{o}C 48V (3X Vr)	4787.46	3.32	5335.48
	165^{o}C 54V (3.4X Vr)	3087.29	2.95	3459.73
	165^{o}C 64V (4xVr)	1710.94	4.08	1885.37
	165^{o}C 72V (4.5xVr)	998.04	3.53	1108.74
	165^{o}C 80V (5x Vr)	529.27	4.17	582.54
	175^{o}C 72V (4.5xVr)	111.84	2.21	126.28
	155^{o}C 72V (4.5xVr)	3029.82	3.47	3368.76
for verification	135^{o}C 72V (4.5xVr)	19097.00	3.82	21124.00

Determination of Acceleration Functions (Cont'd)

- Up to this point the TTF data were processed with Weibull modeling only
- The most widely known acceleration function, the Prokopowicz and Vaskas equation, is now applied to process the Weibull modeling data and determine the acceleration factors E_a and n, respectively

Prokopowicz and Vaskas Equation (*P-V* Equation):

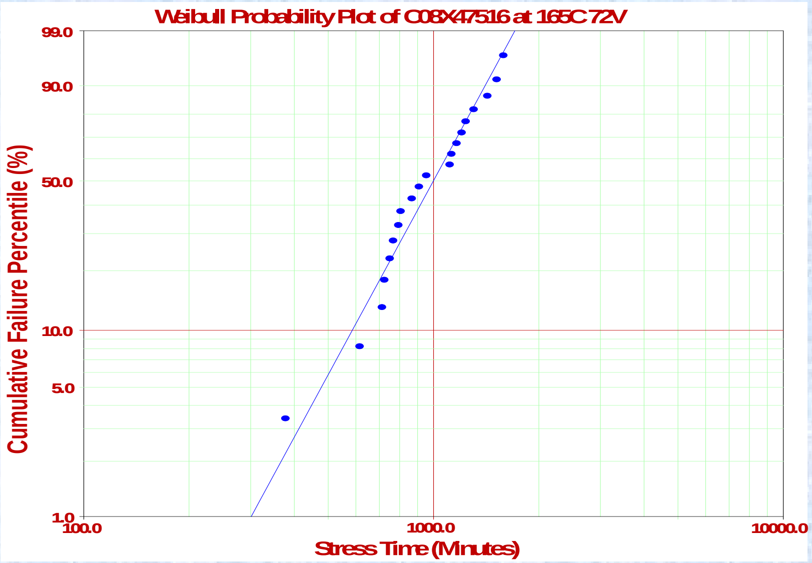
$$\frac{MTTF_1}{MTTF_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

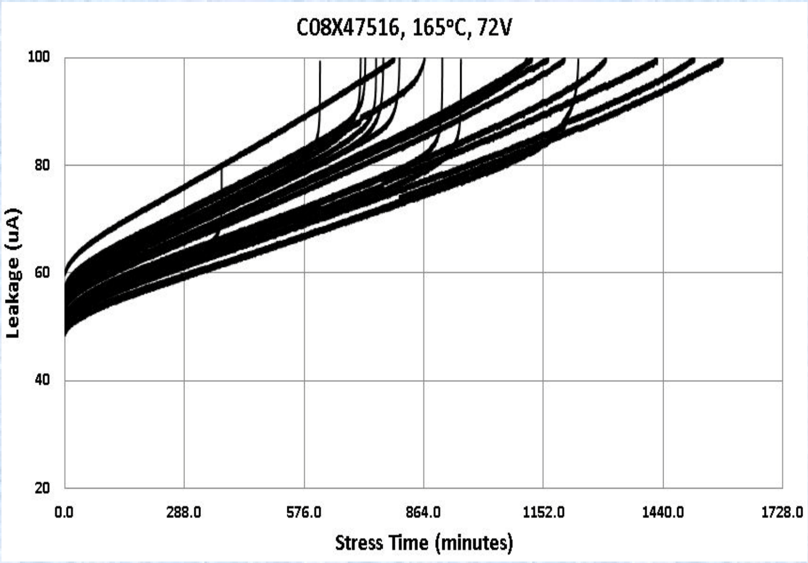
	Acceleration Factors from P-V Equation and MTTF Calculated for 135°C, 72V					
Model Parameters	β	η	E_a (eV)	n	MTTF(min)	MTTF (Hours)
Calculated Model Results	2.755	3.587E+07	2.60	4.524	126670.20	**2111.17**
Verification data at 135°C, 72V	3.822	21124	N/A	N/A	19097.00	**318.28**

- The calculated MTTF data using a single Weibull model and *P-V* equation has been widely found to always be longer than that of the measured MTTF for most BME capacitors

Determination of Acceleration Functions (Cont'd)

- The gap between the calculated and the measured has been thought due to the introduction of some new failure modes that were not found, nor dominant in PME capacitors.
- The traditional HALT modeling, using only the TTF data and *P-V* equation, is not adequate to characterize the complexity of the failure mechanisms in BME capacitors.
- In this study the leakage current against stress time has been measured together with TTF data





Determination of Acceleration Functions (Cont'd)

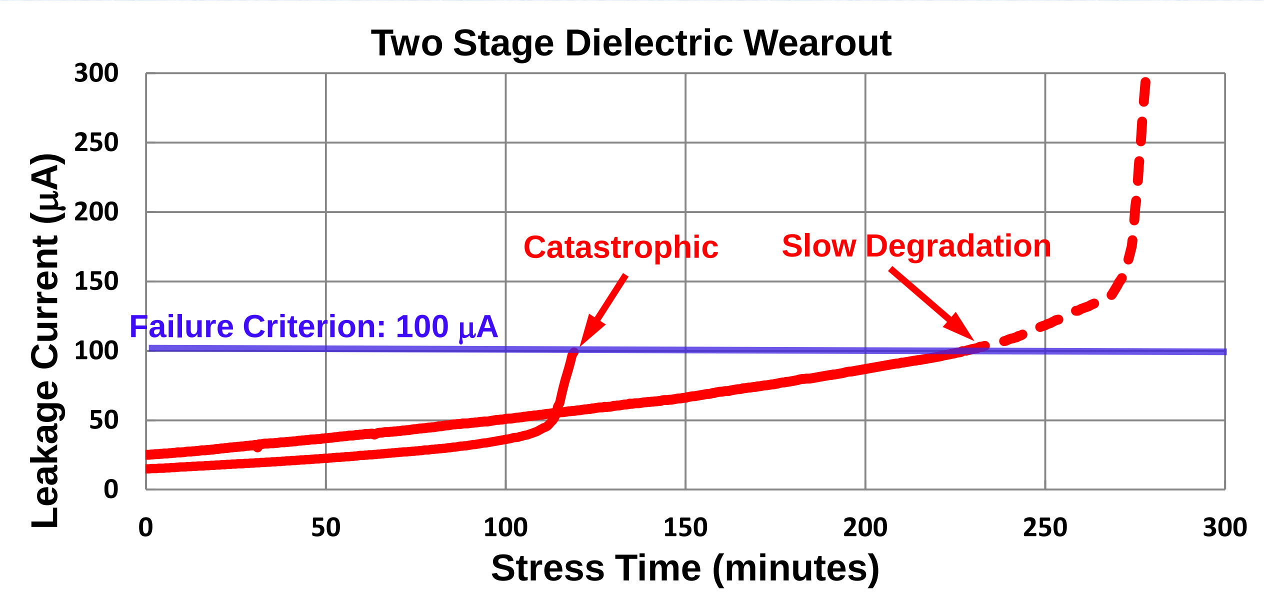
C08X47516, 165°C, 72V			Exponential Fitting Eq. (10)			Power-Law Fitting Eq. (11)		
Position on PCB Board	TTF (minutes)	Failure Mode	τ (Hrs)	I(0)	R^2	Slope *m*	A_0	R^2
C15	377.26	Catastrophic	27.778	25.68	0.979	7.528	3.0E-25	0.849
C12	614.70	Catastrophic	27.778	33.80	0.992	4.832	2.0E-16	0.875
C16	712.00	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	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

