NASA Electronic Parts and Packaging (NEPP) Program

The Significance of Breakdown Voltages for Quality Assurance of Low-Voltage BME Ceramic Capacitors

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Base-Metal-Electrode (BME)

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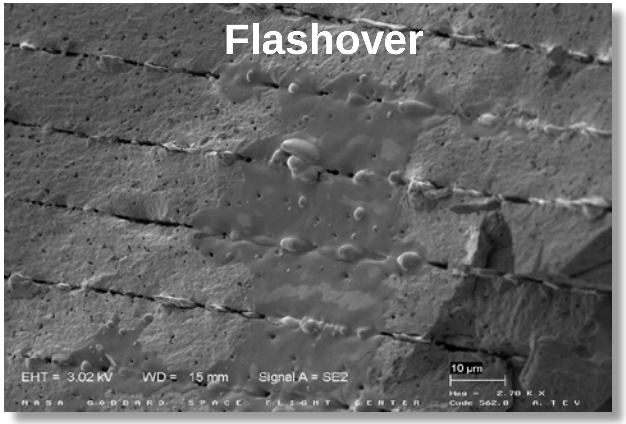
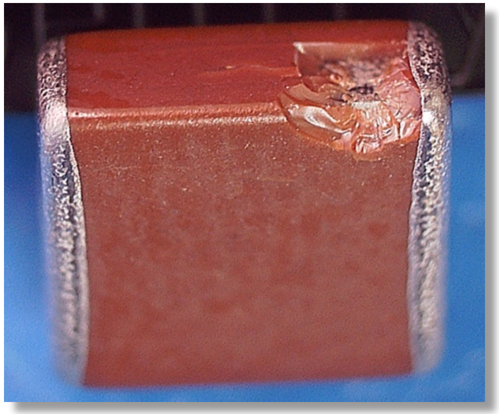
List of Acronyms and Symbols

AF	acceleration factor	**R_d**	resistance associated with defects
BME	base metal electrode	**R_i**	intrinsic resistance
C	capacitance	**RSH**	resistance to soldering heat
CVR	constant voltage ramp	**S&Q**	screening and qualification
DCL	direct current leakage	**T**	temperature
DF	dissipation factor	**Tc**	Curie temperature
DWV	dielectric withstanding voltage	**TS**	thermal shock
HALT	highly accelerated life testing	**TSD**	terminal solder dip
HV	high voltage	**TTF**	time to failure
IR	insulation resistance	**VBR**	breakdown voltage
LV	low voltage	**VBR_{75}**	third quartile of VBR distribution
MF	mechanical fracture	**V_O^{++}**	charged oxygen vacancy
MLCC	multilayer ceramic capacitor	**VR**	rated voltage
PME	precious metal electrode	**X-sect**	cross-section
r	charge absorption resistance	**PDA**	percent defective allowable

Outline

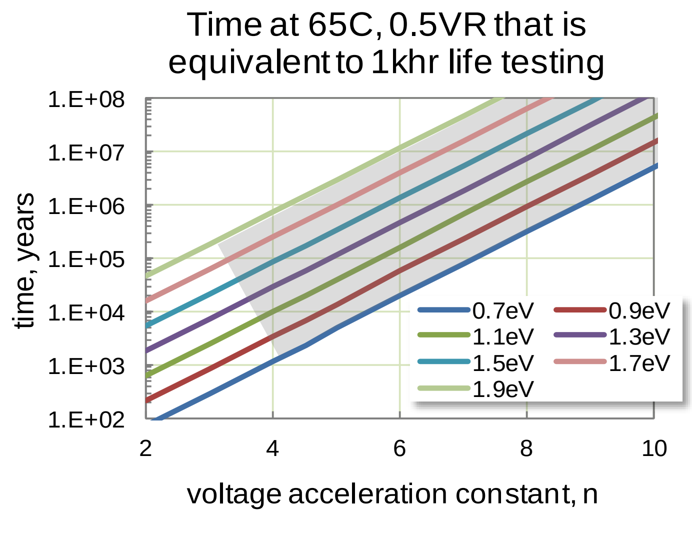
- What limits application of BME MLCCs in hi-rel electronics?
- Drawbacks of the existing system of quality assurance for MLCCs.
- Factors affecting VBR.
- Distributions of VBR and their use for quality assurance.
- Modeling of life testing.
- Flash testing for screening.
- Recommendations.
- Summary.





What Impedes Application of BME Capacitors in Hi-Rel Systems?

- It is assumed that reliability is limited by high concentration of V_O^{++}.
- The wear-out problem has been resolved by using new materials and processes. (Life testing (1000 hr, 2VR, 125 °C) is equivalent to thousands of years at 65 °C and 0.5 VR).
- Intrinsic wear-out failures caused by V_O^{++} do not limit applications.
- Failures are caused by defects.



Factors impeding applications: (1) lead-free termination finishing;

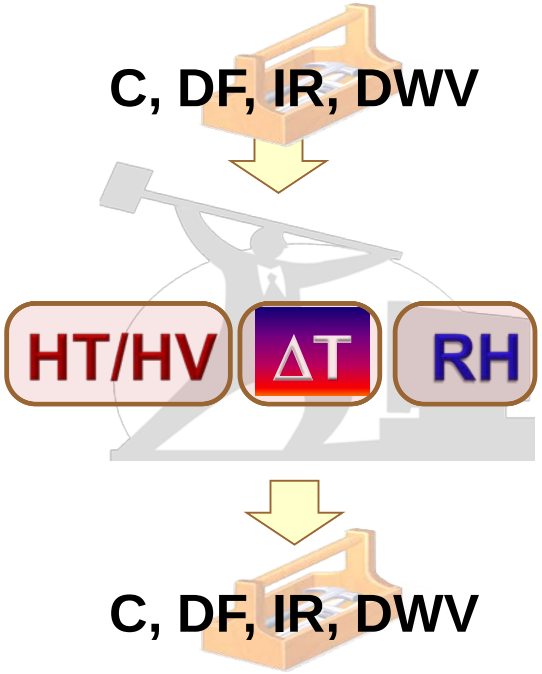
(2) insufficient data on long-term reliability;

(3) the presence of defects introduced either during manufacturing or assembly and handling processes.

