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

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To be presented by David Liu at the 2015 Components for Military and Space Electronics (CMSE) Conference and Exhibition, Los Angeles, CA, March 1-3, 2015.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BME</td>
<td>Base-Metal Electrode</td>
</tr>
<tr>
<td>PME</td>
<td>Precious-Metal Electrode</td>
</tr>
<tr>
<td>CA</td>
<td>Construction Analysis</td>
</tr>
<tr>
<td>CMSE</td>
<td>Components for Military and Space Electronics</td>
</tr>
<tr>
<td>IR</td>
<td>Insulation Resistance</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
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<tr>
<td>MLCCs</td>
<td>Multi-Layer Ceramic Capacitors</td>
</tr>
<tr>
<td>MTTF</td>
<td>Mean Time to Failure</td>
</tr>
<tr>
<td>SCDs</td>
<td>Specification Control Drawings</td>
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<tr>
<td>TTF</td>
<td>Time to Failure</td>
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</table>
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
• Assume $N$ single-layer ceramic capacitors made as identical as possible. Then we would assume:

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

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

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 $R_t$

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

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

- 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 $N$

$$R_t = R_i$$

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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*)

\[
C_t = C_1 + C_2 + C_3 + \cdots = N \times C_N
\]

\[
R_t = R_1 \times R_2 \times R_3 \times \cdots \times R_N = R_i^N
\]

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

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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).

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![Graph of Time-to-Failure of Insulation Resistance Degradation](image)

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

• **Scenario III:** How can the problem be addressed?
  
  – Total capacitance $C_t$ and reliability $R_t$
    
    $C_t = C_1 + C_2 + C_3 + \cdots = N \times C_N$
    
    $R_t = R_1 \times R_2 \times R_3 \times \cdots \times R_N$
    
    $R_1 \neq R_2 \neq R_3 \neq \cdots \neq R_N$

  – Assume $R_i$ follows a Weibull distribution: $R_i = e^{-\left(\frac{t}{\eta_i}\right)^\beta}$, and
    
    $R_t = R_1 \times R_2 \times R_3 \times \cdots \times R_N = e^{-\left(\sum_{i=1}^{N} \left(\frac{1}{\eta_i}\right)^\beta\right)t^\beta}$  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:
    
    $\bar{R}_t = e^{-N \left(\frac{t-\vartheta}{\eta^*}\right)} = \bar{R}_i^N \cdot e^{-\left(\frac{t}{\eta^{**}}\right)^\beta}$  (Product of a time-dependent part and a time-independent part)

    where $\vartheta$ is a location constant and $\eta^{**}$ 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 \( \eta_i \) represents the TTF of a single-layer capacitor, the TTF of an MLCC device \( \eta_t \) is thus: \( \eta_t = \eta_{min} = \min \{\eta_1, \eta_2, \ldots, \eta_N\} \).

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

\[
= \left( \frac{1}{\eta_{min}} \right)^\beta + \left( \frac{1}{\eta_{min} \cdot \gamma_1} \right)^\beta + \left( \frac{1}{\eta_{min} \cdot \gamma_2} \right)^\beta + \cdots + \left( \frac{1}{\eta_{min} \cdot \gamma_N} \right)^\beta
\]

\[
= \left( \frac{1}{\eta_{min}} \right)^\beta \left[ \left( \frac{1}{\gamma_1} \right)^\beta + \left( \frac{1}{\gamma_2} \right)^\beta + \cdots + \left( \frac{1}{\gamma_N} \right)^\beta \right] \quad (\gamma_i > 1, \beta > 1)
\]
Development of an Initial Reliability Model (Cont’d)

• Assume that $\eta_{min}$ can be related to a **processing** reliability defect with a feature size of $r_{max}$ as:

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

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

\[
d \gg \left(\frac{r_{max}}{\gamma_i}\right), \overline{R}_i = 1; \text{ and when } d \approx \left(\frac{r_{max}}{\gamma_i}\right), \overline{R}_i = 0.
\]

• One can thus assume:

\[
\overline{R}_i = 1 - \left[\frac{(r_{max}/\gamma_i)}{d}\right]^\zeta \quad (\zeta > 1)
\]
Development of an Initial Reliability Model (Cont’d)

• Let \( \frac{r_{\text{max}}}{\gamma_i} = c \times \bar{r} \), where \( \bar{r} \) is the average grain size and \( c \) is a constant.

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

where \( \alpha \) is an empirical parameter and \( \alpha = 6 \) 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

- 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:
    - 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