- Although Slow Degradation (SD) appears linear, exponential form fits the data much better :

$$\boxed{I = I_0 e^{\left(\frac{t - t_0}{\tau_{SD}}\right)}}$$

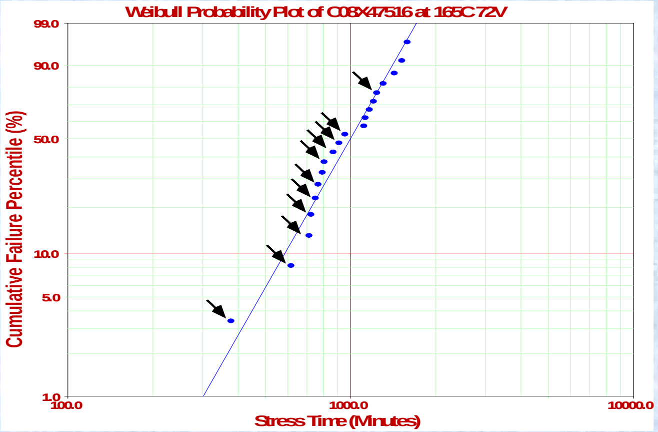
- Neither exponential nor power-law fit well for catastrophic failures

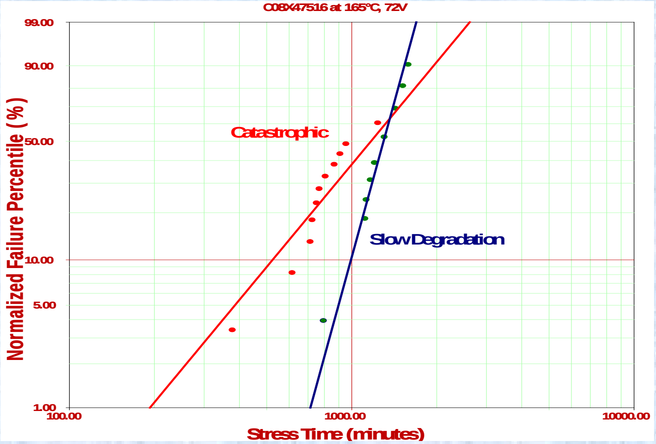
Determination of Acceleration Functions (Cont'd)



- A two-stage dielectric wearout failure mode is better for describing the failure behavior in BME MLCCs with $BaTiO_3$ dielectrics(*supported by Failure analysis results*)
  - *Slow degradation*: leakage increases with time nearly linearly due to oxygen vacancy migration until the failure criterion (100 μA) is reached (parts failed prior to catastrophic failures)
  - *Catastrophic failure*: leakage current increases gradually, followed by time-accelerating catastrophic failures

Determination of Acceleration Functions (Cont'd)

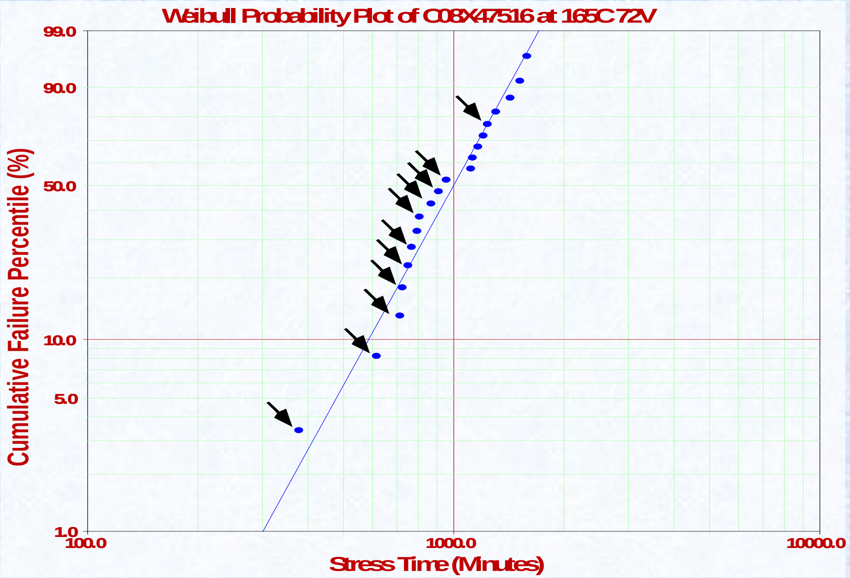


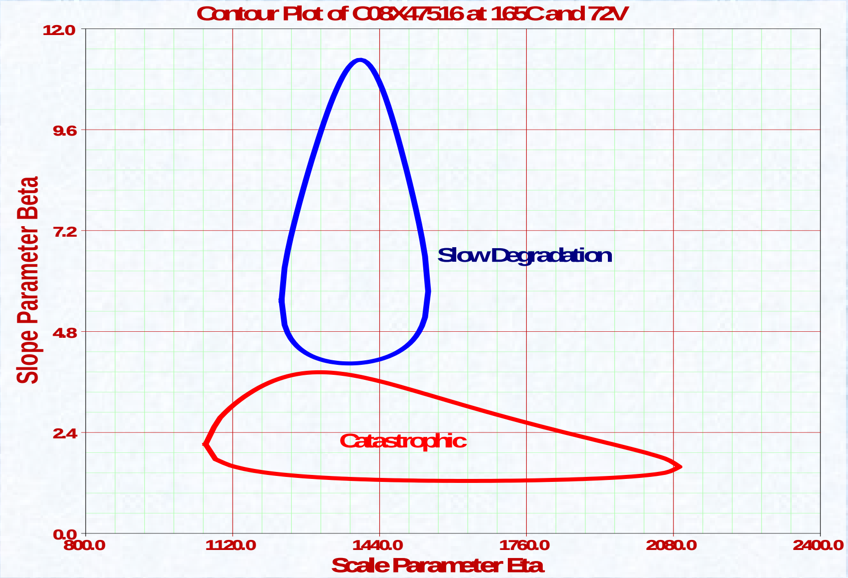


TTF (minutes)	Failure Mode	Single Set (Traditional)	Catastrophic	Slow Degradation
377.26	Catastrophic	F	F	S
614.70	Catastrophic	F	F	S
712.00	Catastrophic	F	F	S
723.40	Catastrophic	F	F	S
749.30	Catastrophic	F	F	S
766.34	Catastrophic	F	F	S
793.25	Slow Degradation	F	S	F
805.29	Catastrophic	F	F	S
866.30	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

- When two failure modes A and B are presented in a group of TTF data, Weibull modeling can be simply processed like this: When TTF data of failure mode A is used for modeling, the TTF data for mode B 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.