- How effective the existing S&Q system for revealing defects in MLCCs?

What is in the Toolbox for S&Q?

- ❑ Specified characteristics: C, DF, and IR.
  - DF and IR have only max limit (unknown margin).
  - VR is assigned by manufacturers so that the parts meet their performance and reliability requirements.
  - DWV test assures that VBR exceeds 2.5VR.
- ❑ Environmental stresses during S&Q testing:
  - HT/HV testing (voltage conditioning and life):
  - Thermal testing (TS, RSH).
  - Humidity testing;
- ❑ No measurements are required during the environmental testing, and PDA has no limits.



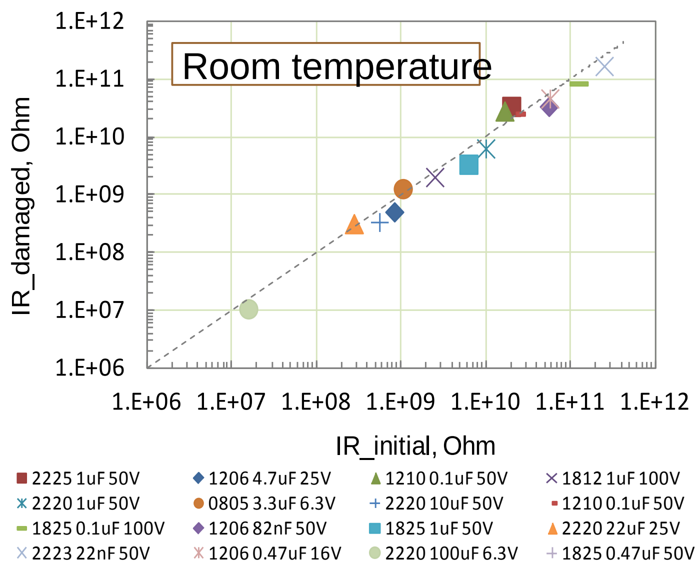
Improvements in the S&Q system can be achieved by:

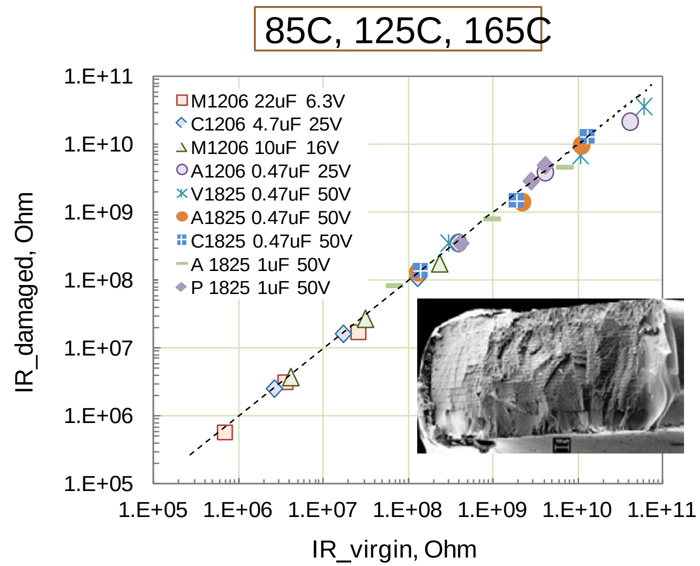
- ✓ increasing the level of stress as necessary;
- ✓ setting PDA limits;
- ✓ monitoring DCL during environmental testing;
- ✓ using new, defect-sensitive, characteristics and tests.

The Effectiveness of IR Measurements

IR is presented by three resistors connected in parallel: absorption (*r*), intrinsic (R_i), and defects (R_d). Limits for military MLCCs: *IR* > 10^{11} Ω or 10^3 MΩ-µF at +25°C(×0.1 at +125°C).

