How to Characterize the Reliability of Ceramic Capacitors with Base-Metal Electrodes (BMEs)

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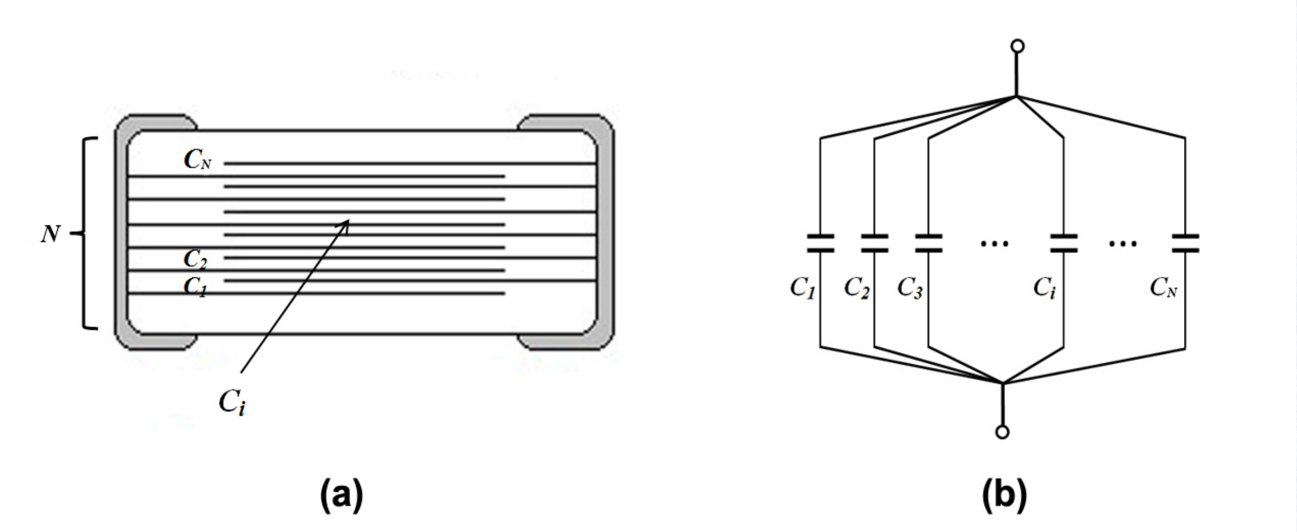
Acronyms

BME	Base-Metal Electrode
PME	Precious-Metal Electrode
CA	Construction Analysis
CMSE	Components for Military and Space Electronics
IR	Insulation Resistance
GSFC	Goddard Space Flight Center
MLCCs	Multi-Layer Ceramic Capacitors
MTTF	Mean Time to Failure
SCDs	Specification Control Drawings
TTF	Time to Failure

Abstract

- The reliability of an MLCC device is the product of a time-dependent part and a time-independent part
  - Time-dependent part is a statistical distribution
  - Time-independent part is the reliability at t=0, the initial reliability
- Initial reliability depends only on how a BME MLCC is designed and processed
- Similar to the way the minimum dielectric thickness ensured the long-term reliability of a PME MLCC, the initial reliability also ensures the long term-reliability of a BME MLCC
- This presentation shows new discoveries regarding commonalities and differences between PME and BME capacitor technologies

Development of a Reliability Model for MLCCs



- Assume ***N*** single-layer ceramic capacitors made as identical as possible. Then we would assume:

$$C_1 = C_2 = C_3 = \cdots\cdots = C_N$$

$$R_1 = R_2 = R_3 = \cdots\cdots = R_N$$

where C_i and R_i are the capacitance and reliability of the ***i***-th single-layer capacitor

- If all of these capacitors were laminated together in parallel, what would be the reliability of the resulting MLCC device?

Development of a Reliability Model for MLCCs (Cont'd)