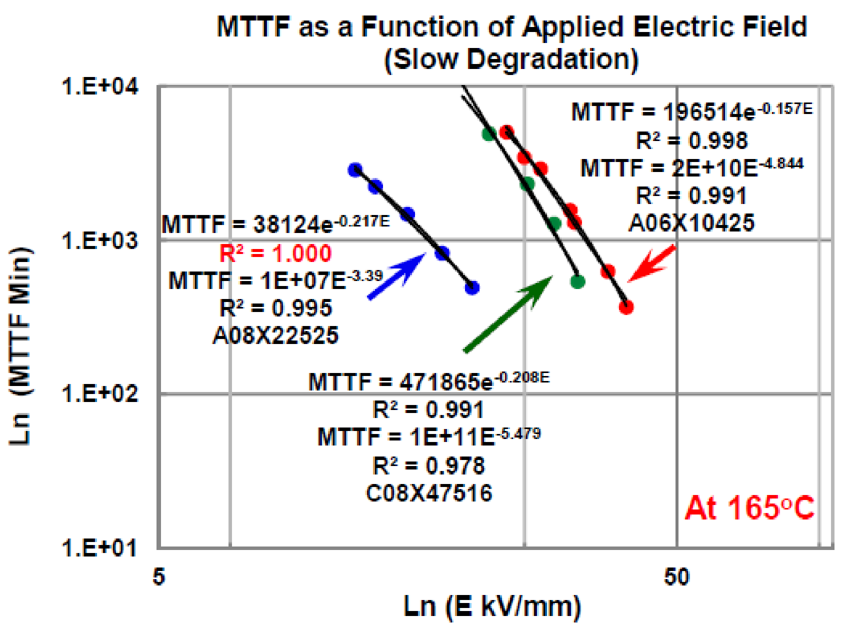
Determination of Acceleration Functions (Cont'd)

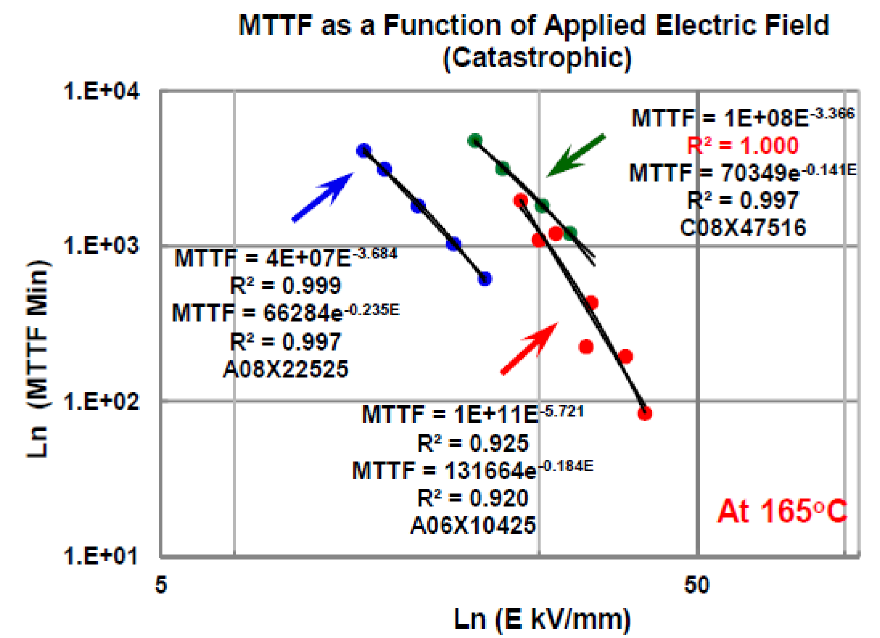




- A interesting Fact: TTF data appears to be a SINGLE failure mode!
- when the leakage current data are used to distinguish the failure modes, TTF data can clearly be separated into two subsets with two different β values, indicating the two subsets have different failure modes.
- Most BME manufacturers did not report the mixed failure modes in their HALT evaluation because they do not measure leakage current!
- *Leakage current combined with TTF data measurement is essential for HALT analysis of BME capacitors*

Determination of Acceleration Functions (Cont'd)





- To repeat the modeling process, a number of MTTF data can be obtained for Catastrophic and slow degradation failure modes (curve-fitting coefficient of determination R^2 is used to compare the fitting results):
  - Catastrophic failures fit power-law (P-V Equation) better: $$\frac{MTTF_1}{MTTF_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$
  - Slow Degradation failures fit exponential-law better: $$\frac{MTTF_1}{MTTF_2} = exp[-b(E_1-E_2)]exp\left[\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$
- There are no exceptions!

Determination of Acceleration Functions (Cont'd)

- 6 quite different Weibull modeling results with respect to three different failure scenarios and two different acceleration functions

Failure Modes	Weibull Modeling Results using P-V Equation				Weibull Modeling Results Using E-Model			
C08X47516	beta	Eta	E_a (eV)	n	beta	Eta	E_a (eV)	-b
Single Set (Traditional)	2.755	3.587E+07	2.60	4.524	2.7953	1.70E+07	2.612	-0.1813
Slow Degradation	3.326	1.322E+10	3.78	7.477	3.3486	2.51E+09	3.862	-0.2621
Catastrophic	3.288	8.055E+05	1.39	3.249	3.2621	4.88E+05	1.393	-0.1341

Calculated MTTF (hours) Data of C08X47516 at 135ºC and 72V for Model Verification

	Acceleration Functions	
Failure Modes	E-Model (Exponential)	Power Law (P-V Equation)
Single Set (traditional)	427.10	2111.17
Slow Degradation	9438.50	~~30835.00~~
Catastrophic	~~79.86~~	318.67
Measured Verification Data		318.28

- Single set scenario with *P-V* equation gives rise to a lifetime of 2111.17 hours which is much longer to that of actually measured 318.28 hours
- The single set with exponential acceleration function gives rise to a lifetime of 427.10 hours, which is a significant improvement when compared to that of measured 318.28 hours (*Murata has use this model to calculate MTTF data for a number of BME capacitors, all the calculated lifetime results are close but still longer than the measured results*)
- The best MTTF result has been obtained in this study for catastrophic failure with a power-law acceleration function