$$IR^{-1} = \left[r(t,C)\right]^{-1} + \left[R_i(T,V)\right]^{-1} + R_d^{-1}$$

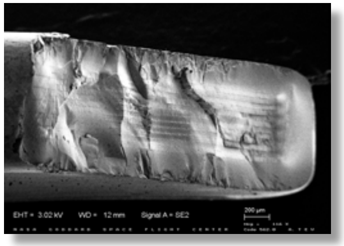


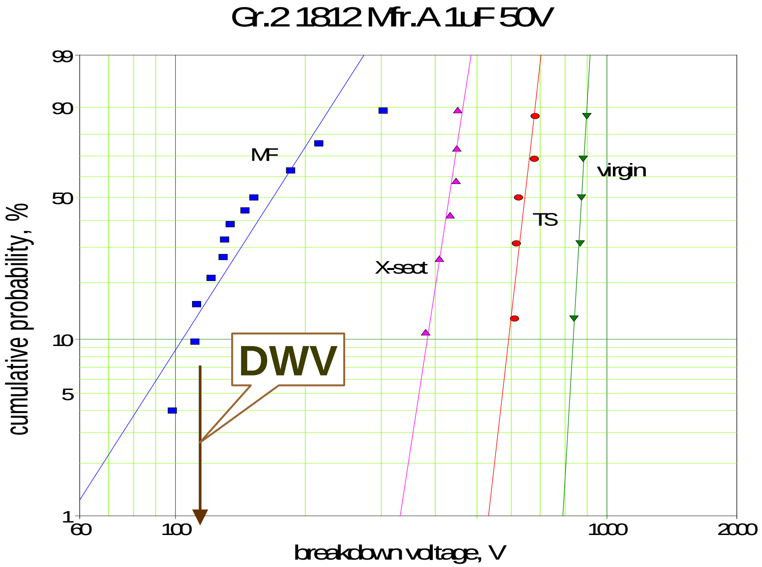


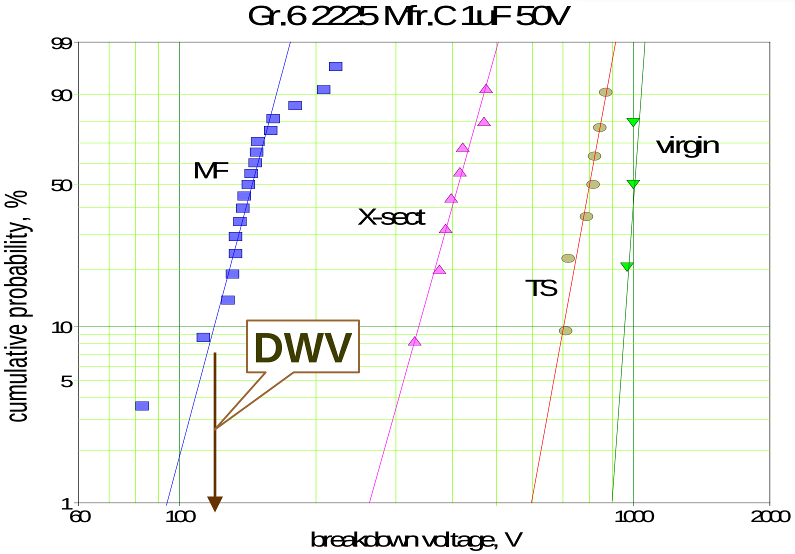
- ✓ High absorption currents at RT, and large intrinsic leakage currents at HT mask the presence of defects.
- ✓ The probability of revealing a defect decreases for capacitors with larger C and smaller VR.

The Effectiveness of DWV Testing

27 lots of low-voltage MLCCs were tested in virgin condition, after mechanical fracture (MF) at the corner, after cross-sectioning (X-sect), and after thermal shock (TS).



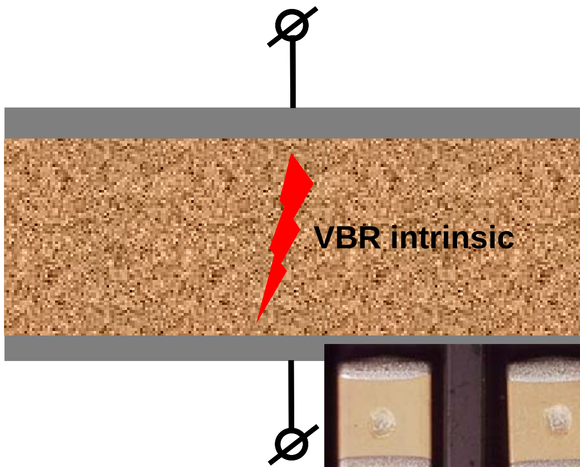




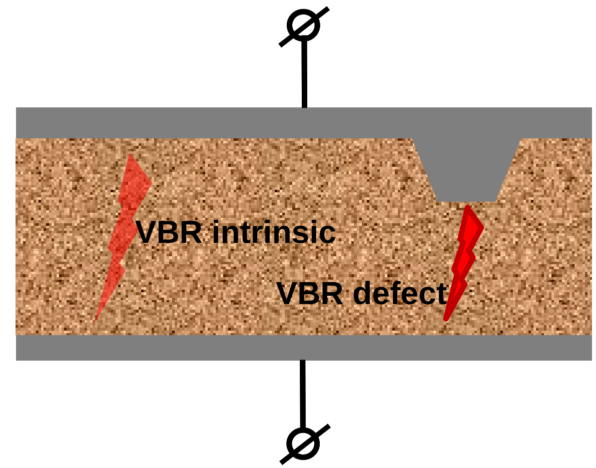
- ✓ The probability of failure during DWV testing for capacitors even with rough mechanical fractures was low.
- ➢ The existing screening techniques (C, DF, IR, and DWV) are capable to determine only gross defects in the parts.

The Effectiveness of VBR Measurements

- Local defects do not change C, DF and IR, but affect VBR.



$VBR_i < VBR_d$



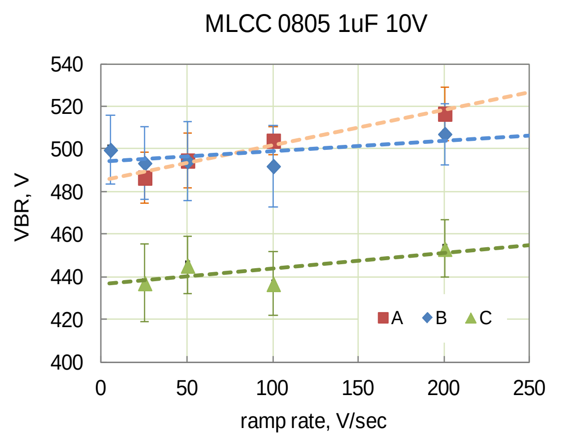
If a capacitor passed DWV testing, should we care about VBR? (Designers' and QA approaches)

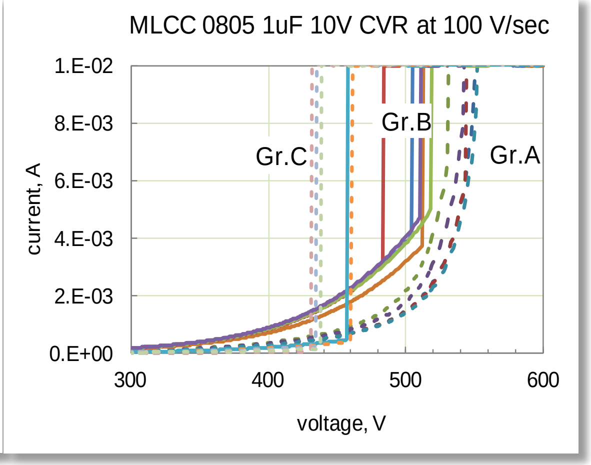
- ✓ High values of VBR (similar to IR) provide assurance that the parts have no gross defects that might cause failures.
- ✓ Contrary to IR, VBR can be measured accurately.
- ✓ The consistency of the distributions indicates stability of the manufacturing process and quality of the product.

