NEPP Capacitor Update - BME Technology for High-Reliability Applications

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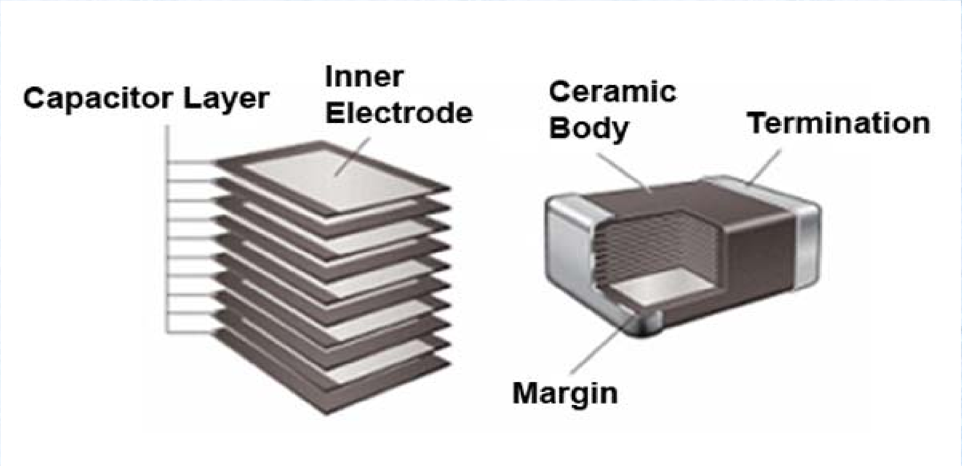
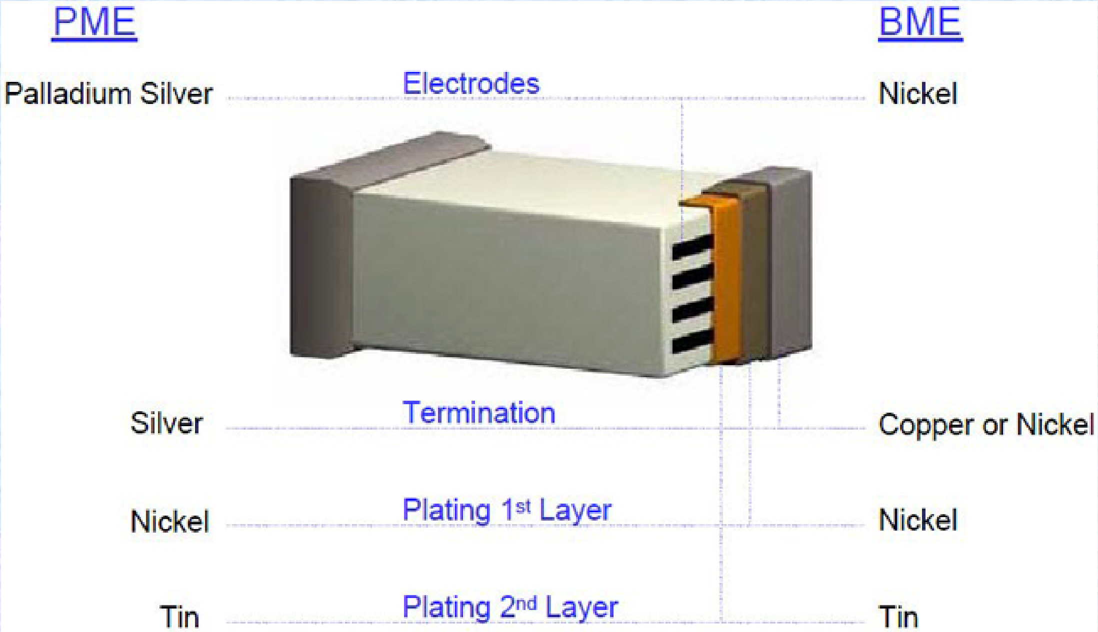
What are Multilayer Ceramic Capacitors (MLCCs)?



- **MLCCs are monoliths of dielectric oxide and alternated internal metals co-fired at around 1350 ^{o}C**
- **Capacitance:** $$C = \varepsilon_0 \cdot \varepsilon_r \cdot N \cdot \frac{S}{d}$$
- **Challenges:**
  - **Dielectric needs oxygen for insulating resistance (IR)**
  - **Electrode needs no oxygen for conducting**
- **Solution:**
  - **The first MLCCs were made with oxidation resistance *precious metal electrodes* (PME) made from combinations of Ag, Pt, and Pd**

Why Change from PME to BME?



- **High materials cost plus questionable supply assurance forced an industry shift from PME to *base metal electrode* (Ni, Cu) technology (BME) for commercial applications**
  - **Palladium: $675/oz on 1/20/2012 ($1080/oz in 2/2001)**
  - **Nickel: $0.61/oz on 1/20/2012 ($1.65/oz in 4/1007)**
  - **Russia controls 90% of world palladium supply?**
- **The change was totally driven by economics!**

PME vs. BME: The Reality

- 99% of MLCCs worldwide are manufactured using BME technology
  - Lion’s share of research activity and technical support
  - Complete selection of products with short lead time
  - Low cost
- NASA had used BME capacitors for some non-critical applications
  - NASA cautious to new technologies due to type of business
  - Restrictions in MIL-PRF-123
  - Concerns regarding the reliability of BME technology
- It is just a matter of time to begin using BME capacitors for high reliability applications
  - Several hybrid manufacturers have used BME capacitors for space-level products
  - Comparable reliabilities and better performance
  - Limited product selection for PME products and long lead time
  - BME technology is more than 20 years old
- It is about time to take action!