Reliability Model of BNE Capacitors

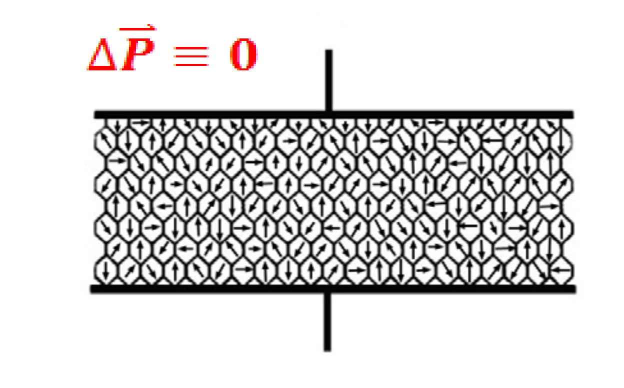
$$R(t) = \varphi(N, d, \bar{r}, S) \times AF(V, T) \times \gamma(t)$$

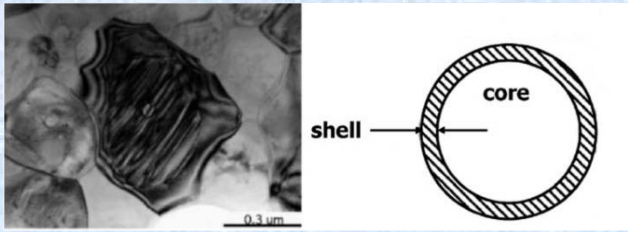
$$= \varphi(N, d, \bar{r}, S) \times \{ \mathbf{p} \times e^{-\left[\frac{t}{\frac{A}{V^n} \cdot e^{\left(\frac{E_{a1}}{kT}\right)}}\right]^{\beta_1}} + (\mathbf{1} - \mathbf{p}) \times e^{-\left[\frac{t}{\mathrm{C}e^{-bE} \cdot e^{\left(\frac{E_{a2}}{kT}\right)}}\right]^{\beta_2}} \}$$

Now It is time to find $\varphi(N, d, \bar{r}, S)$!

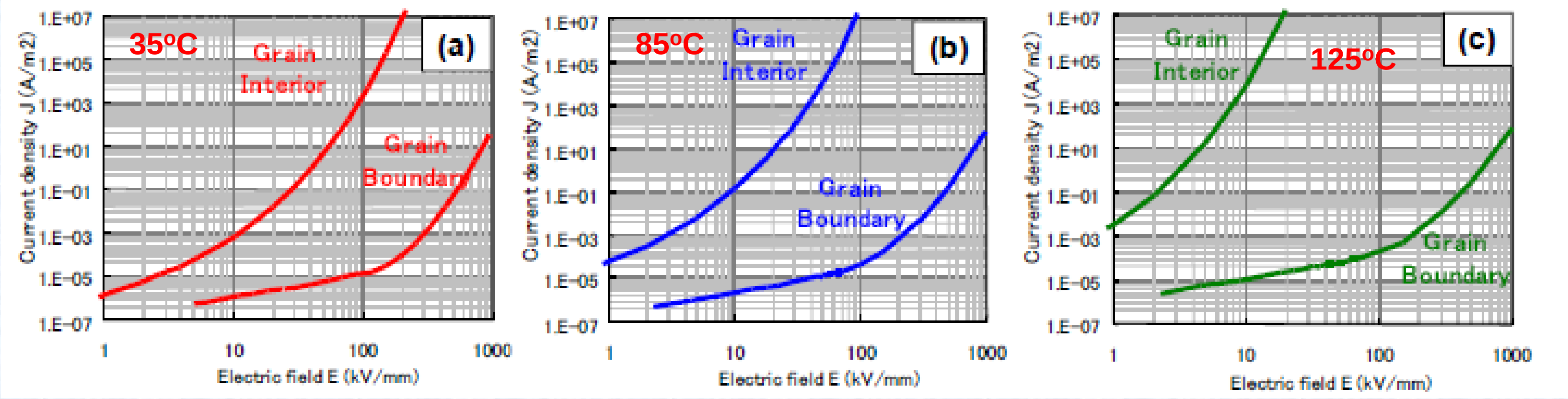
Ceramic Structure of BME Capacitors with $BaTiO_3$

- Ceramic is a polycrystalline structure that contains great number of closed-packed single crystal *grains*
- In a ceramic $BaTiO_3$ structure, although each grain is polarized, the ceramic posses a *centrosymmetric* structure and is neither polarized, nor piezoelectric
- Microstructures of each grain is inhomogeneous, a core-shell structure is often reported due to the inhomogeneity between a grain boundary and the interior of a grain
  - Core: Ferroelectric $BaTiO_3$ single crystal
  - Shell: Non-Ferroelectric, different composition and structure





Ceramic Structure of BME Capacitors with $BaTiO_3$ (Cont'd)



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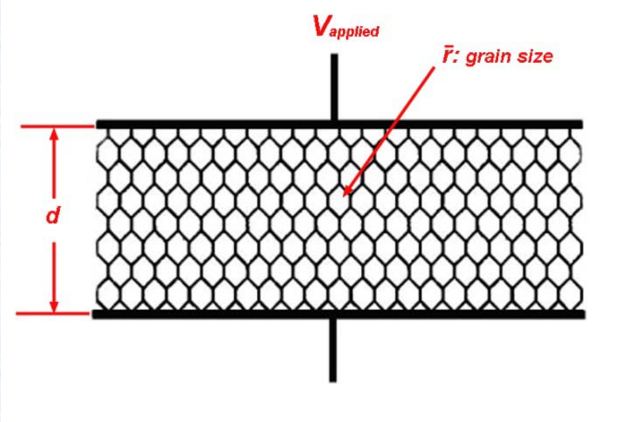
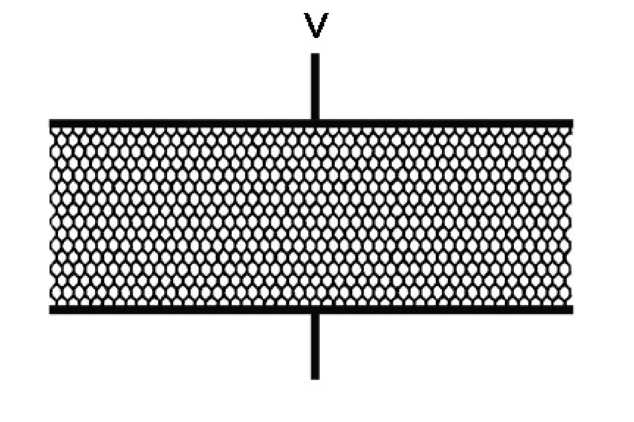
- Resistivity is also inhomogeneous
  - Core is relative conductive; shell is highly resistive (holding the insulating resistance (IR) for a $BaTiO_3$ grain)
  - The applied voltage distribution is inhomogeneous
  - Due to the formation of a high **insulating** layer at the grain boundary, most of the voltage will be applied on the grain boundary region

Ceramic Structure of BME Capacitors with $BaTiO_3$ (Cont'd)