- Scenario I: The total capacitance C_t and the total reliability R_t

$$C_t = C_1 + C_2 + C_3 + \cdots\cdots = N \times C_N$$

$$R_\mathrm{t} = R_1 = R_2 = R_3 = \cdots\cdots = R_N = R_i$$

- Assuming that all of the dielectric layers are degraded uniformly:
  - The degradation failures should be identical among all layers
  - No single failure site should be identified
  - MLCC reliability R_t should be *independent* of the number of dielectric layers N

$$\boxed{R_\mathrm{t} = R_i}$$

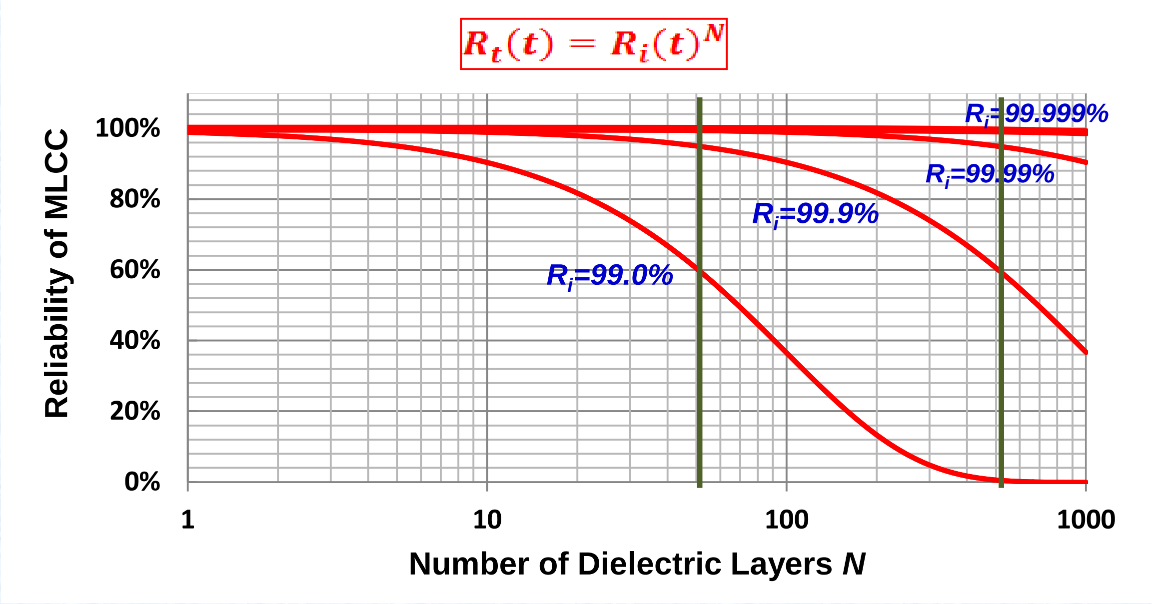
Development of a Reliability Model for MLCCs (Cont'd)

- Scenario II: If N single-layer capacitors are independent from each other and the whole MLCC system fails if one of the component C_i fails, then the reliability R_t can be expressed as a series system reliability of N components (*M. Rausand and A. Hoyland, System Reliability Theory, 2nd Edition, John Wiley & Sons, Inc., Hoboken, New Jersey, 2004*)