A Glimpse of BME Technology

- **BMEs represent a commercial technology, developed for high volumetric efficiency ($\mu F/cm^3$) applications, not for high-reliability applications. However, BME capacitors can be manufactured for high-reliabilities comparable to PME capacitors.**

- **To meet the high demand for volumetric efficiency, manufacturers have pushed the technology envelope to the limit:**
  - **Number of dielectric layers N: >500 → 1000**
  - **Dielectric thickness: <1.0 μm, → 0.5 μm or less**

- **To meet the high demand for volumetric efficiency, suppliers and end users have mutually agreed to lower the bar for reliability:**
  - **Life test: 2X rated voltage → 1.5X, 1.25X, 1.0X**
  - **Dielectric: X7R characteristics → X5R**

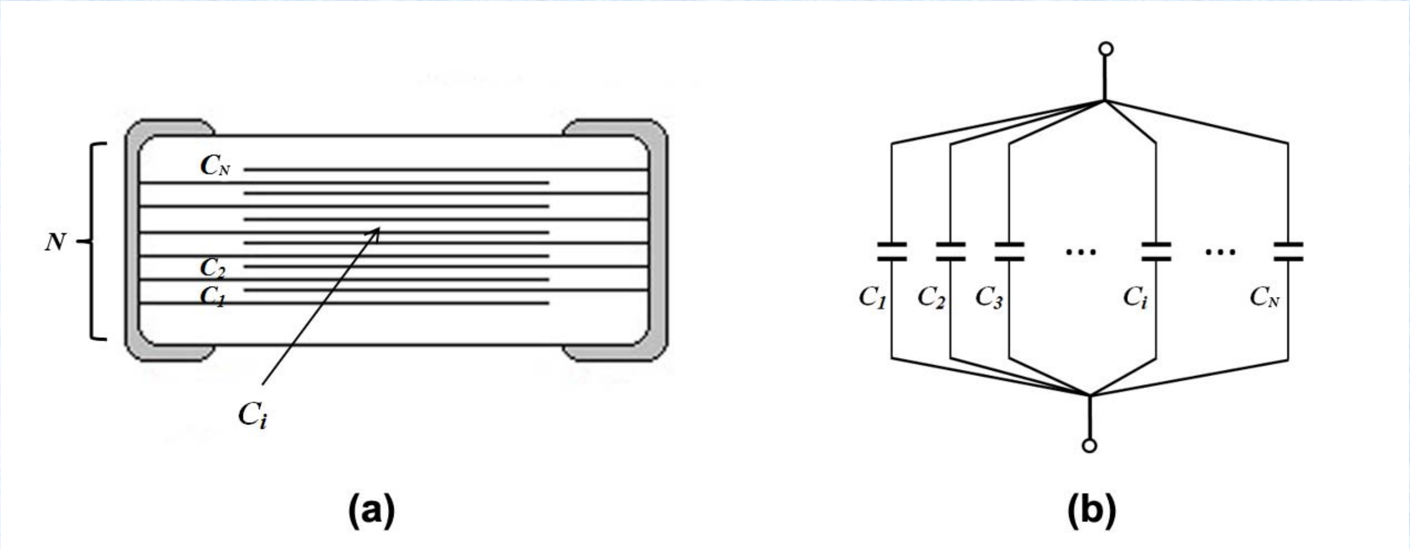
MLCCs for High-Reliability Applications

- The reliability of an MLCC device is determined by its microstructure. An MLCC can't be qualified for high reliability; it has to be made for it!

- Historically, the minimum dielectric thickness requirement per MIL-PRF-123 has ensured that most PME capacitors have been able to be used for high-reliability applications for many years without major issues.
  - MIL-PRF-123, paragraph 3.4.1: Dielectric parameters. Capacitors supplied to this specification shall have a minimum dielectric thickness of 0.8 mil (20 μm) for 50 volt-rated capacitors or 1 mil (25 μm) for capacitors with ratings above 50 volts.
  - MIL-PRF-123 requires all MLCCs for high-reliability and space projects to be PME capacitors.

- A simple dielectric thickness requirement may not qualify BME products for high-reliability applications due to their complexity and diversity with regard to capacitor structure.