- Impact of Grain Size
  - When applied voltage and the dielectric thickness is identical for two capacitors, the one with a smaller grain size has a better dielectric strength
  - This is why powders with smaller particle sizes are always preferred for making BME capacitors
  - The voltage per grain is the key to characterize the voltage robustness in $BaTiO_3$

$$\text{Voltage Per Grain} = V_{grain} = \frac{V_{applied}}{\left(\frac{d}{\bar{r}}\right)} = V_{applied} \times \left(\frac{\bar{r}}{d}\right)$$

$\bar{r}$: average grain size (μm)
d : dielectric thickness (μm)

$\left(\frac{\bar{r}}{d}\right)$ **A key Structural parameter that determines the dielectric strength and reliability!**

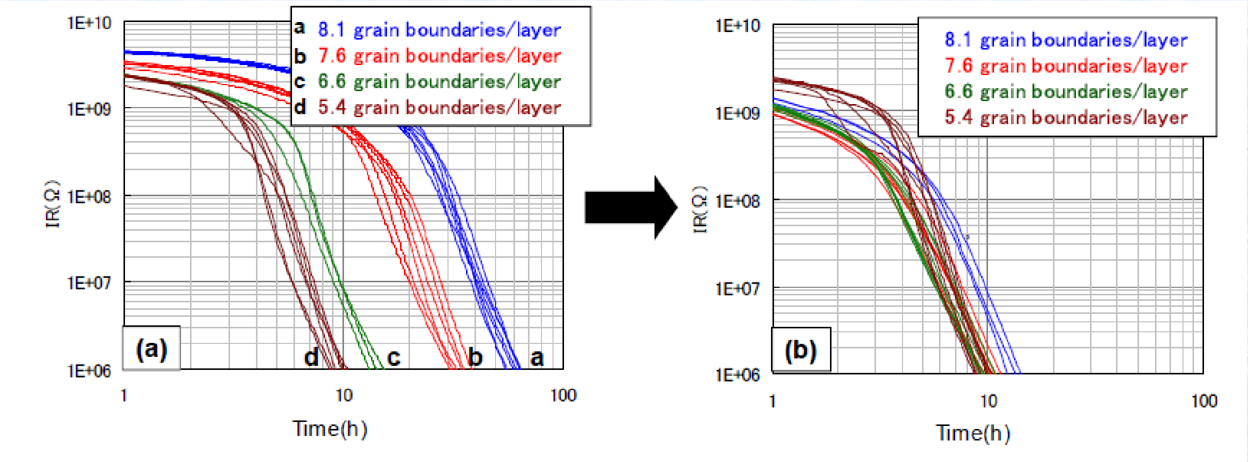
Microstructure Determines the Rated Voltage of BME Capacitors

CAP ID	Grain Size (μm)	Dielectric Thickness(μm)	# of grains per layer	Voltage per Grain
A08X22525	0.305	3.89	12.75	1.96
B08X10525	0.400	4.60	11.50	2.17
C08X22525	0.320	3.80	11.88	2.11
B08X33425	0.420	5.80	13.81	1.81
A06X10425	0.470	7.89	16.79	1.49
B06X22425	0.340	4.20	12.35	2.02
B04X47325	0.305	4.00	13.11	1.91
C04X47325	0.386	4.40	11.40	2.19
B12X10525	0.421	6.15	14.61	1.71
B12X47525	0.376	4.34	11.54	2.17
C08X56425	0.339	4.00	11.80	2.12
P08X10425	0.790	20.20	25.57	0.98
A06X10516	0.296	3.01	10.17	1.57
A12X10616	0.344	3.51	10.20	1.57
C04X10416	0.332	3.40	10.24	1.56
A08X47416	0.319	3.75	11.76	1.36
B12X68416	0.375	6.21	16.56	0.97
C08X22516	0.224	3.81	17.01	0.94
C12X10616	0.264	2.80	10.61	1.51
B08X22516	0.340	3.23	9.50	1.68
B08X56416	0.373	4.21	11.29	1.42
C08X47516	0.230	2.49	10.83	1.48
B12X10516	0.475	7.82	16.45	0.97
B04X10416	0.342	3.05	8.91	1.80
B12X10606	0.365	3.11	8.51	0.74
B04X10406	0.323	2.50	7.74	0.81
B04X56306	0.407	3.00	7.37	0.85
B06X10506	0.426	2.80	6.57	0.96
C08X10606	0.330	2.23	6.76	0.93
B08X22506	0.419	3.42	8.16	0.77
A12X22606	0.309	1.82	5.90	1.07
B06X22406	0.373	4.01	10.76	0.59
P06X10405	0.770	12.60	16.36	0.39

- A number of BME capacitors from different manufacturers with different chip size, capacitance, and rated voltage have been processed for microstructure analysis
- At a given rated voltage, the V_{grain} is almost constant! It decreases with decreasing rated voltage
- Similarly, number of grains per dielectric layer also does not change much when the rated voltage is the given
- **The rated voltage is determined by the microstructure of BME capacitors**

$$\boxed{Rated\ Voltage \sim V_{grain} \sim V_{applied} \times \left(\frac{\bar{r}}{d}\right)}$$

Reliability vs. Microstructure Parameter $\left(\frac{d}{\bar{r}}\right)$



- Mean-time-to-failure (MTTF) data as a function of number of grains per dielectric layer has been measured at 150ºC and 10KV/mm
  - More grains per dielectric layer, longer the MTTF
  - When voltage per grain is normalized to a constant value, the MTTF data are identical to a single grain

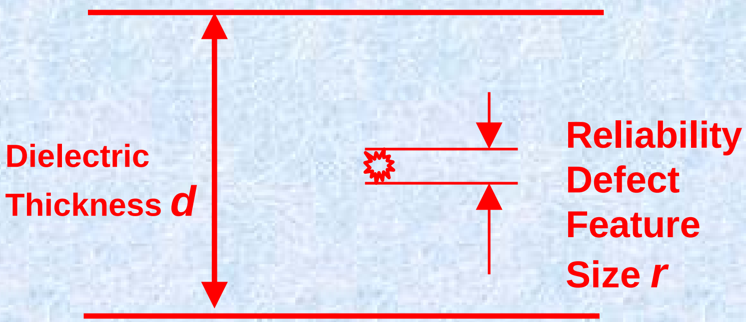
Prokopowicz and Vaskas Equation: $$MTTF = \frac{C}{V^n} \cdot e^{\left(\frac{E_a}{kT}\right)}$$

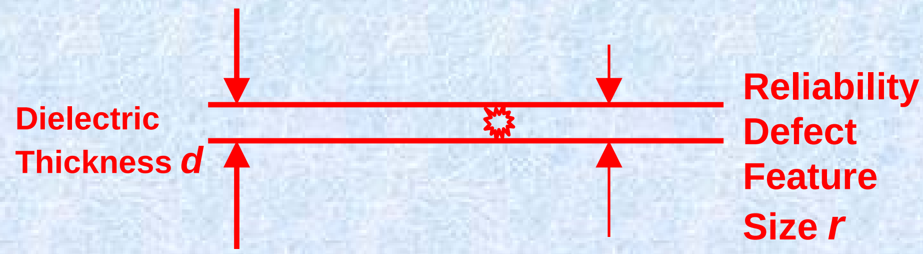
At a given temperature: $$MTTF = \frac{c}{{V_{grain}}^n} = \frac{c}{\left[\frac{V_{applied}}{\left(\frac{d}{\bar{r}}\right)}\right]^n} = \frac{c}{{V_{applied}}^n} \times \left(\frac{d}{\bar{r}}\right)^n$$