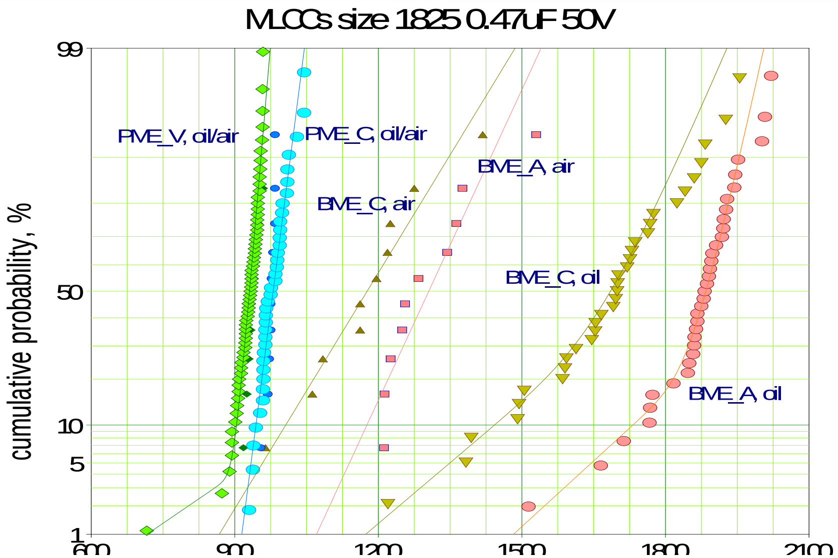
Constant Voltage Ramp Technique

- Factors affecting VBR:
  - Ramp rate.
  - Maximum current.
  - Medium.

- ✓ No significant variations in VBR at ramp rates from 25 V/s to 100 V/s.
- ✓ Current limit in the range from 1 mA to 10 mA will not result in substantial variations of VBR.
- ✓ CVR failures are due to thermal breakdown.
- ✓ Testing in oil increases VBR by 10% to 50%.

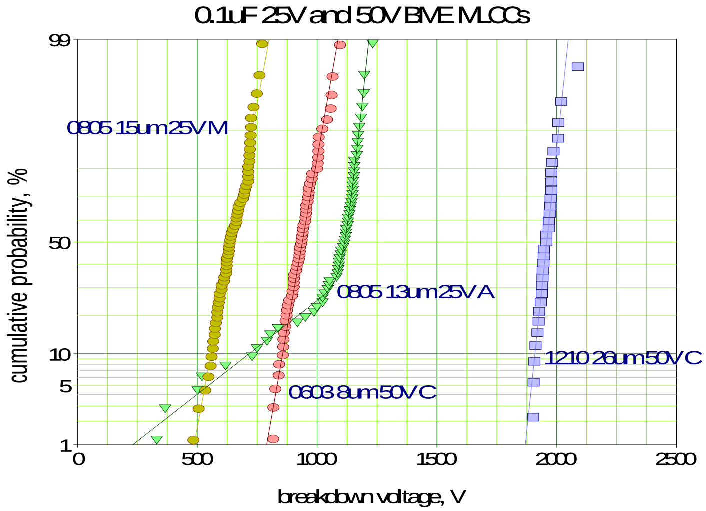


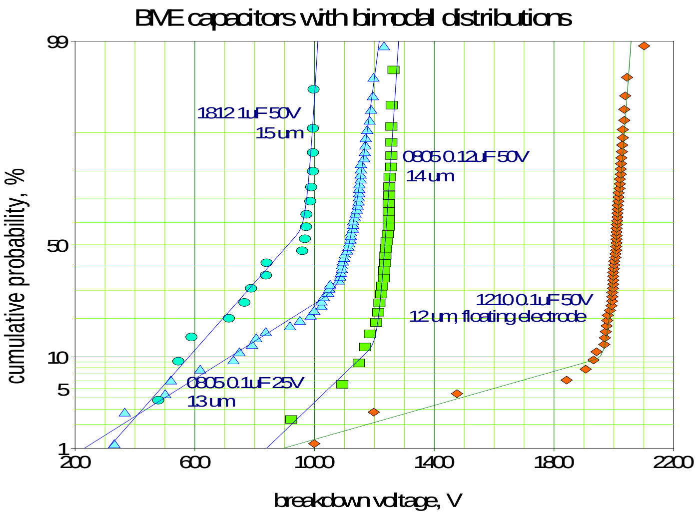




Distributions of VBR

- In most cases distributions of VBR for BME capacitors are bimodal.
- The HV mode has tight distributions (STD/Mean ~4%) indicating intrinsic breakdown.
- The presence of LV subgroup is due to defects.