$$C_t = C_1 + C_2 + C_3 + \cdots\cdots = N \times C_N$$

$$R_t = R_1 \times R_2 \times R_3 \times \cdots\cdots \times R_N = {R_i}^N$$

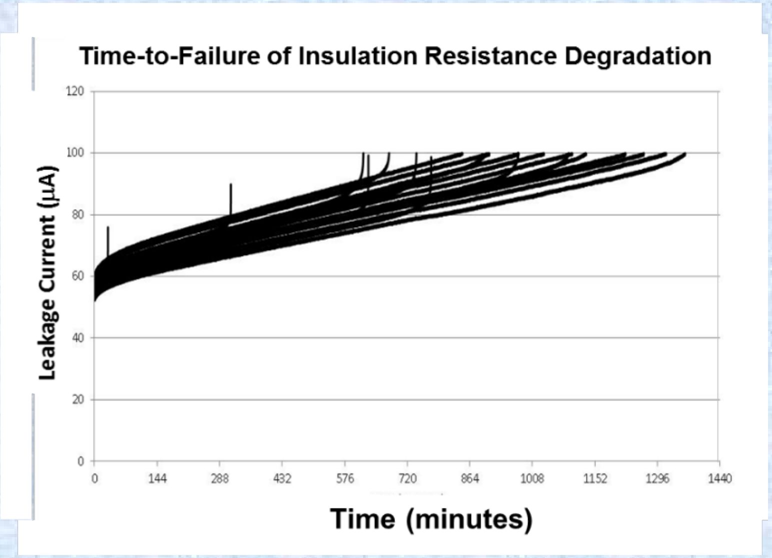
$$\boxed{R_t = R_i^N}$$

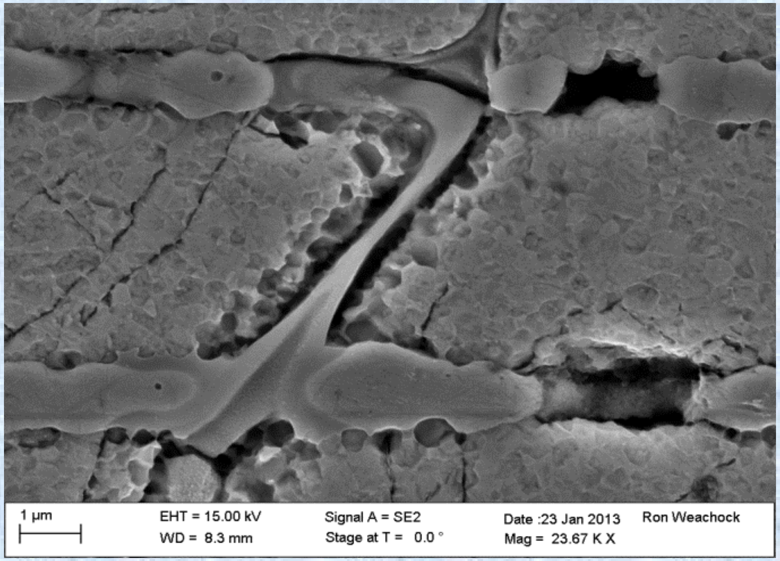


- Total MLCC reliability R_t is highly dependent on the single-layer reliability R_i and number of dielectric layers N

Development of a Reliability Model for MLCCs (Cont'd)

- Scenario III: The facts on actual MLCC failures:
  - Even with a uniform failure mode such as insulation resistance (IR) degradation, the MLCCs do not fail at the same time
  - Regardless of how uniform a failure mode is, there will always be differences resulting from micro-scale structural inhomogeneities (from Failure Analysis result)





D. Liu, "Highly Accelerated Life Stress Testing (HALST) of Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, p. 235, (2013)

R. Weachock and D. Liu, "Failure Analysis of Dielectric Breakdowns in Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, p. 151, (2014)

Development of a Reliability Model for MLCCs (Cont'd)

- Scenario III: How can the problem be addressed?
  - Total capacitance C_t and reliability R_t

$$C_t = C_1 + C_2 + C_3 + \cdots\cdots = N \times C_N$$

$$R_t = R_1 \times R_2 \times R_3 \times \cdots\cdots \times R_N$$

$$R_1 \neq R_2 \neq R_3 \neq \cdots\cdots \neq R_N$$

  - Assume R_i follows a Weibull distribution: $R_i = e^{-\left(\frac{t}{\eta_i}\right)^{\beta}}$, and

$$R_t = R_1 \times R_2 \times R_3 \times \cdots\cdots \times R_N = e^{-\left(\left[\sum_{i=1}^{N}\left(\frac{1}{\eta_i}\right)^{\beta}\right]t^{\beta}\right)}$$

Still a Weibull distribution!

  - Since an MLCC structure is at most as reliable as the least reliable component, it becomes a typical *smallest extreme value distribution* problem. Per Gumbel's approach, the final reliability of a MLCC can be expressed as:

$$\bar{R}_t = e^{-Ne^{\left(\frac{t-\vartheta}{\eta^*}\right)}} = \bar{R}_i^{\,N} \cdot e^{-\left(\frac{t}{\eta^{**}}\right)^{\beta}}$$

(Product of a time-dependent part and a time-independent part)

where ϑ is a location constant and η^{**} is a normalized scale parameter for Weibull distribution.

Development of an Initial Reliability Model for BME Capacitors

- When *t=0*,

$$\bar{R}_t = \bar{R}_i^{\,N} \cdot e^{-\left(\frac{t}{\eta^{**}}\right)^{\beta}} = \bar{R}_i^{\,N}$$

- $\bar{R}_i$ is the ***initial reliability***. $\bar{R}_i$ is determined by the design/processing parameters in place when an MLCC device was manufactured.