BME Capacitor Reliability: Reliability Defects

- Reliability failure is caused by reliability defects
- Quality Defects and Reliability Defects:
  - **Quality Defects:** refer to deficient products or components at present, particularly deficient parts that are out of the standard specifications; quality is generally expressed in percentages.
  - **Reliability Defects:** refer to failures that might occur in the future inside a product that has been working well so far. Therefore, reliability must be regarded as a ratio expressed in terms of units of time.
- Reliability defects may behave in two ways:
  - They can be benign for the rest of the product life without causing a failure
  - They can be catastrophic depending on the feature size and the level of external stress
- It is equivalent to increase external stress level:
  - To increase the applied voltage for a given dielectric thickness
  - To decrease the dielectric thickness at a constant voltage

BME Capacitor Reliability: Reliability Defects (Cont'd)





Dielectric layer reliability**:** $R_i(t) \to 1, when\ d \gg r; R_i(t) \to 0, when\ d \approx r.$

For Weibull model: $R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \cdot \left[1 - \left(\frac{r}{d}\right)^{\xi}\right]$

Since: $r \approx c \times \bar{r}, \quad \bar{r}\ is\ the\ average\ grain\ size$

We have: $P = \left[1 - \left(\frac{r}{d}\right)^{\xi}\right] = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right], \quad (\alpha \geq 5)$

***P* is a geometric factor that determines the dielectric reliability with respect to the microstructure of an MLCC.**

BME Capacitor Reliability: Reliability Defects (Cont'd)

With External Stress: $\eta(V,T) = \frac{C}{V^n} \cdot e^{-\frac{E_a}{kT}}$

We have: $R_i(t) = R_w(t) \cdot \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right] = e^{-\left[\frac{t}{C} \cdot V^n \cdot e^{\frac{E_a}{kT}}\right]^{\beta}} \cdot \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right], \alpha \geq 5$

In general: $R_w(t \leq \eta) = e^{-\left[\frac{t}{C} \cdot V^n \cdot e^{\frac{E_a}{kT}}\right]^{\beta}} = 1$

So finally, *single layer dielectric reliability* can be simplified as:

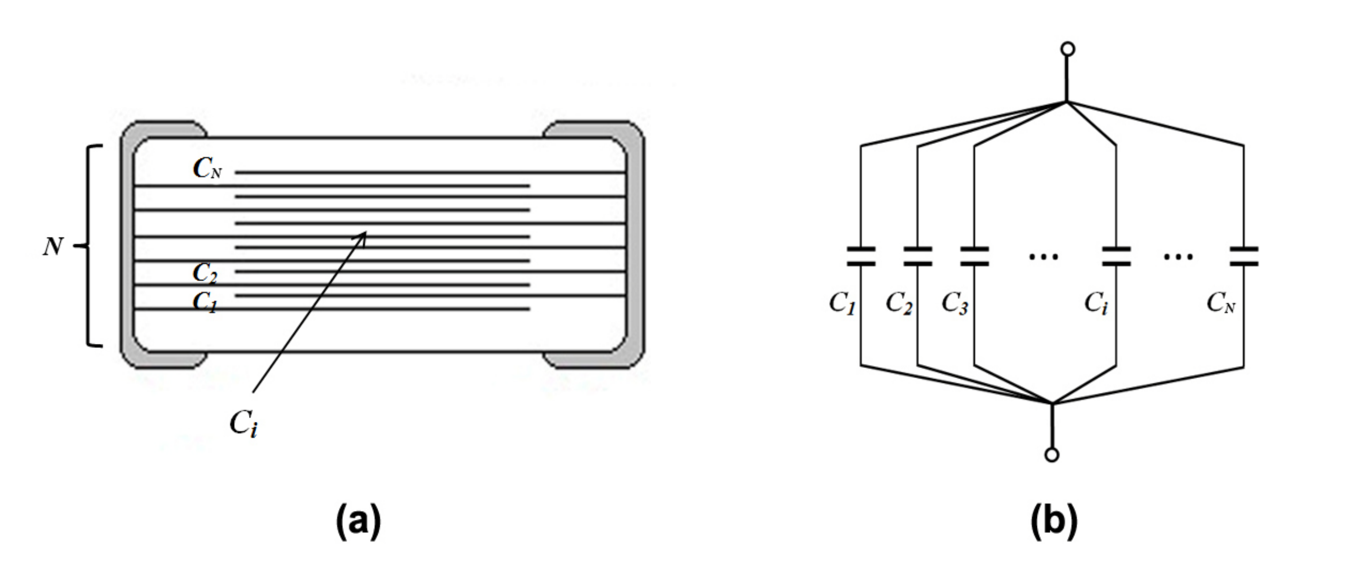
$$R_i(t \leq \eta) \approx \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]$$

α is an empirical constant that depends on the processing conditions and microstructure of a ceramic capacitor.