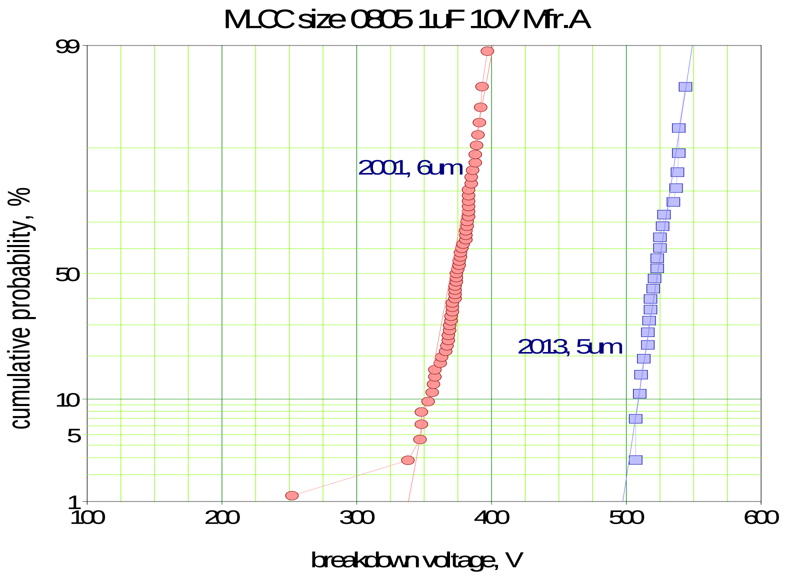


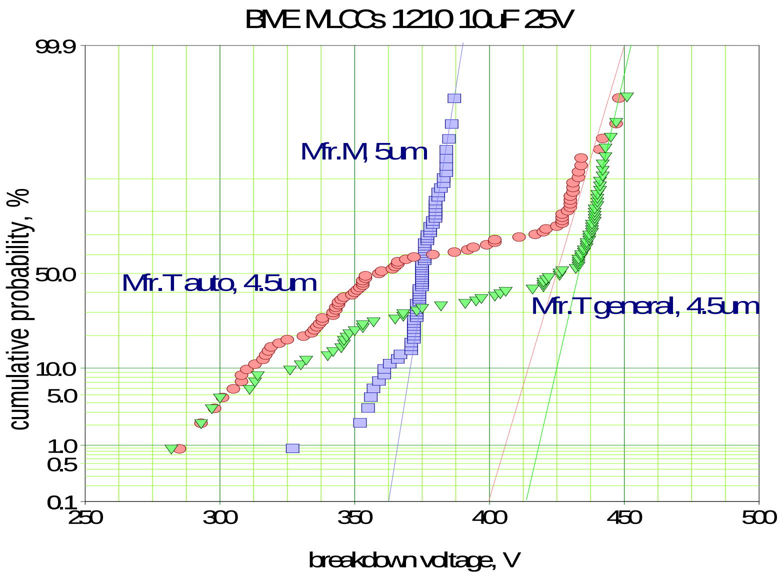
✓ The point of interception indicates proportion of defects in the lot.

✓ The spread of VBR towards low voltages indicates the significance of these defects.

Distributions of VBR, Cont'd

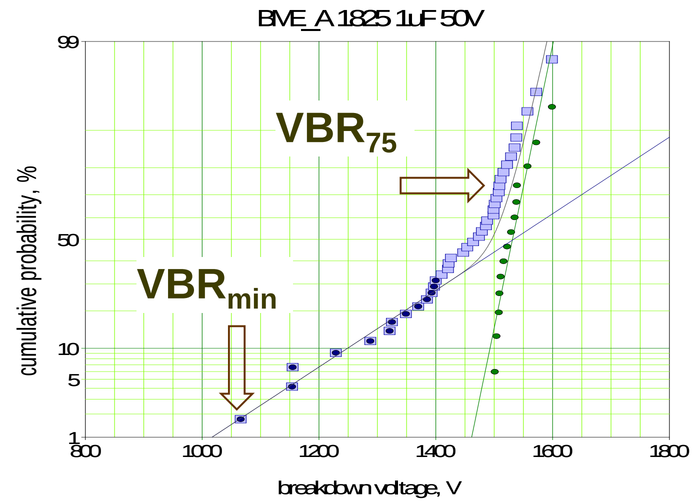
Comparison of distributions for the same type of BME capacitors.





- ✓ Analysis of distributions allows for assessment of the quality of capacitors and revealing improvements.
- ✓ Automotive industry and general purpose parts might be from the same population and have similar defects.

Analysis of VBR Distributions for QA



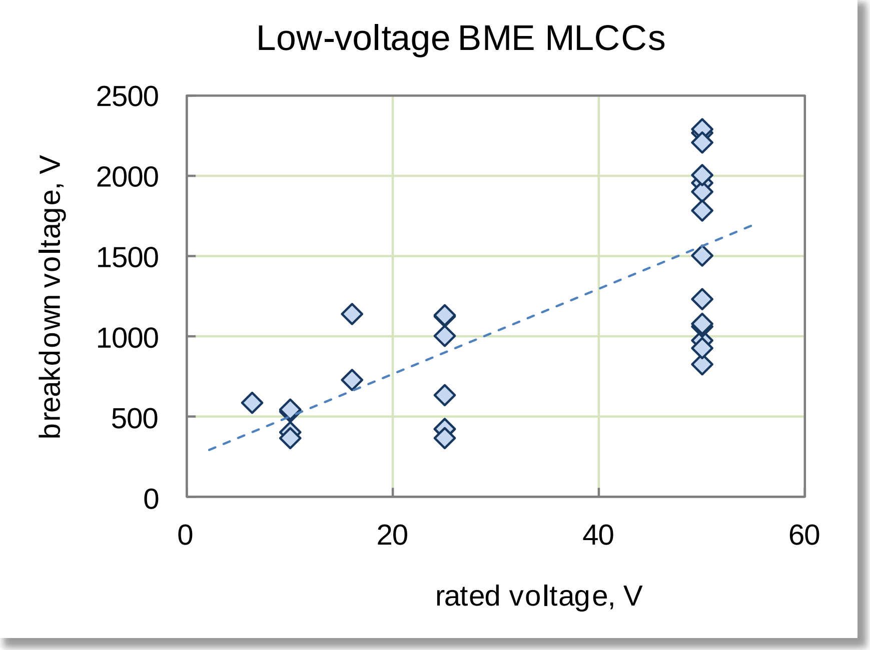
- Out of 27 types of BME capacitors 67% had bimodal distributions.
- The proportion of capacitors with defects was from 2.6% to 80%.
- The significance of the defects (the ratio of VBR_{min} and VBR_{75}) varied from 0.3 to 0.95.
- Assuming that acceptable defects would reduce breakdown voltage less than 2 times, 5 out of 27 lots should be rejected.

✓ Analysis of distributions of VBR allows for the assessment of the quality of the lot.

✓ The lot is acceptable for space applications if $VBR/VBR_{75} > 0.5$.