What Determine the Reliability of a MLCC?
1. Number of Dielectric Layers *N*

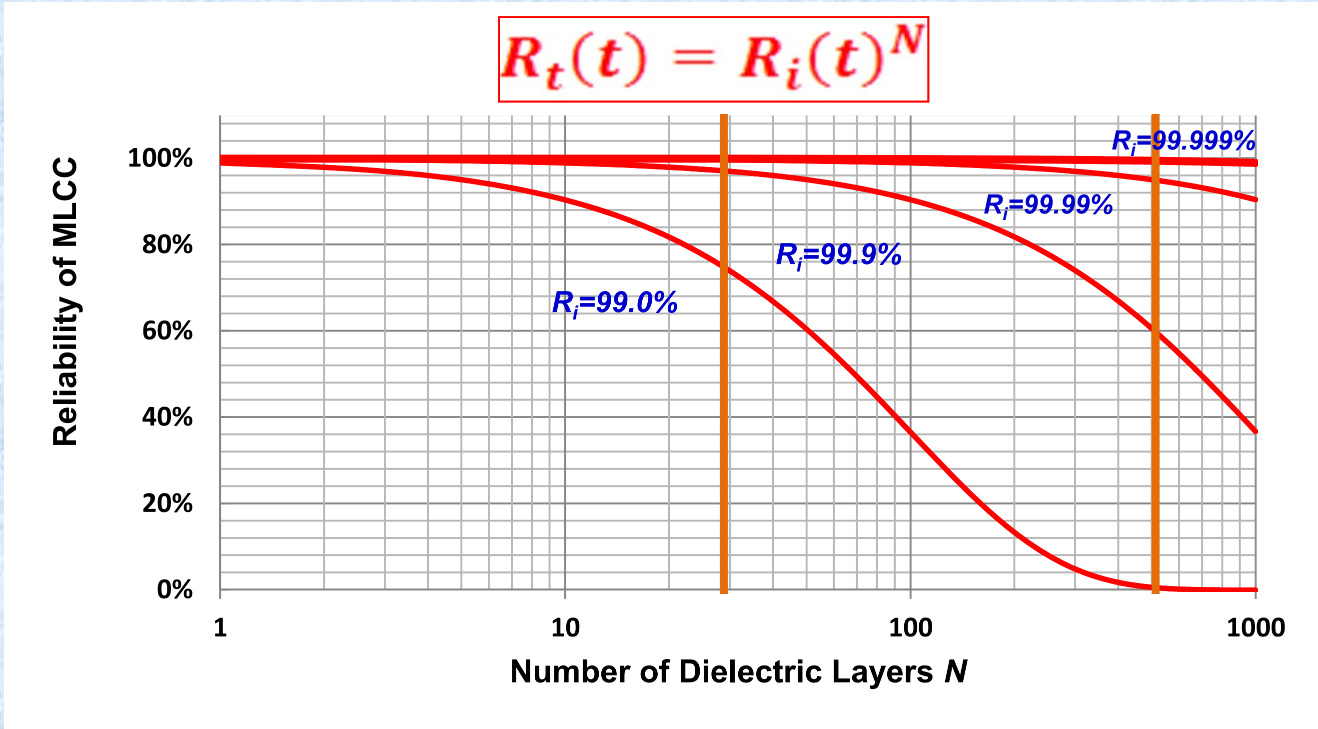


Total capacitance: $C_t = C_1 + C_2 + C_3 \dots + C_i \dots + C_N = N \cdot C_i$

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

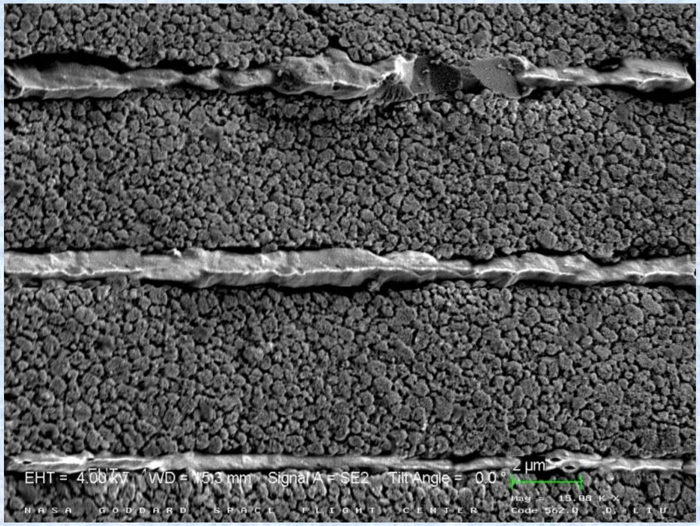
Weibull reliability: $R_i(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ $R_i(t)$: **Dielectric reliability**

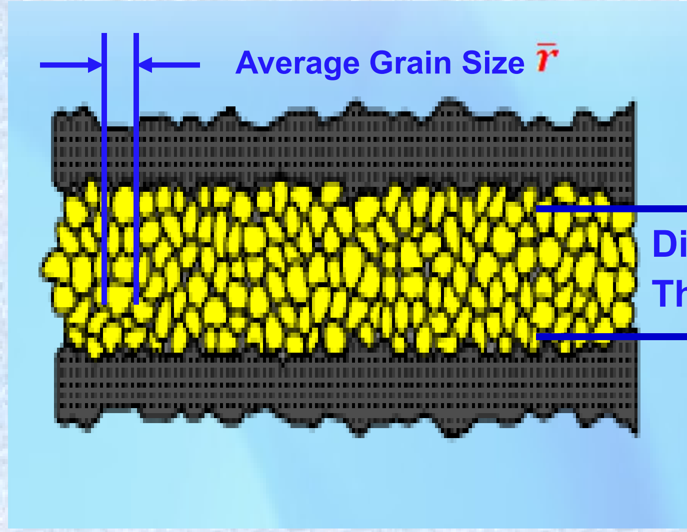
What Determine the Reliability of a MLCC?
1. Number of Dielectric Layers *N*



- The reliability of an MLCC R_t decreases with increasing ***N***. R_t is almost independent from ***N*** if the reliability of the dielectric layer R_i is very close to unity.
- The ***N*** will make the R_t go from bad to worse quickly if R_i declines only slightly, demonstrating the ***amplifying effect*** of ***N***.
- **Most BME capacitors** have a very high ***N*** value, and so they pose higher challenges to the reliability of the single-layer dielectric R_i.

What Determine the Reliability of MLCC?
2. Microstructure Parameter $\left(\frac{d}{\bar{r}}\right)$





- **Important microstructure parameter of a single-layer capacitor:**

$\left(\frac{d}{\bar{r}}\right)$: **Number of stacked grains per dielectric layer**

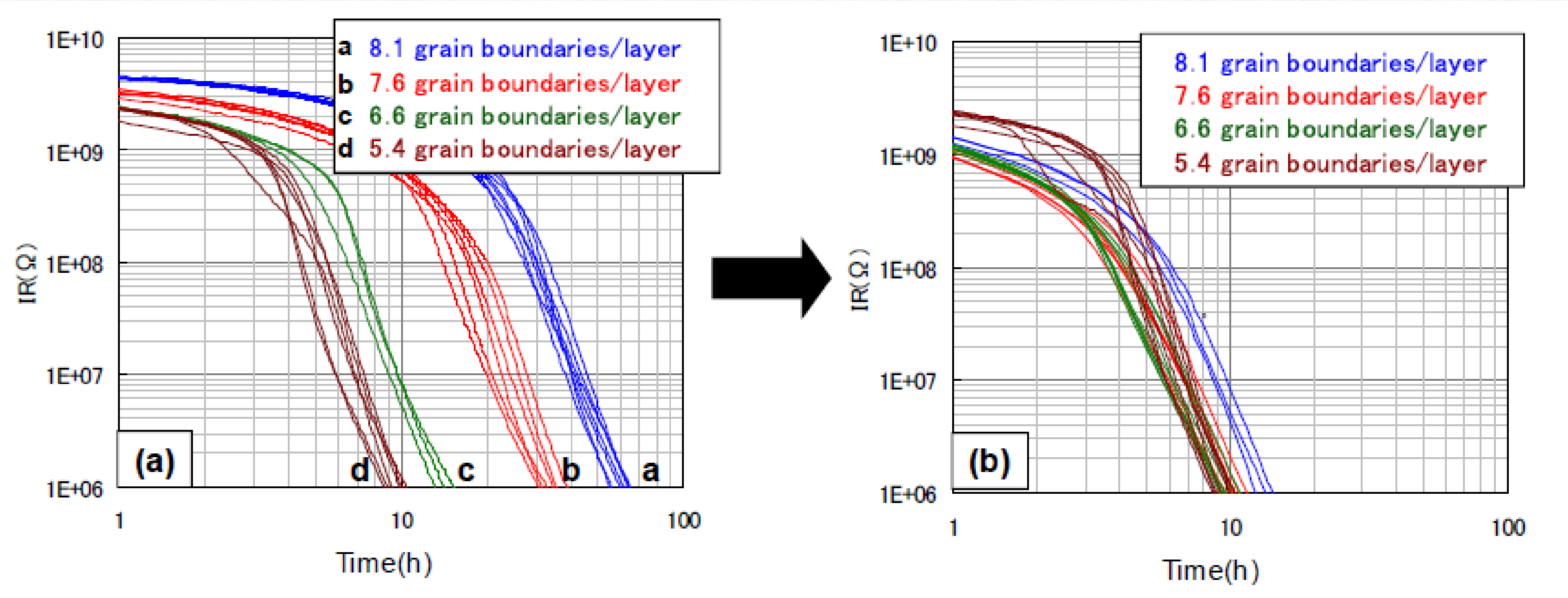
What Determine the Reliability of MLCC?
3. Voltage Robustness vs. $\left(\frac{d}{\bar{r}}\right)$