α ≈ 6 (V ≤ 50) and α ≈ 5 (V >50) For BME MLCCs

α ≈ 5 for most PME MLCCs

BME Capacitor Reliability: From Single Layer to Multilayer

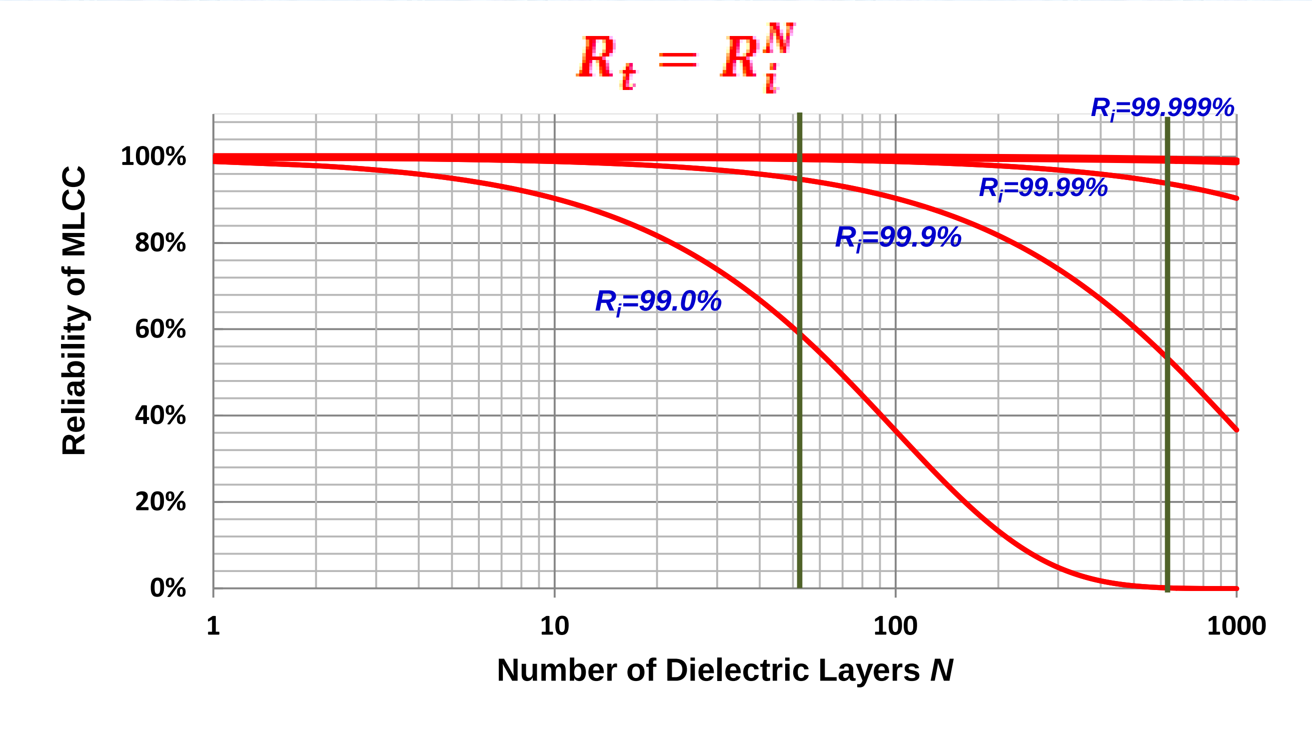


Total capacitance: $C_t = C_1 + C_2 + C_3 \ldots + C_i \ldots + C_N = N \cdot C_i$

Total reliability: $R_t = R_1 \times R_2 \times R_3 \ldots \times R_i \ldots \times R_N = R_i^N$

$R_i(t)$: Single dielectric layer reliability, as discussed earlier

BME Capacitor Reliability: From Single Layer to Multilayer



- The reliability of an MLCC R_t decreases with increasing N
- The value of N can be as high as 1000!

$$\varphi(N, d, \bar{r}, S) = R_t(t < \eta) = R_i(t < \eta)^N = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^N, \qquad (\alpha \geq 5)$$

Reliability Model of BME Capacitors

$$R(t) = \varphi(N, d, \bar{r}, S) \times AF(V, T) \times \gamma(t)$$

$$= \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} \times \left\{ \mathbf{p} \times e^{-\left[\frac{t}{\frac{A}{V^{n}} \cdot e^{\left(\frac{E_{a1}}{kT}\right)}}\right]^{\beta_1}} + (1 - \mathbf{p}) \times e^{-\left[\frac{t}{Ce^{-bE} \cdot e^{\left(\frac{E_{a2}}{kT}\right)}}\right]^{\beta_2}} \right\}$$

Key Issues

- BME capacitors can't be screened to be high-reliability, they have to be made for space-level applications
  - Practices by individual manufacturers are based on lessons learned
  - Need better understanding of failure mechanisms, and quality on high reliability (As has been discussed previously)
  - Design rules
    - Dielectric thickness vs. rated voltage
    - Number of dielectric layers
    - Margins (JAXA guidelines)
    - Chip sizes
  - Raw Materials Control
    - How to control
    - Requires lot specific verification
  - A Specification Controlled Drawing (SCD) in the format of GSFC S-311 document is in development

Key Issues (Cont'd)

- Different manufacturers, different behaviors
  - Two BMEs with same cap, chip size, and rated voltage can reveal quite different reliability life
  - To team up with ONE manufacturer: like ESA and AVX
  - Need to find a supplier to team up and also find a way to balance the sole source supplier (for FY14)
- Almost all BME capacitors are manufactured outside USA
  - In-Process Inspection would be performed for each production lot during the qualification. The inspection should be performed as per Table below
  - The raw material control and lot inspection shall follow MIL-PRF-123, paragraph 4.5.2.1.

In-Process Inspection Plan

In-process inspection	Requirement MIL-PRF-123	Test method MIL-PRF-123	Sample size
Nondestructive internal examination (C-SAM)	Paragraph 3.5	Paragraph 4.6.1	100%
Pre-termination destructive physical analysis	Paragraph 3.6	Paragraph 4.6.2	80 (1)
Visual examination	Paragraph 3.7	Paragraph 4.6.3	100%
Post termination, unencapsulated destructive physical analysis	Paragraph 3.15	Paragraph 4.6.11	40 (0)

***: 0.65 AQL for J size for normal inspection per ANSI/ASQ Z 1.4. AQL for MIL-PRF-123 is 1.50 for the same lot size and inspection level.**

Key Issues (Cont'd)

- Screening of commercial BMEs for high-reliability has been practiced at NASA Goddard (*Non-critical missions only*)
  - All BME capacitors are commercial, made for high volume, high volumetric efficiency: i.e., highest capacitance/volume
  - Select units from various suppliers (typically 100% screened and meeting a certain level of reliability: e.g., *automotive grade*) with moderate cap values, and perform significant voltage derating
  - Evaluation is still in progress (*to be completed in FY14*)
  - The results will help to develop an independent section for IEEE-INST-002 for BME capacitors (*for FY14*)

Selection of BME Capacitors for High Reliability Applications

Table 1. Selection criteria of BME capacitors for space-level applications

Inspection/Test	Test Methods, Conditions, and Requirements	Part Type/Level 1	2	3
1. Dielectric Type	The voltage temperature characteristic shall be referenced to the +25°C value and shall be applicable over the entire temperature range of -55°C to +125°C. Dielectric type C0G (N) shall be 0±30 ppm/°C, and dielectric type X7R (X) shall be +15, -15%.	X	X	X
2. Destructive Physical Analysis (DPA)	Destructive physical analysis shall be performed on each inspection lot of capacitors supplied to this specification. - DPA sample size shall follow MIL-PRF-123, Table XVII. - DPA shall be performed in accordance with the requirements of MIL-PRF-123, paragraph 4.6.1, except that paragraphs 3.4.1 and 3.4.2 shall be replaced with paragraph 2.3 herein. - Margin defects shall be determined using EIA 469, paragraph 5.1.3.	X	X	X
3. Microstructure Analysis	BME capacitors shall not be used for high reliability space applications if the following construction and microstructure criteria are not satisfied	X	X	X
3.1. Nickel Electrodes	All BME capacitors shall use nickel for internal electrodes			
3.2.Capacitor Structure Parameter	The structure parameter of a BME ceramic capacitor *P* with respect to its microstructure and construction details can be expressed as: $\boldsymbol{R = \left[1 - \left(\frac{\bar{a}}{d}\right)^{\alpha}\right]^{N}}$ Where: d = Dielectric thickness that is the actual measured thickness of the fired ceramic dielectric layer. Voids, or the cumulative effect of voids, shall not reduce the total dielectric thickness by more than 50%. ā= Averaged ceramic grain size measured per the linear interception method. N = Number of individual dielectric layers. α= An empirical parameter that is applied voltage-dependent: α= 6 for V ≤ 50V, and α= 5 for V > 50V.			
3.3. Acceptance Criterion for X7R	The calculated *R* shall be greater than **1.00000** for X7R dielectric			
3.4. Acceptance Criterion for C0G1/	The minimum dielectric thickness shall be greater than 3.0 micrometers for the NPO dielectric at V ≤ 50V and greater than 5.0 micrometers at V > 50V; *N* should be less than 300.			
4. Maximum dielectric constant	The maximum dielectric constant shall be 4000 for the X7R dielectric and 100 for the C0G dielectric.	X	X	X
5. Termination	Devices supplied to this specification shall have a termination coating of copper, nickel, or their alloy, or shall be base-metal barrier tin-lead solder (MIL-PRF-123, type Z) plated. Tin-lead solder plating shall contain a minimum of 4% lead, by mass.	X	X	X

1/: BME capacitors with NPO dielectric of $CaZrO_3$ are not ferroelectric and the MTTF is not controlled by the grain boundaries, therefore, NPO capacitors have a different selection criterion from those with X7R dielectric.