Rated and Breakdown Voltages

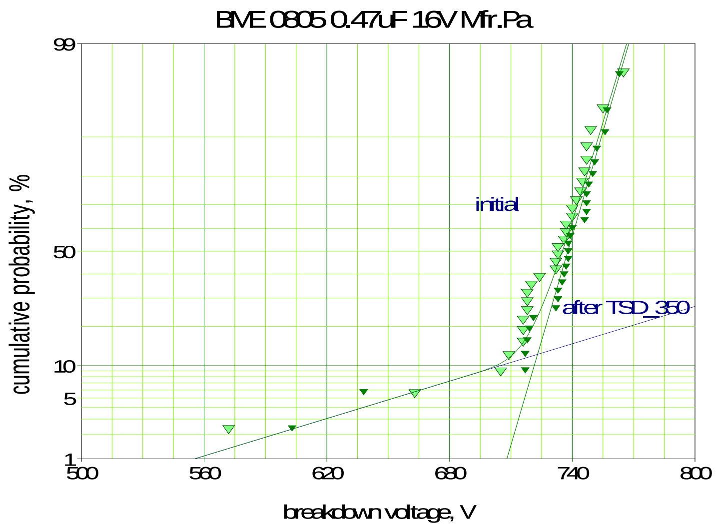
- ❑ VBR exceeds VR more than 15 times.
- ❑ Breakdown voltages on average increased with the rated voltage.
- ❑ The spread of the data was large: at VR = 50 V, VBR varied from 17VR to 45VR.

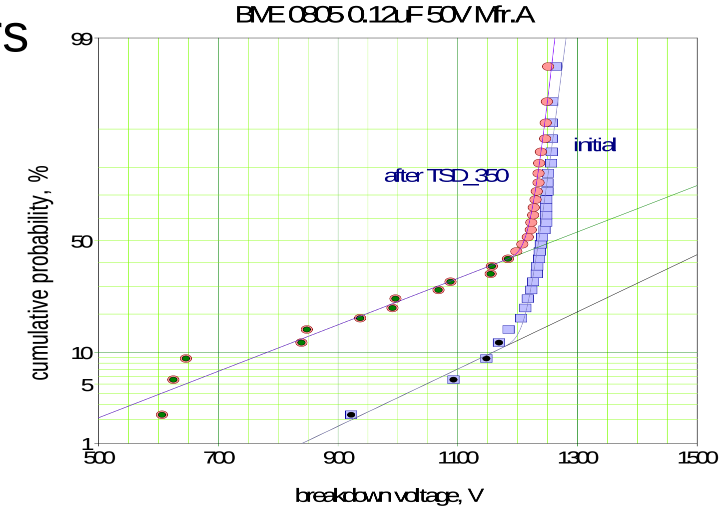


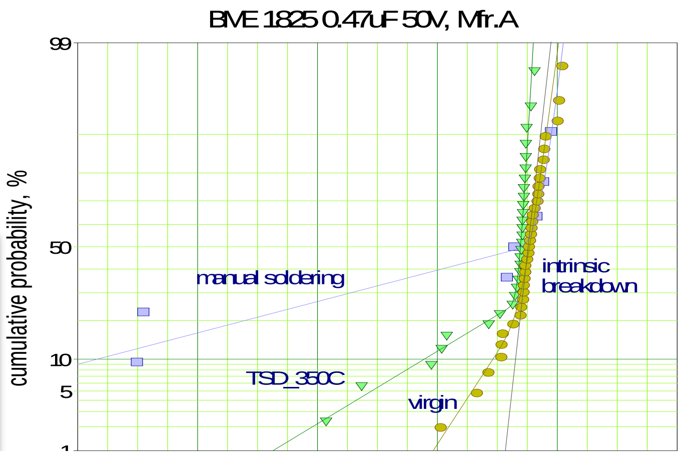
- ✓ Breakdown voltage is not a limiting factor in assigning VR to low-voltage capacitors.
- ✓ In class II dielectrics VR is limited by the non-linearity of polarization that results in decrease of capacitance with voltage.

Effect of Soldering Stresses

- 3 cycles of TSD testing at T_{solder} = 350 °C.
- Case size 1825, 0.47 µF, 50 V capacitors were tested after manual soldering with a soldering iron set to 350 °C.





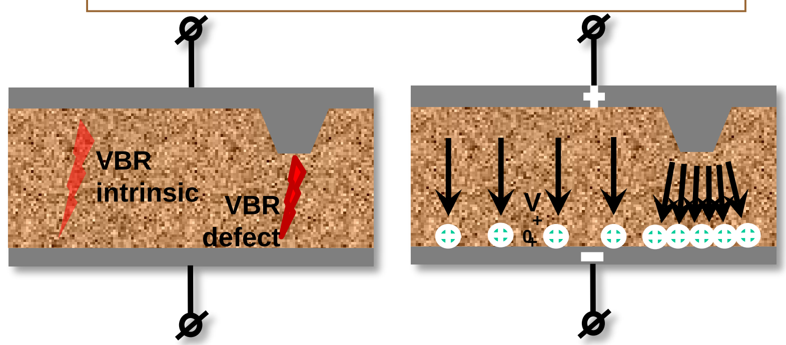


- ✓ Stresses related to manual soldering can degrade VBR.
- ✓ VBR should be used to assess the possibility of manual soldering.

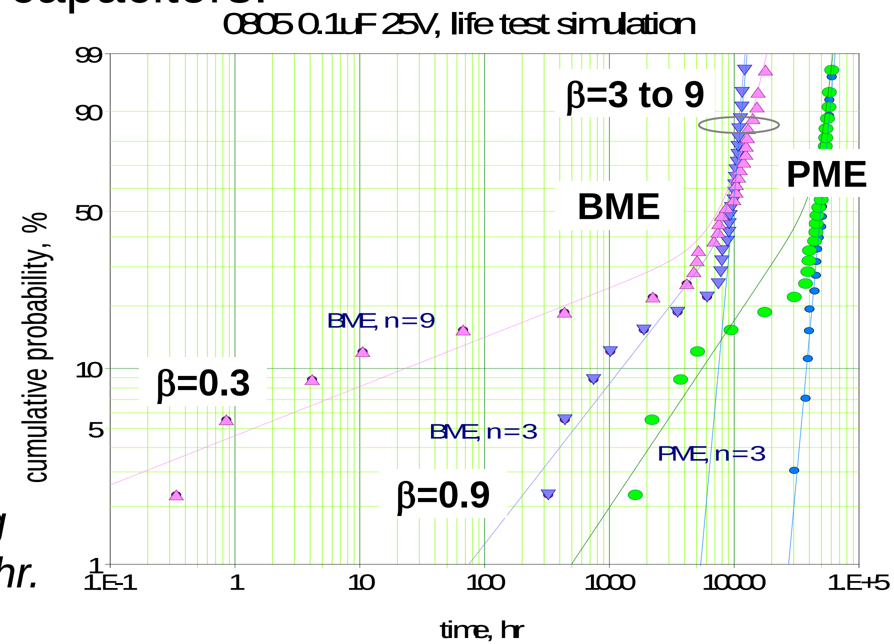
Simulation of Life Testing (2VR, 125°C)

