

Lessons Learned from Failure Cases of MLCCs

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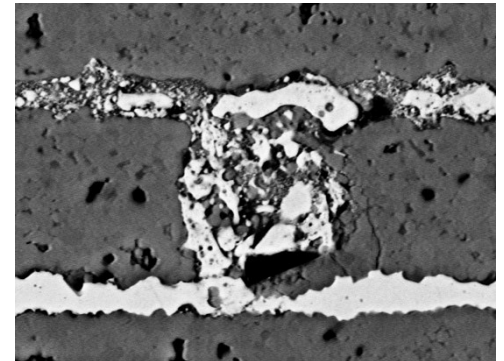
Acronyms

AC	alternating current	LT	life test
AF	acceleration factor	MLCC	multilayer ceramic capacitor
BI	burn-in	PE	parts engineer
BME	base metal electrode	PME	precious metal electrode
COTS	commercial-off-the-shelf	PWB	printed wiring board
CTE	coefficient of thermal expansion	RH	relative humidity
DC	direct current	RSH	resistance to soldering heat
DF	dissipation factor	RUS	resonant ultrasound spectroscopy
DWV	dielectric withstanding voltage	S&Q	screening and qualification
EMR	electromechanical resonance	SAM	scanning acoustic microscopy
FA	failure analysis	SCD	source control drawing
FR	failure rate	TDDB	time dependent dielectric breakdown
HALT	highly accelerated life testing	TDR	time domain reflectometry
HSSLV	humidity steady state low voltage	THB	temperature humidity bias
I&T	integration and testing	TS	thermal shock
IDC	inter-digitated capacitor	TSD	terminal solder dip
IFT	indentation fracture toughness	TTF	time-to-failure
IR	insulation resistance	VBR	voltage breakdown
LL	lessons learned	VR	voltage rating

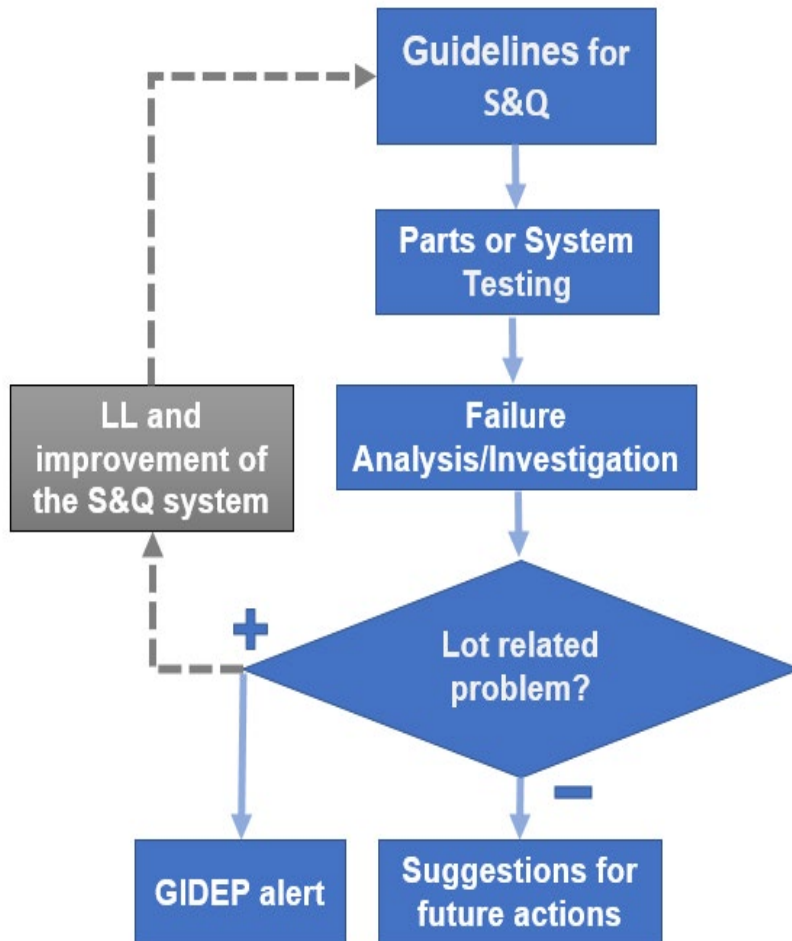
Outline



- ❖ Parts engineering process.
- ❖ Cracking/delamination in MLCCs.
 - Reasons for cracking/delamination.
 - Mechanisms of failure in the presence of cracks.
 - Deficiencies of the existing S&Q system and possible improvements.
- ❖ Life test failures in COTS BME MLCCs.
 - Mechanism of failures.
 - Can we use COTS capacitors that fail LT?
- ❖ Conclusion.