Capacitor ID	Cap (μF)	Chip Size	Mfg.	Processing Technology	Dielectric Thickness (μm)	Avg. Grain Size (μm)	$\left(\frac{d}{\bar{r}}\right)$
A08X22525	2.20	0805	A	BME	3.5	0.31	11.29
A08X15425	0.15	0805	A	BME	9.8	0.46	21.30
A06X10425	0.10	0603	A	BME	7.6	0.47	16.17
B06X22425	0.22	0603	B	BME	4.2	0.34	12.35
B08X33425	0.33	0805	B	BME	5.8	0.42	13.81
B08X10525	1.00	0805	B	BME	4.6	0.40	11.50
C06X10525	1.00	0603	C	BME	3.1	0.44	7.05
C08X22525	2.20	0805	C	BME	4.0	0.32	10.26

- A number of commercial BME capacitors, all with 25 V rated voltage and various chip sizes and capacitance, have significantly different dielectric thicknesses.
- The number of stacked grains per layer is relatively unvaried, indicating that $\left(\frac{d}{\bar{r}}\right)$ is a determining factor for the rated voltage.

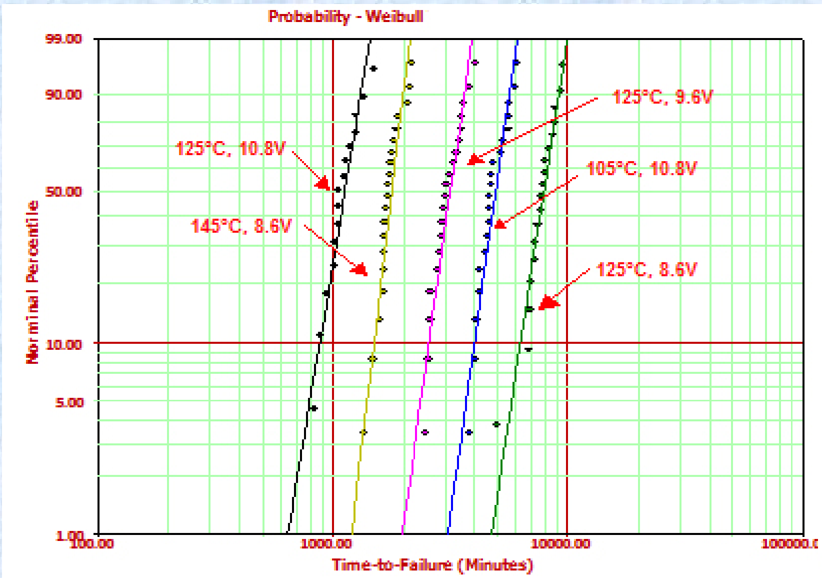
What Determine the Reliability of MLCC?

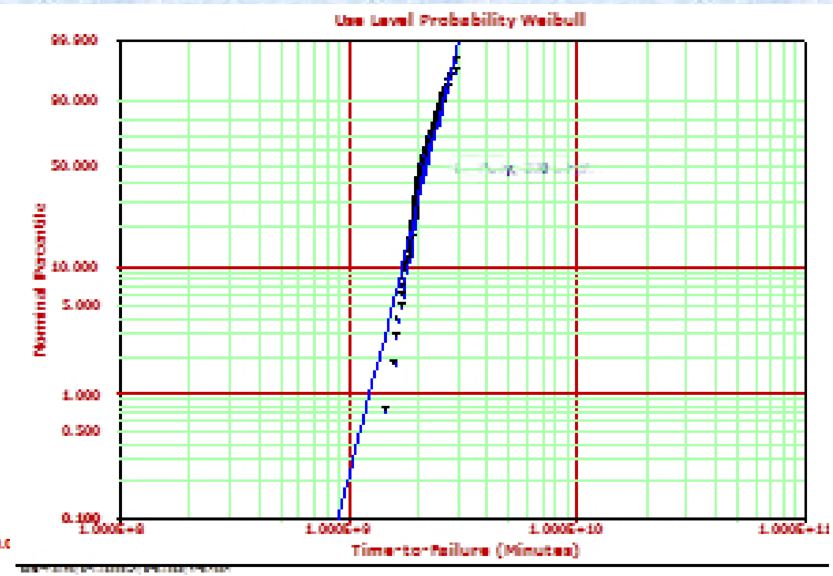
4. Mean-Time-To-Failure (MTTF) vs. $\left(\frac{d}{\bar{r}}\right)$



- MTTF is directly related to the microstructure parameter $\left(\frac{d}{\bar{r}}\right)$.
- Longer MTTF is attainable with higher $\left(\frac{d}{\bar{r}}\right)$ values (left).
- When applied voltage per grain is adjusted to a similar value, all four MLCCs with different $\left(\frac{d}{\bar{r}}\right)$ values show similar MTTF values.