- Since η_i represents the TTF of a single-layer capacitor, the TTF of an MLCC device η_t is thus: $\eta_t = \eta_{min} = \min\{\eta_1, \eta_2, \ldots, \eta_N\}$.

$$\sum_{i=1}^{N}\left(\frac{1}{\eta_i}\right)^{\beta} = \left(\frac{1}{\eta_1}\right)^{\beta} + \left(\frac{1}{\eta_2}\right)^{\beta} + \cdots + \left(\frac{1}{\eta_N}\right)^{\beta}$$

$$= \left(\frac{1}{\eta_{min}}\right)^{\beta} + \left(\frac{1}{\eta_{min}\cdot\gamma_1}\right)^{\beta} + \left(\frac{1}{\eta_{min}\cdot\gamma_2}\right)^{\beta} \ldots + \left(\frac{1}{\eta_{min}\cdot\gamma_N}\right)^{\beta}$$

$$= \left(\frac{1}{\eta_{min}}\right)^{\beta}\left[\left(\frac{1}{\gamma_1}\right)^{\beta} + \left(\frac{1}{\gamma_2}\right)^{\beta} \ldots + \left(\frac{1}{\gamma_N}\right)^{\beta}\right] \quad (\gamma_i > 1, \beta > 1)$$

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Development of an Initial Reliability Model (Cont'd)

- Assume that η_{min} can be related to a *processing* reliability defect with a feature size of r_{max} as:

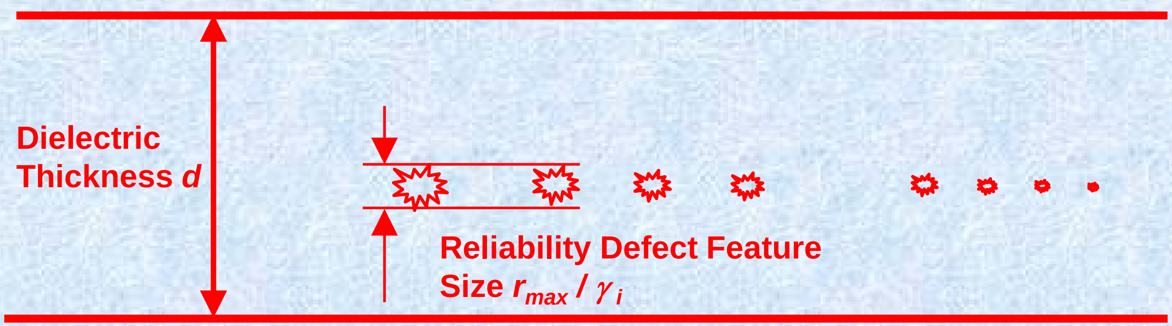
$$\eta_{min} = \frac{\boldsymbol{b}}{\boldsymbol{r_{max}}}, \text{ and } \eta_i = \frac{\boldsymbol{b}}{\boldsymbol{r_{max}/\gamma_i}} \ (\gamma_i > 1).$$

- Initial reliability can be found for different values of dielectric thickness d:

$$d >> \left(\frac{r_{max}}{\gamma_i}\right), \overline{\boldsymbol{R}}_{\boldsymbol{i}} = 1; \text{ and when } d \approx \left(\frac{r_{max}}{\gamma_i}\right), \overline{\boldsymbol{R}}_{\boldsymbol{i}} = 0.$$

- One can thus assume:

$$\overline{\boldsymbol{R}}_{\boldsymbol{i}} = \mathbf{1} - \left[\frac{\left(\frac{\boldsymbol{r_{max}}}{\gamma_i}\right)}{\boldsymbol{d}}\right]^{\zeta} \ (\zeta > \mathbf{1})$$



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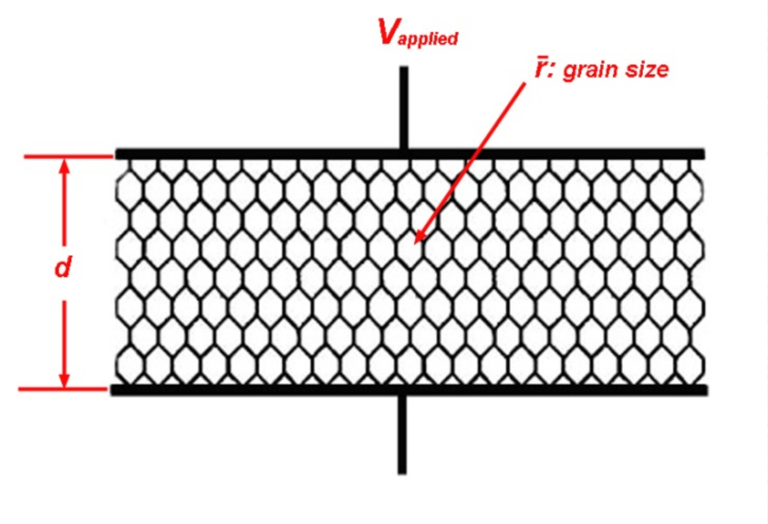
Development of an Initial Reliability Model (Cont'd)