Assumptions: intrinsic degradation for a defect-free part results in failures at TTF_0 and the voltage AF follows Prokopowicz-Vaskas equation with *n* ~ 3 for PME and *n* from 4 to 9 for BME capacitors.

$$TTF = TTF_0 \times \left(VBR_d / VBR_i \right)^n$$



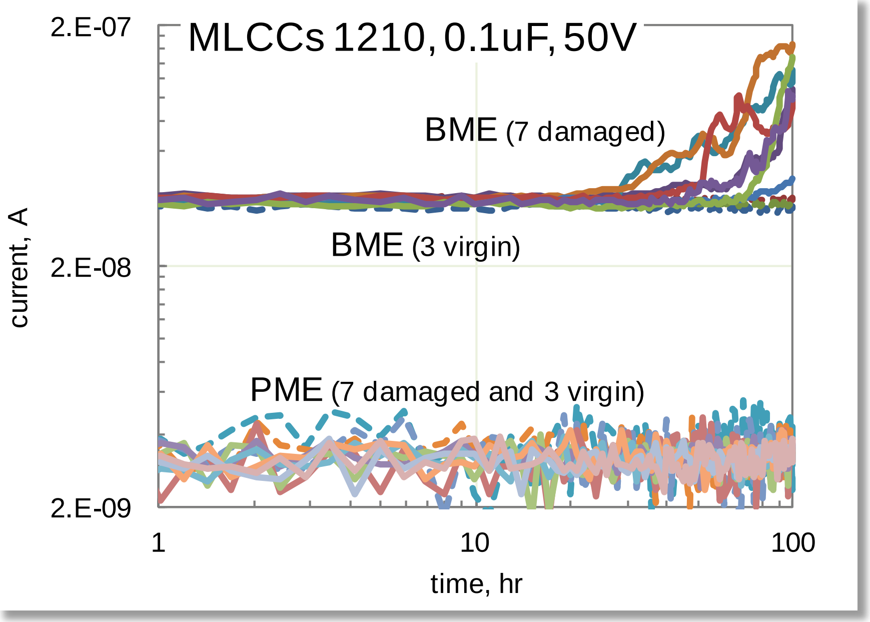
TTFs were calculated based on VBR assuming for PME TTF_0=50 khr, and for BME TTF_0=10 khr.

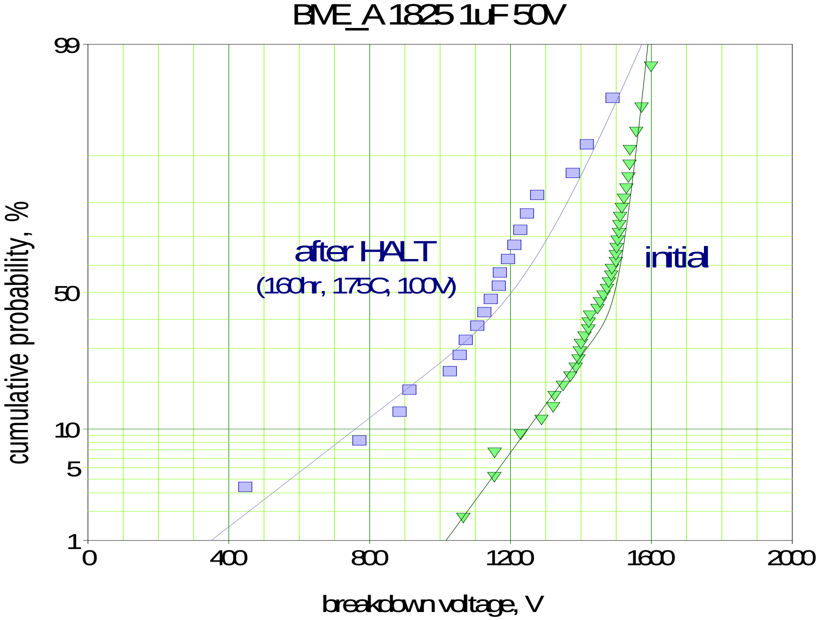


- ✓ Similar defects are more likely to cause life test failures in BME compared to PME capacitors.
- ✓ The greater the voltage acceleration constant *n* and the lower VBR/VBR_{75} , the more probable infant mortality failures are.

Effect of Defects in MLCCs on Reliability

BME and PME MLCCs with introduced defects were stressed by HALT.