<table>
<thead>
<tr>
<th>Capacitor ID</th>
<th>Electrode</th>
<th>Dielectric Thickness (µm)</th>
<th>Avg. Grain Size (µm)</th>
<th>No. of grain stacking</th>
<th>β</th>
<th>$E_a$(eV)</th>
<th>n</th>
<th>MTTF (yrs)</th>
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</thead>
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<tr>
<td>A08X22525</td>
<td>BME</td>
<td>3.5</td>
<td>0.31</td>
<td>11.29</td>
<td>All units were short during HALT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A08X15425</td>
<td>BME</td>
<td>9.8</td>
<td>0.46</td>
<td>21.30</td>
<td>5.21</td>
<td>1.52</td>
<td>4.63</td>
<td>7.62E09</td>
</tr>
<tr>
<td>A06X10425</td>
<td>BME</td>
<td>7.6</td>
<td>0.47</td>
<td>16.17</td>
<td>8.47</td>
<td>1.70</td>
<td>3.86</td>
<td>1.84E10</td>
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<td>1.00</td>
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<td>6.11E05</td>
</tr>
<tr>
<td>B08X33425</td>
<td>BME</td>
<td>5.8</td>
<td>0.42</td>
<td>13.81</td>
<td>9.54</td>
<td>1.45</td>
<td>4.35</td>
<td>1.73E12</td>
</tr>
<tr>
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<td>4.6</td>
<td>0.40</td>
<td>11.50</td>
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<td>1.24</td>
<td>4.92</td>
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<td>C06X10525</td>
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<td>7.05</td>
<td>4.14</td>
<td>1.82</td>
<td>8.70</td>
<td>9.72E11</td>
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<tr>
<td>C08X56425</td>
<td>BME</td>
<td>4.0</td>
<td>0.39</td>
<td>10.26</td>
<td>3.99</td>
<td>1.57</td>
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<tr>
<td>D06X10405</td>
<td>PME</td>
<td>12.4</td>
<td>0.77</td>
<td>16.11</td>
<td>1.54</td>
<td>0.99</td>
<td>2.83</td>
<td>2.62E05</td>
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<tr>
<td>D04X10310</td>
<td>PME</td>
<td>15.1</td>
<td>0.68</td>
<td>22.21</td>
<td>1.34</td>
<td>1.01</td>
<td>3.04</td>
<td>3.81E12</td>
</tr>
</tbody>
</table>
| D08X10425     | PME       | 20.2                      | 0.61                 | 33.11                 | No failures during HALT  


Correlation between TTF calculated based on HALT for different BME and PME capacitors

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

• **MTTF** is simply not a reliability \( R(t) \):

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

• For 2-parameter Weibull distribution:

\[
MTTF = \eta \Gamma(1 + 1/ \beta)
\]

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

\[
MTTF = \left( \frac{1}{V} \right)^n e^{-\frac{E_a}{kT}} \quad \text{(Prokopowicz and Vaskas equation)}
\]

• For Ni-BaTiO\(_3\) MLCCs, the \(P-V\) equation must be modified when an initial reliability and an “E-model” are taken into account (\(E=\text{electrical Field}\)):

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

• When relating MTTF to initial reliability, the comparison should be made at the same electrical field, and the difference in \(E_a\) should also be taken into consideration.

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## Verification of the Proposed Initial Reliability Model (Cont’d)

<table>
<thead>
<tr>
<th>CAP ID</th>
<th>Average Grain Size (µm)</th>
<th>Dielectric Thickness (µm)</th>
<th>No. of Dielectric Layers $N$</th>
<th>Electrical Field (KV/mm)</th>
<th>MTTF (min) at 165°C</th>
<th>[1 - \left(\frac{T}{d}\right)\alpha^N]</th>
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</thead>
<tbody>
<tr>
<td>B12X10606</td>
<td>0.365</td>
<td>3.11</td>
<td>348</td>
<td>24.12</td>
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<td>19.84</td>
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<tr>
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<td>147</td>
<td>40.61</td>
<td>1215.88</td>
<td>0.9999951</td>
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</tbody>
</table>

To be presented by David Liu at the 2015 Components for Military and Space Electronics (CMSE) Conference and Exhibition, Los Angeles, CA, March 1-3, 2015.
• The MTTF data were determined from the Weibull plot of 20 directly measured TTF data points
• There is a clear relationship between \textbf{MTTF} and initial reliability

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

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

• 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

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

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

\[
\text{TABLE V. Product level designator:}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Product level</th>
</tr>
</thead>
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<tr>
<td>C</td>
<td>non-ER</td>
</tr>
<tr>
<td>M</td>
<td>1.0 1/1</td>
</tr>
<tr>
<td>P</td>
<td>0.1 1/1</td>
</tr>
<tr>
<td>R</td>
<td>0.01 1/1</td>
</tr>
<tr>
<td>S</td>
<td>0.001 1/1</td>
</tr>
</tbody>
</table>

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

\[
\text{BX life to failure rate:}
\text{M: B1% life}
\]

\[
\text{P: B0.1% life}
\]

\[
\text{R: B0.01% life}
\]

\[
\text{S: B0.001% life}
\]

\[
\text{BX life to reliability:}
\text{M: B1% life} \quad \eta\left[-\ln\left(R(x_1\%\right))\right]^{1/\beta}
\]

\[
\text{P: B0.1% life} \quad \eta\left[-\ln\left(R(x_2\%\right))\right]^{1/\beta}
\]

\[
\text{R: B0.01% life} \quad \eta\left[-\ln\left(R(x_3\%\right))\right]^{1/\beta}
\]

\[
\text{S: B0.001% life} \quad \eta\left[-\ln\left(R(x_4\%\right))\right]^{1/\beta}
\]

\[
\text{where } R(x_1\%) = 0.99 \quad \text{where } R(x_2\%) = 0.999 \quad \text{where } R(x_3\%) = 0.9999 \quad \text{where } R(x_4\%) = 0.99999
\]

MIL-PRF-55681, paragraph, 1.2.1.7

To be presented by David Liu at the 2015 Components for Military and Space Electronics (CMSE) Conference and Exhibition, Los Angeles, CA, March 1-3, 2015.
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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