- Let $\left(\frac{r_{max}}{\gamma_i}\right) = c \times \bar{r}$, where $\bar{r}$ is the average grain size and **c** is a constant.

$$\bar{R}_i = 1 - \left[\frac{\left(\frac{r_{max}}{\gamma_i}\right)}{d}\right]^{\zeta} = 1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}$$

where α is an ***empirical parameter*** and α = 6 when rated voltage is less than 100V.



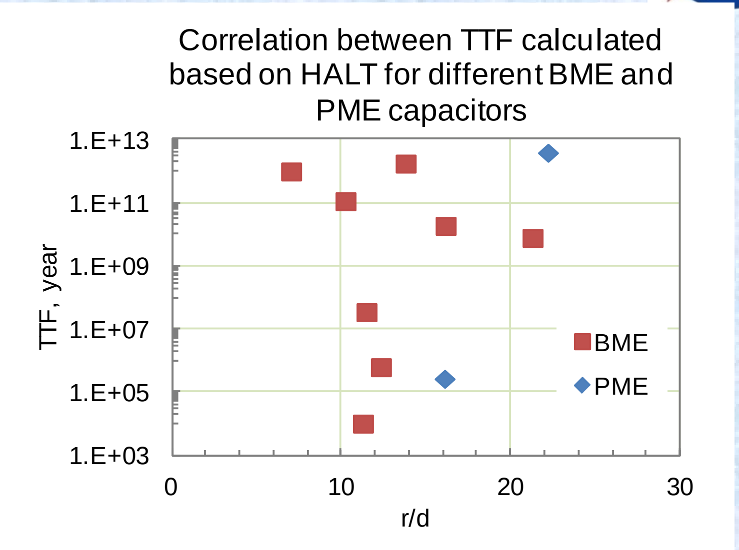
- The *initial reliability* of an MLCC can finally be expressed as:

$$\bar{R}_t(t=0) = \bar{R}_i^{\,N} = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$$

  - The initial reliability is only determined by design parameters ***N*** and ***d*** and processing parameter $\bar{r}$
  - A microstructure with a tight grain size distribution will yield a better reliability
  - When reducing dielectric layer thickness to gain capacitance volumetric efficiency, the grain size should also be reduced accordingly (*important for BME MLCCs!*)
  - MLCC reliability $\bar{R}_t$ will decrease with an increasing number of dielectric layers N

Verification of the Proposed Initial Reliability Model

Capacitor ID	Electrode	Dielectric Thickness (μm)	Avg. Grain Size (μm)	No. of grain stacking	β	E_a(eV)	*n*	MTTF (yrs)
A08X22525	BME	3.5	0.31	11.29	All units were short during HALT			
A08X15425	BME	9.8	0.46	21.30	5.21	1.52	4.63	7.62E09
A06X10425	BME	7.6	0.47	16.17	8.47	1.70	3.86	1.84E10
B06X22425	BME	4.2	0.34	12.35	2.71	1.00	4.58	6.11E05
B08X33425	BME	5.8	0.42	13.81	9.54	1.45	4.35	1.73E12
B08X10525	BME	4.6	0.40	11.50	2.42	1.24	4.92	3.39E07
C06X10525	BME	3.1	0.44	7.05	4.14	1.82	8.70	9.72E11
C08X56425	BME	4.0	0.39	10.26	3.99	1.57	4.82	1.11E11
D06X10405	PME	12.4	0.77	16.11	1.54	0.99	2.83	2.62E05
D04X10310	PME	15.1	0.68	22.21	1.34	1.01	3.04	3.81E12
D08X10425	PME	20.2	0.61	33.11	No failures during HALT			



D. Liu and M. Sampson, "Reliability Evaluation of Base-Metal Electrode Multilayer Ceramic Capacitors for Potential Space Applications," *CARTS Proceedings*, p. 45, (2011)

- Why does there appear to be no relationship? MTTF data were calculated per a SINGLE failure mode assumption and were extended to room temperature using the values of activation energy E_a and voltage parameter *n* obtained in the temperature region between 145°C and 175°C.
- Per later reliability studies of Ni-$BaTiO_3$ MLCCs:

  D. Liu, "Highly Accelerated Life Stress Testing (HALST) of Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, p. 235, (2013);

  D. Liu, "A General Reliability Model for Ni-BaTiO3-Based Multilayer Ceramic Capacitors," *CARTS Proceedings*, p. 31, (2014).
  - two failure mode approach fits the MTTF data better, and an "E-model" is better than a power-law voltage dependence
  - calculated MTTF fits the actual measured results better at 125°C and 2X rated voltage than at room temperature mainly due to a phase transition at ~120°C

Verification of the Proposed Initial Reliability Model (Cont'd)

- ***MTTF*** is simply not a reliability $\boldsymbol{R(t)}$:

$$\boldsymbol{MTTF = -\int_0^\infty t\frac{d}{dt}R(t)dt = -[tR(t)]_0^\infty + \int_0^\infty R(t)dt = \int_0^\infty R(t)dt}$$

- For 2-parameter Weibull distribution:

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

- For an MLCC device, the empirical relationship is better known as:

$$\boldsymbol{MTTF = \left(\frac{1}{V}\right)^n e^{-\frac{E_a}{kT}}}$$ ***(Prokopowicz and Vaskas equation)***

- For Ni-$BaTiO_3$ MLCCs, the *P-V* equation must be modified when an initial reliability and an "*E-model*" are taken into account (*E=electrical Field*):

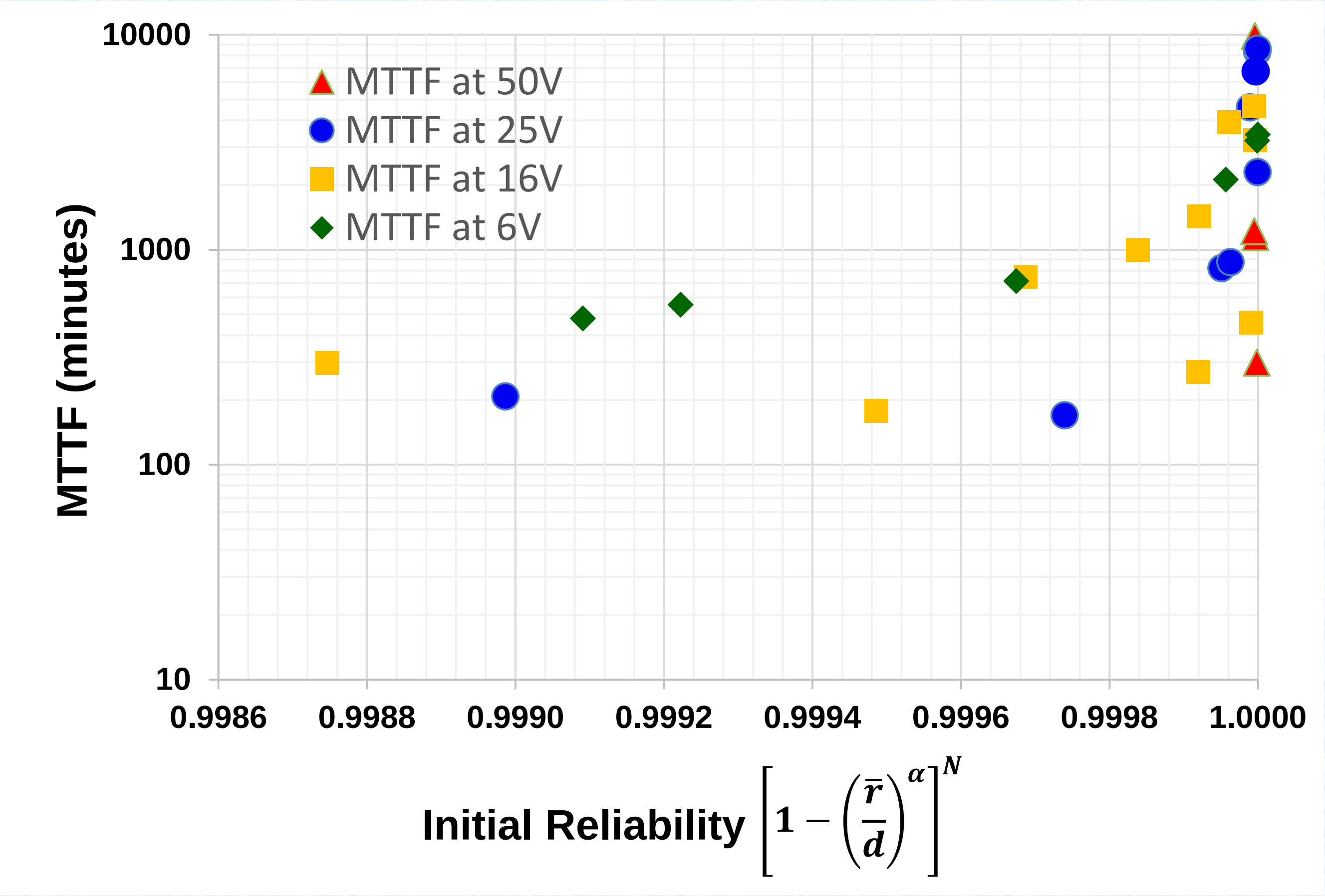
$$\boldsymbol{MTTF = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^N \times e^{-b\times E} \cdot e^{-\frac{E_a}{kT}}}$$