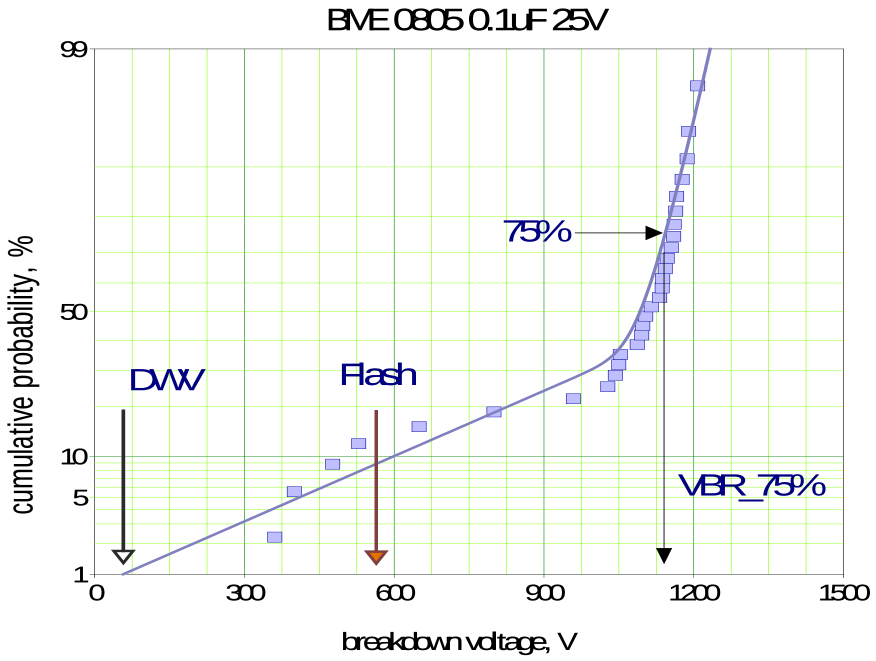




- ✓Defects resulting in DCL degradation of BME capacitors might not affect PME capacitors.
- ✓VBR for BME capacitors degrades after HALT.
- ✓The effect is more significant for the LV subgroup of MLCCs.

Flash Testing

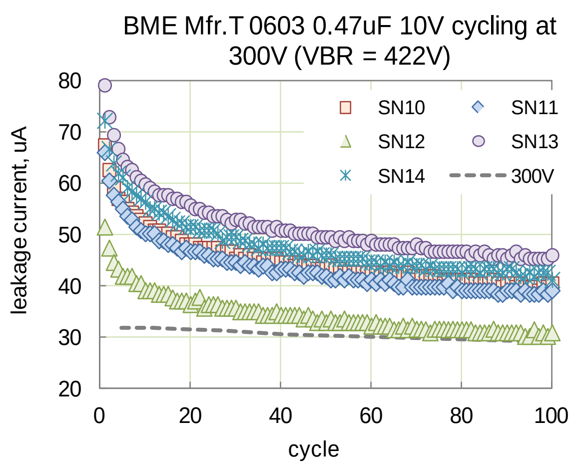
- DWV testing can reveal only gross defects in low-voltage BME capacitors.
- Testing at higher voltages would be more effective.
- Time of exposure to HV should be reduced.
- The third quartile is close to the mean value of VBR for the HV subgroup of capacitors.

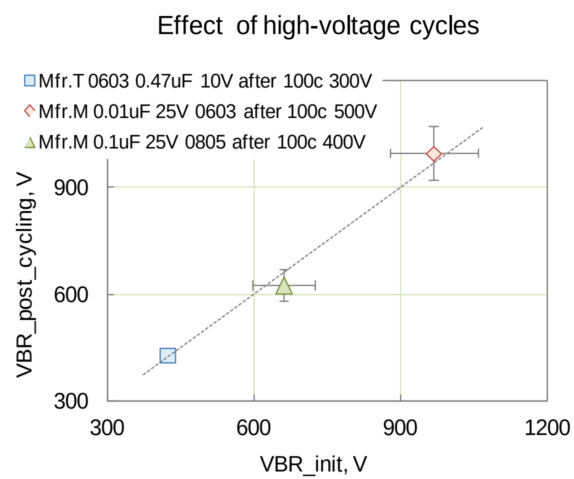


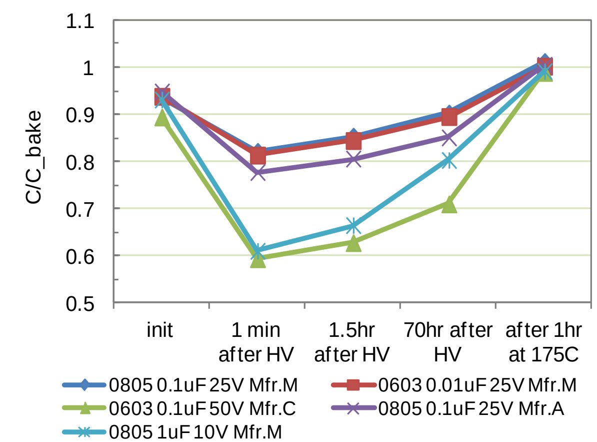
✓ Flash testing should be carried out at the same conditions as VBR measurements, except for it does not require oil as the medium and maximum applied voltage is limited to $0.5\times VBR_{75}$_air.

Can Exposure to HV Cause Damage?

Different types of BME MLCCs were characterized before and after stressing with 1 to 5 sec pulses at V ~ 0.7VBR







- ✓ No effect on leakage current and VBR.
- ✓ Remnant polarization can decrease C; however, this effect decreases with time of storage and disappears after annealing at T > Tc (~ 120 °C).
- ➢ No risks associated with HV exposure.

Recommendations

- A lot should be characterized by a distribution of VBR based on 50 samples tested in oil (and in air for gr. C qualification testing) at maximum current of 10 mA and voltage ramp of 25 V/sec for C ≥ 1 μF and 100 V/sec for C < 1 μF. The values of VBR_{75}_oil, VBR_{75}_air, and VBR_{min} allow for the assessment of the consistency in quality, as a baseline to determine conditions for the flash testing, and to evaluate results of the RSH test.
- Lots with VBR_{min}< 0.5×VBR_{75}_oil have a higher risk of failures and should not be accepted for space applications.
- Flash testing should be used as a screening procedure at the same conditions as VBR measurements, except for it does not require oil as the medium and maximum applied voltage is limited to 0.5×VBR_{75}_air.
- VBR measurements should be used as a lot acceptance procedure after RSH testing using 30 samples minimum. The acceptance criterion: VBR_{min} > 0.5×VBR_{75}_oil or VBR_{min} > 0.5×VBR_{75}_air for the parts soldered onto a test board.

Summary

- Reliability of BME MLCCs is limited by defects.
- The existing S&Q system can reveal only gross defects.
- Analysis of VBR distributions allows for estimation of the proportion and severity of the defects.
- Recommendations for using VBR measurements for S&Q are suggested.