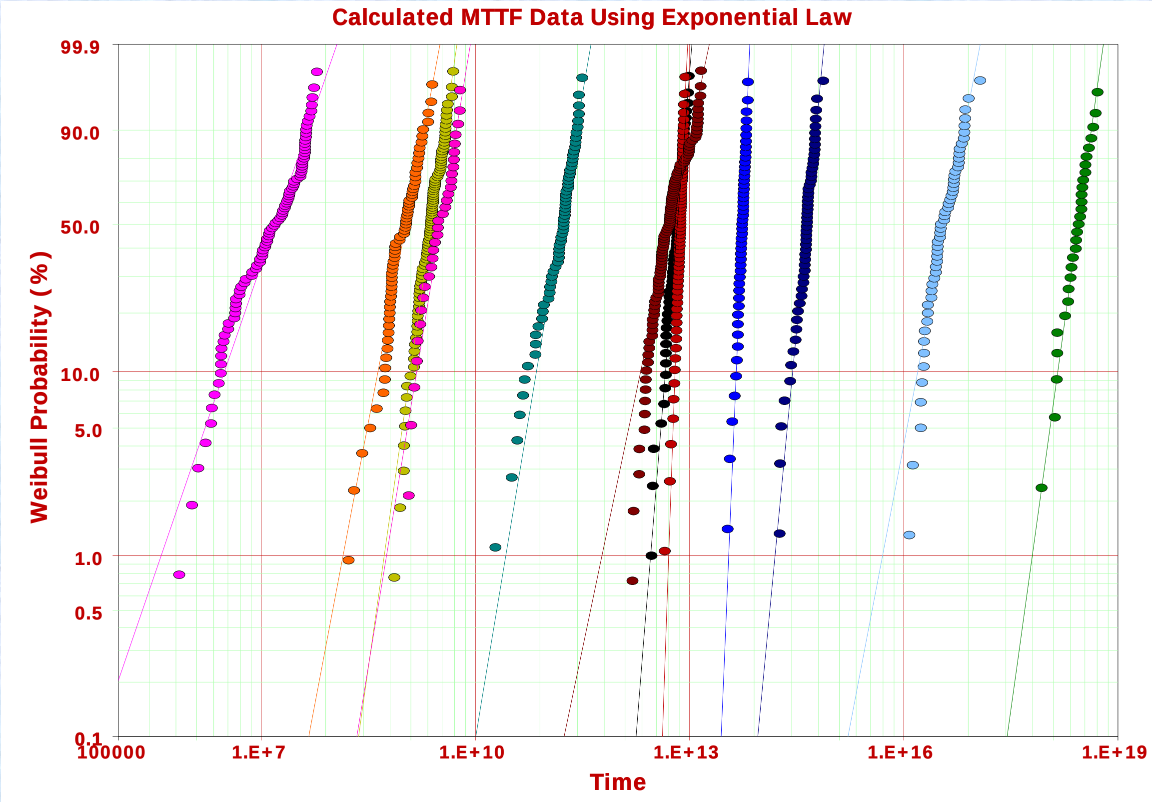
How to Characterize MTTF? HAST





- **Highly Accelerated Stress Testing (voltage and temperature typical):**
  - ***Reverse Power Law (Eyring Model):*** $$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \left(e^{\frac{E_a}{K}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)}\right)$$
- **Use-level Weibull probability plots are extrapolated using a *maximum likelihood estimation algorithm* for each failure obtained at a given overstress condition. *This can be done using ALTA-Pro!***

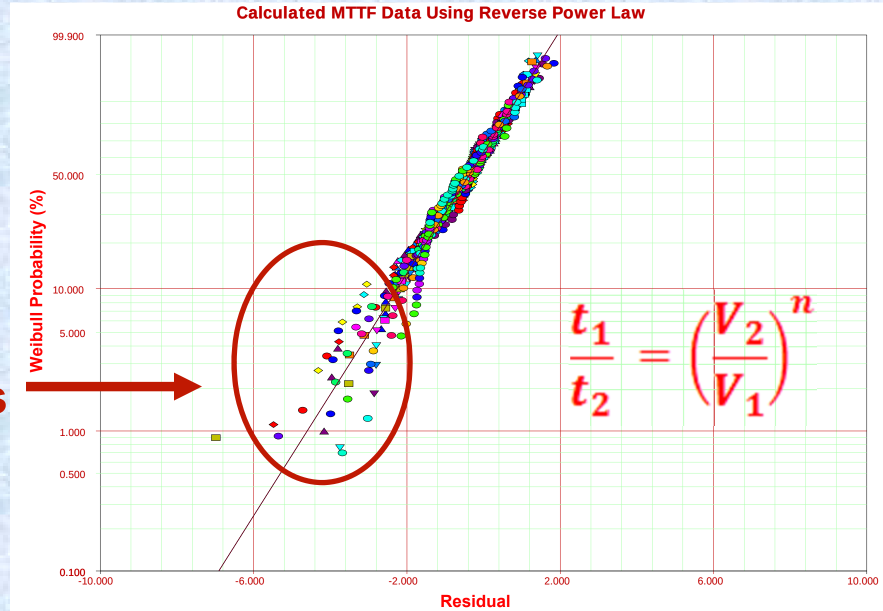
How to Characterize MTTF? HAST (2)



- **Use-level MTTF data for a BME capacitor can be normalized into one plot for better comparison.**
- **In many cases, calculated MTTF using dielectric wearout failure mode is longer than that obtained experimentally. (Why?)**

Reliability of MLCCs: Mixed Failure Modes

Early Failures



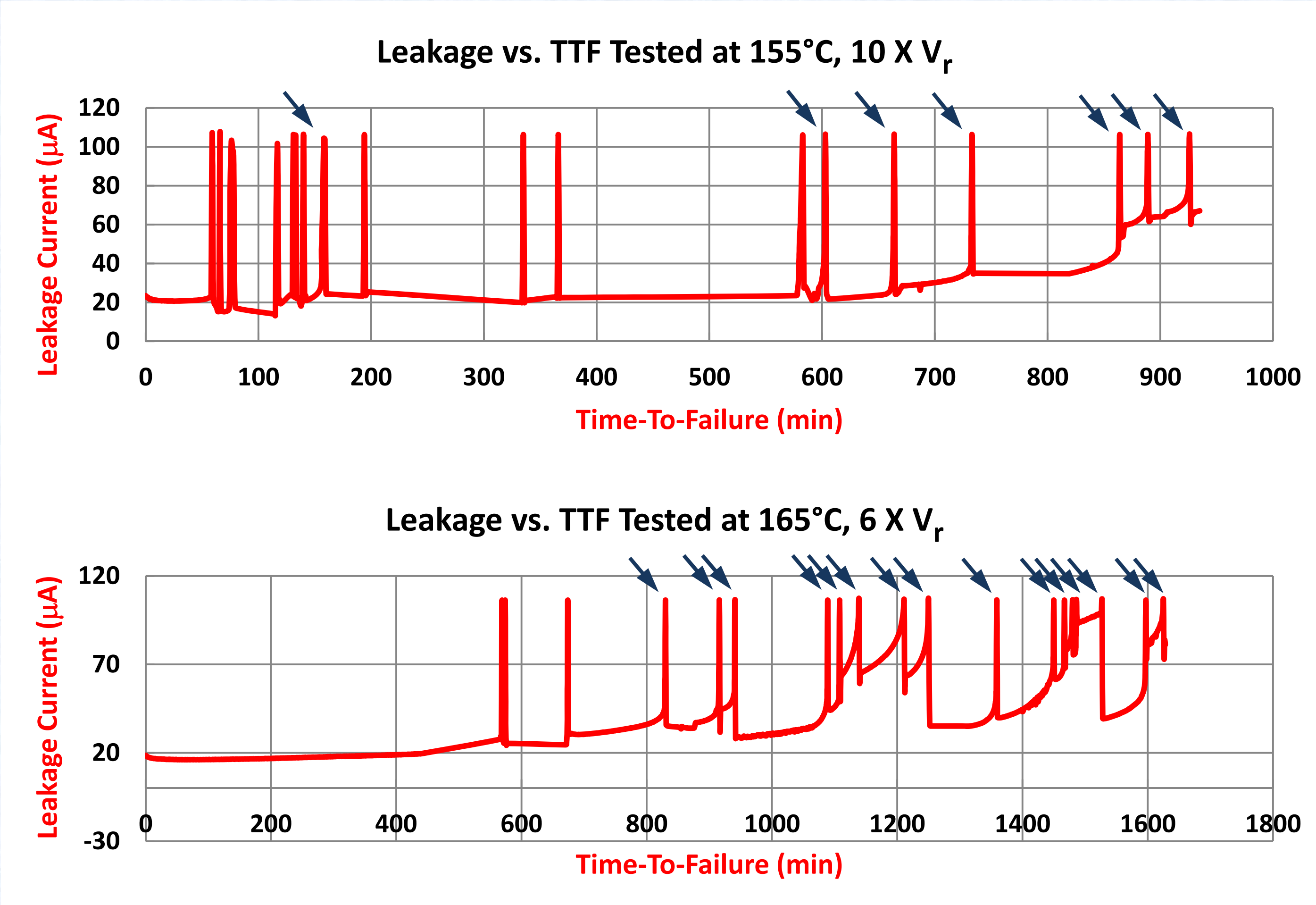
$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n$$