- When relating MTTF to initial reliability, the comparison should be made at the same electrical field, and the difference in $\boldsymbol{E_a}$ should also be taken into consideration.

Verification of the Proposed Initial Reliability Model (Cont'd)

CAP ID	Average Grain Size (μm)	Dielectric Thickness (μm)	No. of Dielectric Layers N	Eletrical Field (KV/mm)	MTTF (min) at 165°C	$\left[1-\left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$
B12X10606	0.365	3.11	348	24.12	479.23	0.9990910
B04X10406	0.323	2.5	70	20.00	714.62	0.9996745
B08X22506	0.419	3.42	230	21.93	555.37	0.9992225
A08X10406	0.49	12.5	34	20.00	3435.16	0.9999999
B06X22406	0.373	4.01	67	24.94	2115.33	0.9999566
D06X10405	0.77	12.6	24	19.84	3212.13	0.9999987
B06X10516	0.273	2.29	179	27.95	177.66	0.9994863
A08X47416	0.319	3.75	208	26.67	1425.37	0.9999212
B12X68416	0.375	6.21	64	24.15	3230.11	0.9999969
C08X22516	0.224	3.81	212	26.25	457.65	0.9999912
B08X22516	0.34	3.23	230	19.81	747.49	0.9996872
B08X56416	0.373	4.21	80	35.63	3920.00	0.9999613
C08X47516	0.23	2.49	260	28.92	998.04	0.9998385
B12X10516	0.475	7.82	99	25.58	4650.16	0.9999950
B04X10416	0.497	3.05	67	24.59	295.65	0.9987464
C12X10616	0.231	2.81	260	28.47	269.20	0.9999198
A08X22525	0.305	3.89	211	19.28	818.44	0.9999510
B08X33425	0.42	5.8	74	20.69	4589.67	0.9999893
A08X15425	0.46	9.8	43	20.41	2291.38	0.9999995
C06X10525	0.44	3.2	150	21.88	207.13	0.9989868
A06X10425	0.47	7.89	62	19.01	6739.35	0.9999972
A12X47425	0.492	10.4	58	19.23	8325.25	0.9999993
C12X10625	0.28	2.8	260	22.86	169.20	0.9997400
D08X10425	0.79	20.2	23	12.38	8569.39	0.9999999
C08X22525	0.283	3.79	212	19.79	872.35	0.9999633
AB08X47450	0.328	5.80	100	43.09	1139.76	0.9999967
AC08X47450	0.377	6.39	98	39.12	9869.00	0.9999959
AA08X47450	0.403	8.10	103	37.04	297.97	0.9999984
AB08X68450	0.349	6.16	147	40.61	1215.88	0.9999951

Verification of the Proposed Initial Reliability Model (Cont'd)



- The MTTF data were determined from the Weibull plot of 20 directly measured TTF data points
- There is a clear relationship between ***MTTF*** and initial reliability

Verification of the Proposed Initial Reliability Model (Cont'd)