Selection Criterion and the Number of Zeros

$$R(t < \eta) = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} = 1.00000$$

TABLE V. Product level designator.

Symbol	Product level
C	non-ER
M	1.0 1/
P	0.1 1/
R	0.01 1/
S	0.001 1/

1/ FRL (percent per 1,000 hours).

MIL-PRF-55681, paragraph, 1.2.1.7

BX life to failure rate:

M: B1% life
P: B0.1% life
R: B0.01% life
S: B0.001% life

BX life to Reliability:

M: B1% life $= \eta \cdot \{-ln[R(x_1\%)]\}^{1/\beta}$ **where $R(x_1\%)$ =0.99**
P: B0.1% life $= \eta \cdot \{-ln[R(x_2\%)]\}^{1/\beta}$ **where $R(x_2\%)$ =0.999**
R: B0.01% life $= \eta \cdot \{-ln[R(x_3\%)]\}^{1/\beta}$ **where $R(x_3\%)$ =0.9999**
S: B0.001% life $= \eta \cdot \{-ln[R(x_4\%)]\}^{1/\beta}$ **where $R(x_4\%)$ =0.99999**

Number of zeros represents the level of failure rate!

Qualification Plan

- Qualification Inspection shall be performed at a laboratory acceptable to the qualifying agency on sample units produced with equipment and procedures normally used in production

BME Capacitors Qualifications

Inspection/Test	Test Methods, Conditions, and Requirements	Sample Size		
		AEC-Q200	MIL-PRF-123	This Document
Group I				
1. Thermal Shock	MIL-STD-202, Method 107, Condition B, min. rated temp. to max. rated temp. (when specified in the product specification/ data sheet, the min. and max. "storage" temp. shall be used in lieu of the specified operating temp.)	N/A	182	200
2. Voltage Conditioning (Burn-In)	4 x rated voltage, 125 °C, 160 hours (Level 1) 125 °C, 96 hours (Level 2) 125 °C, 48 hours (Level 3)	N/A	182	200
3. Electrical Measurements	As specified			
Capacitance Dissipation Factor DWV Insulation Resistance	MIL-STD-202, Method 305 MIL-STD-202, Method 305(shall be 306) MIL-STD-202, Method 301 MIL-STD-202, Method 302	100%	100%	100%
Group II				
1. Visual and Mechanical Examination, material, design, construction and workmanship	Visual and sample-based mechanical inspection to be performed to requirements of applicable military specification	30	15(1)	15(0)
2. Destructive physical analysis	Destructive physical analysis shall be performed on each inspection lot of capacitors supplied to this specification. - DPA shall be performed in accordance with the requirements of MIL-PRF-123, paragraph 4.6.1, except that paragraphs 3.4.1 and 3.4.2 shall be replaced with paragraph 2.3 herein. - Margin defects shall be determined using EIA 469, paragraph 5.1.3.	10	15(1)	15(0)

Qualification Plan (Cont'd)

BME Capacitors Qualifications (Cont'd)

Inspection/Test	Test Methods, Conditions, and Requirements	Sample Size: AEC-Q200	Sample Size: MIL-PRF-123	Sample Size: This Document
Group IIIb - Nonleaded devices				
1. Terminal strength	AEC-Q200-006; MIL-STD-202, Method 211	30	12(1)	15(0)
2. Solderability	MIL-STD-202, Method 208	15	12(1)	15(0)
3. Resistance to soldering heat	MIL-STD-202, Method 210; condition C	30	12(1)	15(0)
Group IV				
1. Voltage-temperature limits	Capacitance change over the range of temperatures and voltages specified shall not exceed limits of specification. NPO Capacitors shall be tested in accordance with MIL-PRF-123 BP characteristics.	N/A	12(1)	15(0)
2. Moisture resistance	MIL-STD-202, Method 106 20 cycles (first 10 cycles with rated voltage applied) DWV, IR and DC to specification **AEC-Q200-006 removed this test in version D**	77	12(1)	15(0)
Group V				
1. Humidity, steady state, low voltage 1/	Not required for BME capacitors	N/A	12(0)	
1. Biased Humidity	MIL-STD-202, Method 103 **AEC-Q200 Biased Humidity**	77	N/A	125(0)
2. Beam Load Test	**AEC-Q200 -003**	30	N/A	15(0)
3. Resistance to solvents	MIL-STD-202, Method 215	5	12(1)	15(0)
Group VI				
Life 2/	MIL-STD-202, Method 108 T_{test} = maximum operating temperature V_{test} = 2 X Vrated (**1X Vrated perAEC-Q200-006**) Duration: 4,000 hours for level 1, 2,000 hours for levels 2 and 3 IR, ΔC, and DF to specification	77	123(1)	125(0)

Note 1: Humidity, steady state, low voltage in group V is not required. (*This test is required for PME capacitors with potential micro cracks and silver electrode migration. However, the DPA of significant number of virgin BME capacitors did not reveal any cracks and the nickel migration is insignificant when comparing to that of silver.*)

Note 2: Life test, AQL=0.10 for K Size normal inspection per ANSI/ASQ Z 1.4

Voltage Derating of BME capacitors

- Derating shall be performed by the designer in accordance with the requirements set in Table below for different dielectric types.
- Voltage derating is accomplished by multiplying the maximum operating voltage by the appropriate derating factor appearing in Table below.
- The derating factor applies to the sum of peak AC ripple and DC voltage applied.
- Voltage derating factor of 0.6 was determined in this study. A 10V unit will be derated to 0.4X10V = 4V
- Ambient temperature was determined with ripple current simulation results

Voltage Derating Chart for BME Capacitors

Dielectric Type	Voltage Derating Factors	Maximum Ambient Temperature
X7R	0.6	110°C
NPO	0.2	125°C

Summary

- A general reliability model for BME capacitors has been developed with respect to the acceleration function and BME capacitor's structural parameters
- Improved reliability lifetime calculations can be achieved with the proposed reliability model for BME capacitors
- As part of this fiscal year's deliverables, A guideline documentation on Selection, Qualification, Inspection, and Derating of BME capacitors has been completed and uploaded to NASA NEPP website