- If the assumed model adequately fits the data, then the residuals should appear to follow a straight line on such a probability plot.
- The standardized residual plot shows scattering and outliers.

$$\hat{e}_i = \hat{\beta}[ln(t_i) - ln(\hat{\eta}(V))]$$

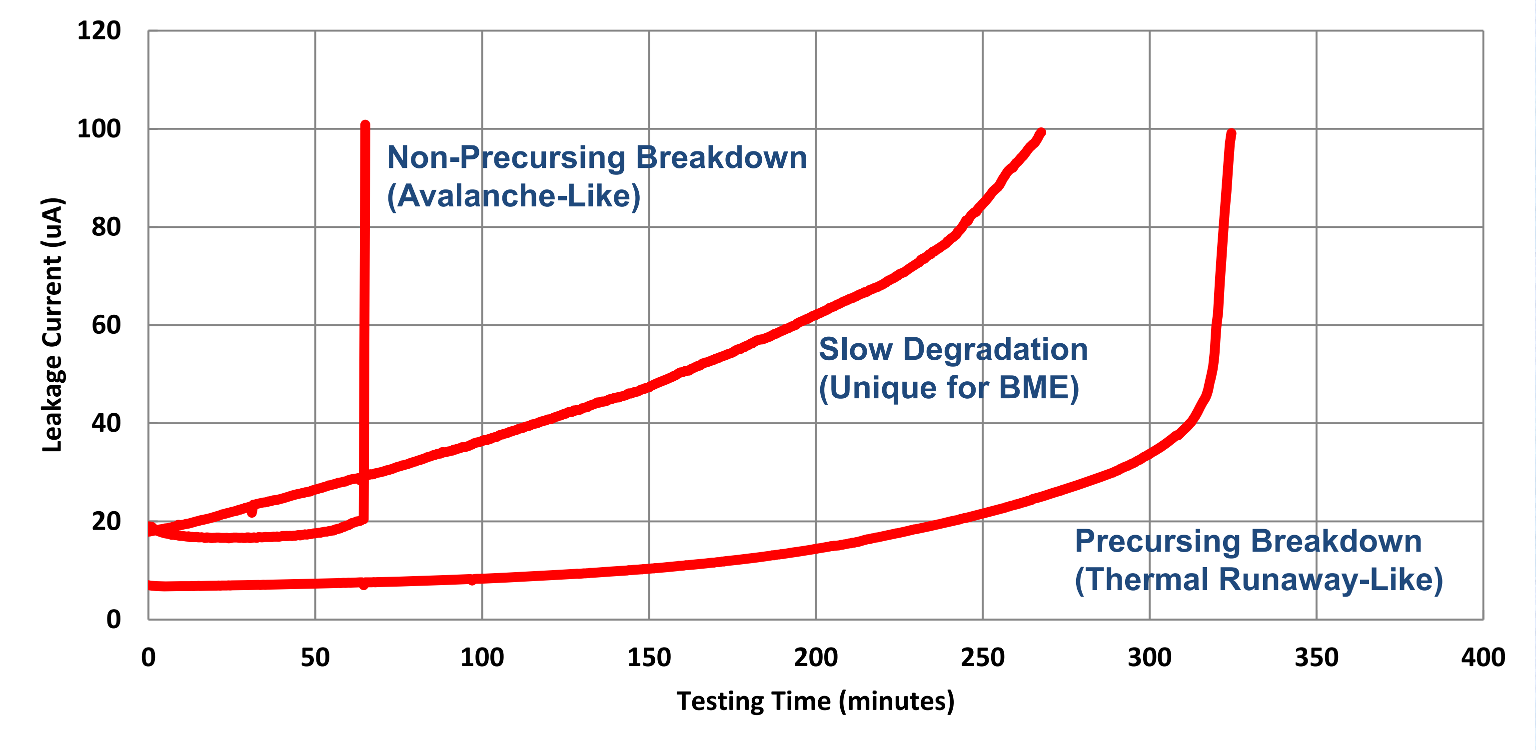
- Two possibilities:
  - Early failures can't be 100% removed (β > 1, failure rate increase with time).
  - The two failure modes are competing with each other. (Under certain conditions, a unit can fail in either one of the two failure modes.)
- Early failures present the worst-case scenario and would determine the reliability of an MLCC!

How to Distinguish the Failure Modes? By Leakage Current



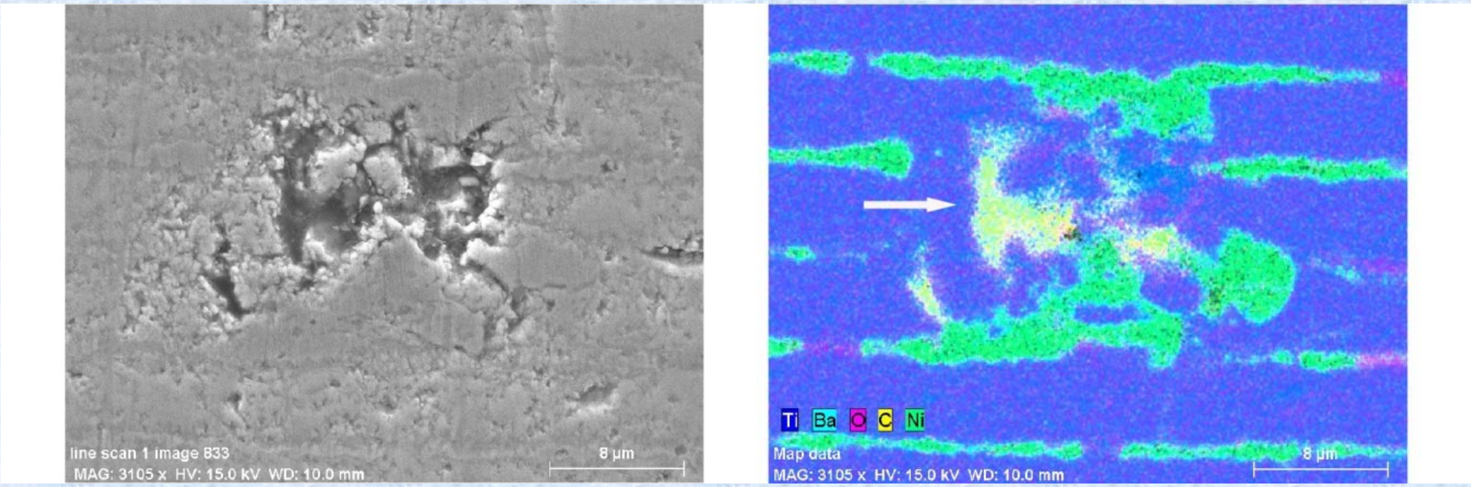
- Leakage current characteristics are experimentally distinguishable: precursing vs. non-precursing. (Arrows indicate *precursing* breakdown.)
- The higher the external stress, the more failures with non-precursing breakdown.