Life Test Results per MIL-PRF-55681 and MIL-PRF-123

CAP ID	Grain Size (μm)	Dielectric Thickness (μm)	No. of Dielectric layers N	$\left[1-\left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$	Life test at 1000 hours	Life test at 4000 hours
B12X10606	0.365	3.11	348	0.9990910	Fail	
B04X10406	0.323	2.5	70	0.9996745	Fail	
B08X22506	0.419	3.42	230	0.9992225	Fail	
A08X10406	0.49	12.5	34	0.9999999	Pass	Pass
B06X22406	0.373	4.01	67	0.9999566	Pass	Fail
D06X10405	0.77	12.6	24	0.9999987	Pass	Pass
B06X10516	0.273	2.29	179	0.9994863	Fail	
A08X47416	0.319	3.75	208	0.9999212	Fail	
B12X68416	0.375	6.21	64	0.9999969	Pass	Pass
C08X22516	0.224	3.81	212	0.9999912	Pass	Fail
B08X22516	0.34	3.23	230	0.9996872	Fail	
B08X56416	0.373	4.21	80	0.9999613	Pass	Pass
C08X47516	0.23	2.49	260	0.9998385	Pass	Fail
B12X10516	0.475	7.82	99	0.9999950	Pass	Pass
B04X10416	0.497	3.05	67	0.9987464	Fail	
C12X10616	0.231	2.81	260	0.9999198	Fail	
A08X22525	0.305	3.89	211	0.9999510	Fail	
B08X33425	0.42	5.8	74	0.9999893	Pass	Pass
A08X15425	0.46	9.8	43	0.9999995	Pass	Pass
C06X10525	0.44	3.2	150	0.9989868	Fail	
A06X10425	0.47	7.89	62	0.9999972	Pass	Pass
A12X47425	0.492	10.4	58	0.9999993	Pass	Fail
C12X10625	0.28	2.8	260	0.9997400	Fail	
D08X10425	0.79	20.2	23	0.9999999	Pass	Pass
C08X22525	0.283	3.79	212	0.9999633	Fail	
AB08X47450	0.328	5.80	100	0.9999967	Pass	Pass*
AC08X47450	0.377	6.39	98	0.9999959	Pass	Pass*
AA08X47450	0.403	8.10	103	0.9999984	Pass	Pass*
AB08X68450	0.349	6.16	147	0.9999951	Pass	Pass*

$$\bar{R}_i = \left[1-\left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} > 0.99999$$

- Several COTS BME MLCCs passed both life tests
- Most automotive-grade BME MLCCs meet this requirement
- The initial reliability can be used as a simple rule of thumb when designing BME MLCCs for high-reliability applications
- This also indicates that high-reliability MLCCs must be built for this purpose; one cannot improve capacitor reliability by "up-screening"

Initial Reliability and BX Life

$$\bar{R}_i = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} > 0.99999$$

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 $= \eta\{-ln[R(x_1\%)]\}^{1/\beta}$ **where *R(x₁%)* =0.99**
P: B0.1% life $= \eta\{-ln[R(x_2\%)]\}^{1/\beta}$ **where *R(x₂%)* =0.999**
R: B0.01% life $= \eta\{-ln[R(x_3\%)]\}^{1/\beta}$ **where *R(x₃%)* =0.9999**
S: B0.001% life $= \eta\{-ln[R(x_4\%)]\}^{1/\beta}$ **where *R(x₄%)* =0.99999**

Applications of initial reliability for BME MLCCs:

- A measure of robustness in the design and processing of BME MLCCs with respect to long-term reliability
- BME capacitors that meet this initial reliability requirement may not all pass reliability life testing per MIL-PRF-55681 or MIL-PRF-123 and would likely pass during the required life testing
- Can be used as an empirical criterion of construction analysis to reject a BME capacitor for high-reliability use prior to tedious life testing, just like the minimum dielectric thickness restriction applied for PME MLCCs

Summary and Future Work

- A reliability model for MLCCs based on component/structure reliability theory was developed. The reliability with respect to insulation resistance failures in MLCCs follows an extreme value distribution and is a product of a time-dependent part and a time-independent part.
- A time-independent *initial reliability* model was developed with respect to dielectric layer thickness, reliability defect feature size, average grain size, and number of dielectric layers.
- Both highly accelerated and regular life test results were used to verify the proposed initial reliability model. The model gives the following guidelines:
  - MLCC reliability will decrease as the number of dielectric layers increases
  - When dielectric thickness is reduced in order to increase capacitance volumetric efficiency, the ceramic grain size should also be reduced to improve device reliability
  - Microstructural homogeneity is critical to minimize early failures and improve the long-term reliability of MLCCs
  - Construction analysis can be used to estimate the long-term reliability of a BME MLCC so that tedious life testing can be avoided
- Future work will focus on the prediction of grain size distribution. Large particles in ceramic powders must be eliminated.
- A similar reliability approach may be applied to other electronic components with multilayer structures for military and space applications.

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