How to Distinguish the Failure Modes? By Leakage Current (2)



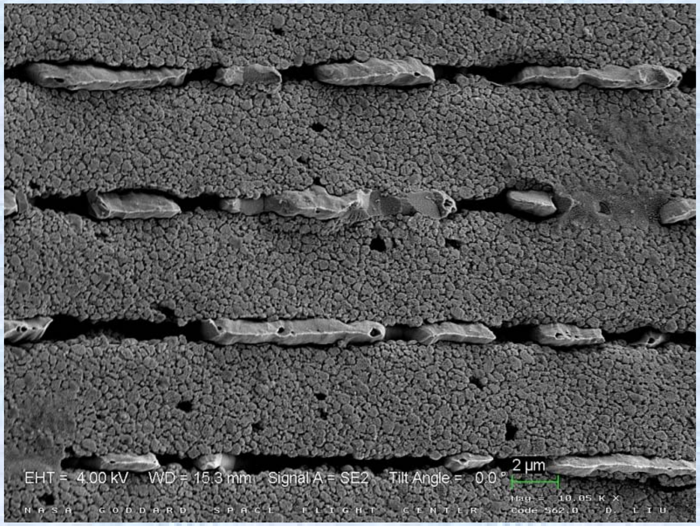
- **Non-precursing breakdown: catastrophic and rapid, no sign of breakdown (*avalanche-like*). *It occurs early and corresponds to early failure defect.***
- **Precursing breakdown: slower and more gradual leakage current increase prior to breakdown (*thermal runaway-like*). *It corresponds to traditional dielectric wearout.***
- **Slow degradation: unique for BME capacitors due to oxygen vacancy migrations. *Indistinguishable* from precursing breakdown mode.**

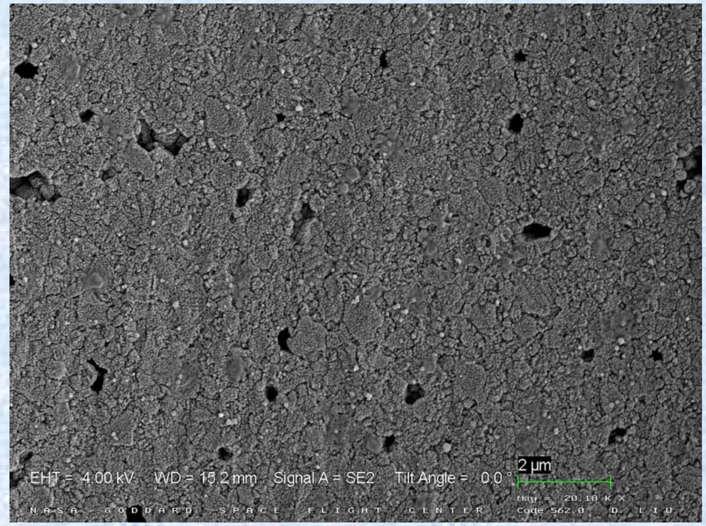
How to Characterize Early Failures: Failure Analysis



- **A number of failure analyses (FA) have been processed for BME MLCCs that failed with precursing leakage breakdown and that failed with non-precursing leakage breakdown.**
- **FA samples that failed with *non-precursing breakdown* normally revealed some visible localized failure sites, likely due to extrinsic processing defects.**
- **High carbon concentrations were often observed at these failure sites. Contaminations were likely introduced during manufacturing (as shown above), i.e., binder residuals.**

How to Characterize Early Failures: Construction Analysis





- **Cross-section SEM examination of 50+ samples per EIA-469D revealed some voids and minor delamination; cracks were rarely observed.**
- **Defect feature size r is generally related to the average grain size $\bar{r}$:**

$$r \approx c \times \bar{r}$$

where c is a constant

A Reliability Model Due to Defects

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

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.**

A Reliability Model Due to 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 many cases: $R_w(t \leq 10^3\ years) = e^{-\left[\frac{t}{C} \cdot V^n \cdot e^{\frac{E_a}{kT}}\right]^{\beta}} = 1$

So finally *a 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

Case Study: Selection of BME MLCCs for High-Reliability Applications

1. **Reliability of an MLCC:** $R_t(t) = R_i(t)^N$

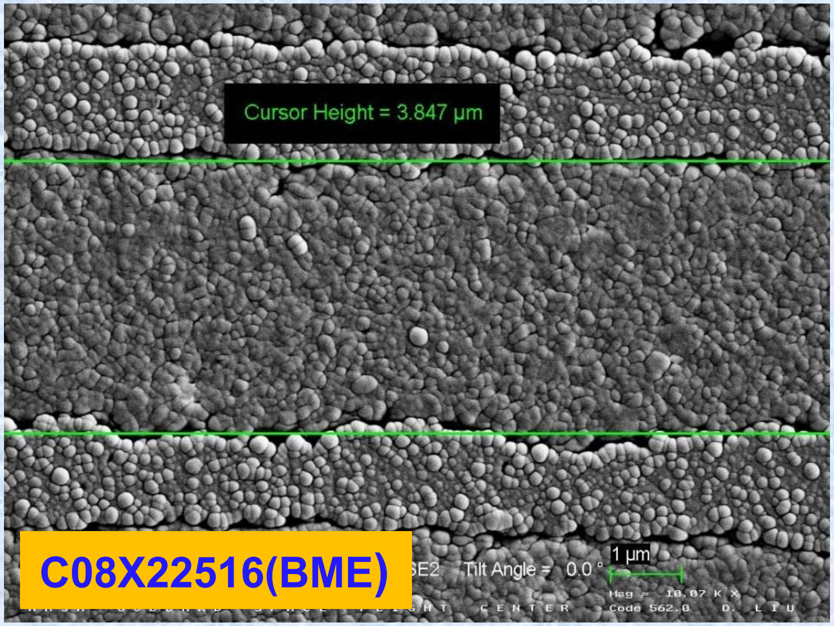
2. **Single-layer dielectric reliability:** $R_i \approx 1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}.$

3. **Reliability with respect to *N* and $\left(\frac{d}{\bar{r}}\right)$:**

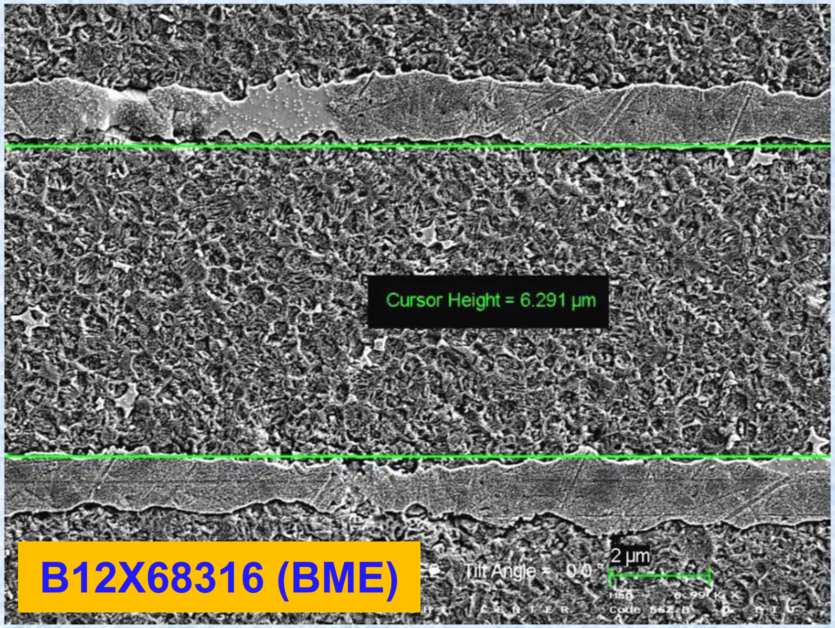
$$R_t = \left[1 - \left(\frac{r}{d}\right)^{\alpha}\right]^{N} \geq 99.999\%$$

Commercial BME capacitors satisfying R_t above will meet the minimum requirements for high-reliability applications

Case Studies: High-Performance BME MLCCs



- 2.2 µF, 16 V, 0805, mfr. C, passed 4000-hr life testing at 125°C at 2X rated voltage
- Meets MIL-PRF-123
- Nano-size grains ≈ 0.11 µm
- 250 dielectric layers
- Dielectric thickness ≈ 3.85 µm



- 0.68 µF, 16 V, 1206, mfr. B, passed 4000-hr life testing at 125°C at 2X rated voltage
- Meets MIL-PRF-123
- Grain size ≈ 0.38 µm
- 64 dielectric layers
- Dielectric thickness ≈ 6.29 µm

When compared with PME MLCCs, high reliabilities can be attained in BME MLCCs with thinner dielectrics.

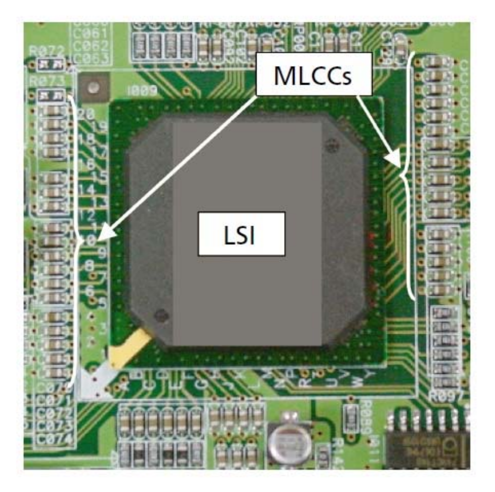
Case Studies: High-Performance BME MLCCs

	Thin Dielectric BME	D08X10425 (PME)	C08X22516 (BME)	B12X68316 (BME)
N	200	30	250	64
d (μm)	1.00	20.2	3.85	6.29
$\bar{a}$ (μm)	0.10	0.61	0.11	0.38
A	6.0	5.0	6.0	6.0
$R_i(5\ year)$	99.9999%	100.0000%	100.0000%	100.0000%
$R_t(5\ year)$	99.9800%	99.9999%	99.9999%	99.9997%

- **MLCC reliability can be empirically estimated using only microstructure and construction parameters N, d, $\bar{a}$, and α.**
- **The microstructure parameters for *thin dielectric BME MLCCs* was assumed based on an Intel report.**
- **Structural parameters for all other MLCCs were experimentally determined.**

Case Studies: An Intel Application

- **0.045 μm Si processing technology**
- **140 MLCCs per package**
- **System reliability: R_s**



$$R_s(5\ year) = R_t(5\ year)^{140} \geq 99.9\%$$

		Thin Dielectric BME	D08X10425 (PME)	C08X22516 (BME)	B12X68316 (BME)
Dielectric	$R_i(5\ year)$	99.9999%	100.0000%	100.0000%	100.0000%
MLCC	$R_t(5\ year)$	99.9800%	99.9999%	99.9999%	99.9997%
System	$R_s(5\ year)$	97.2388%	99.9895%	99.9887%	99.9569%

Summary

- BMEs represent a commercial technology. Not all BME capacitors can be qualified for high-reliability applications.
- A minimum dielectric thickness requirement that has been used for making high-reliability PME capacitors is not applicable to BME capacitors. BME capacitors have more complicated structures than PME capacitors:
  - Number of dielectric layers *N* in a BME capacitor is extremely high;
  - Dielectric thickness *d* is extremely thin;
  - Grain size varies from 0.5 μm down to 0.1 μm.
- The reliability of a BME MLCC has been found to be directly related to the microstructure parameter *N* (# of dielectric layers) and $\left(\frac{d}{\bar{r}}\right)$ (# of stacked grains per dielectric layer).
- A reliability model regarding the microstructure of a BME MLCC is developed and has been applied to eliminate the BME capacitors with potential reliability concerns.
- More reliability evaluations regarding the microstructure of BME capacitors are to be performed.

Acknowledgements

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