Parts Engineering Process

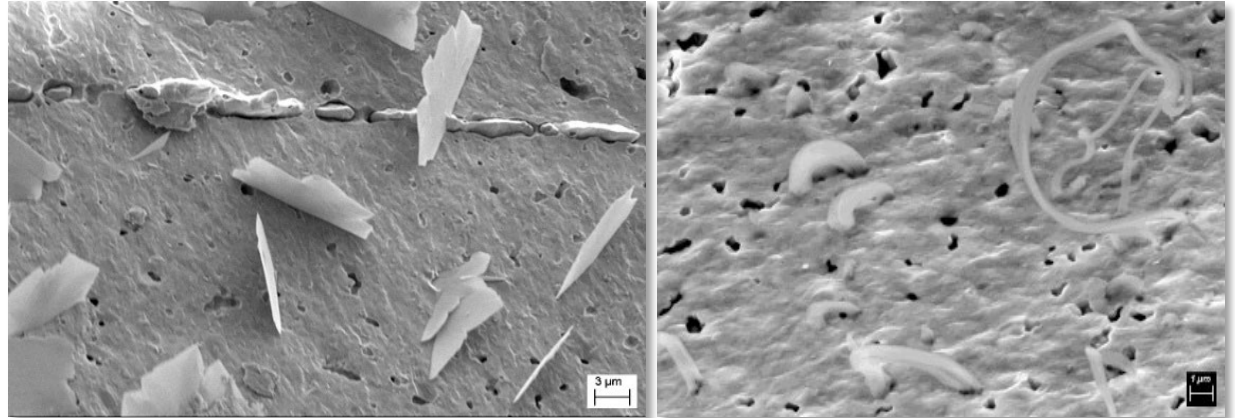


- ❑ The purpose of PE activity is to ensure adequate quality and reliability of components for space projects.
- ❑ Verification that the parts are compliant with different S&Q requirements for the different level projects.
- ❑ Quality = compliance with the rules. But how are the rules set?
- ❑ Failures during component life testing require FA, but failures during I&T or post-launch (at derated conditions) => failure investigation and LL.

✓ The system of S&Q cannot be effective without a feedback => the purpose of LL.

Reasons of Cracking

Anomalous structures in fractured capacitors are evidence of high mechanical stresses and chemical activity of ceramics in MLCCs.

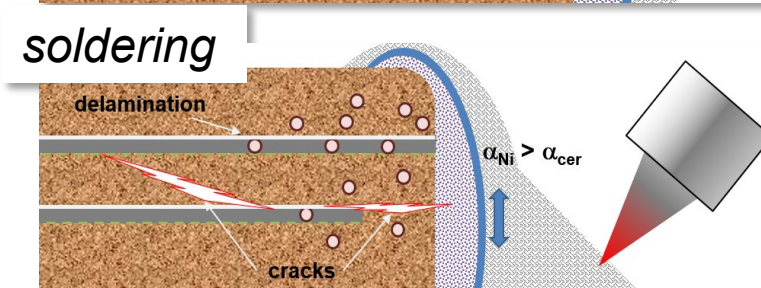
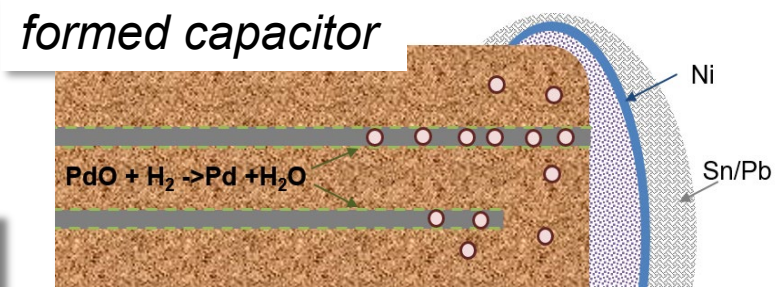
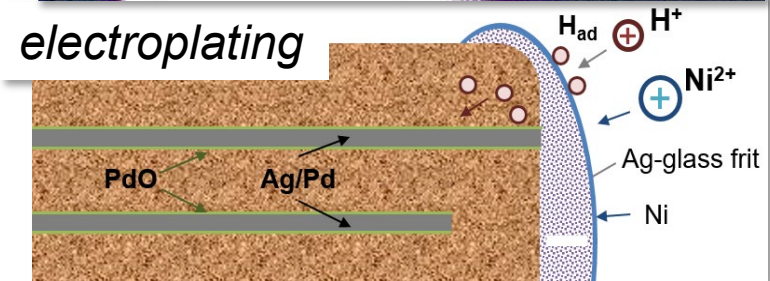
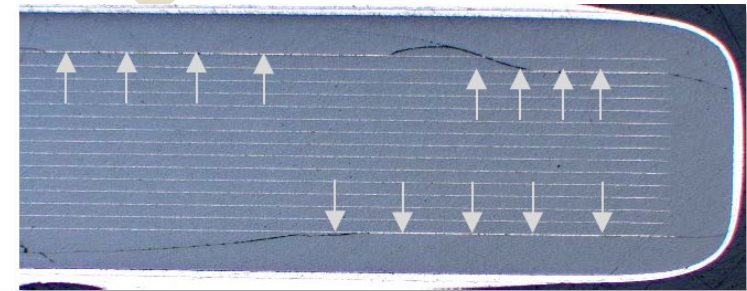


Hydrocerussite-like, $\text{Pb}_3(\text{OH})_2(\text{CO}_3)_2$ platelets and carbon filaments.

- ❑ A reason for cracking: combination of internal and external stresses that result in tension that exceed strength level.
- ❑ Factors affecting cracking-related failures:
 - Internal: design and materials (margins, termination materials and sizes), manufacturing (built-in stresses, ceramic materials)
 - External: operating conditions, soldering, board-level stresses, etc.
- ❑ Effect of attachment: reflow and manual soldering, touch-up.

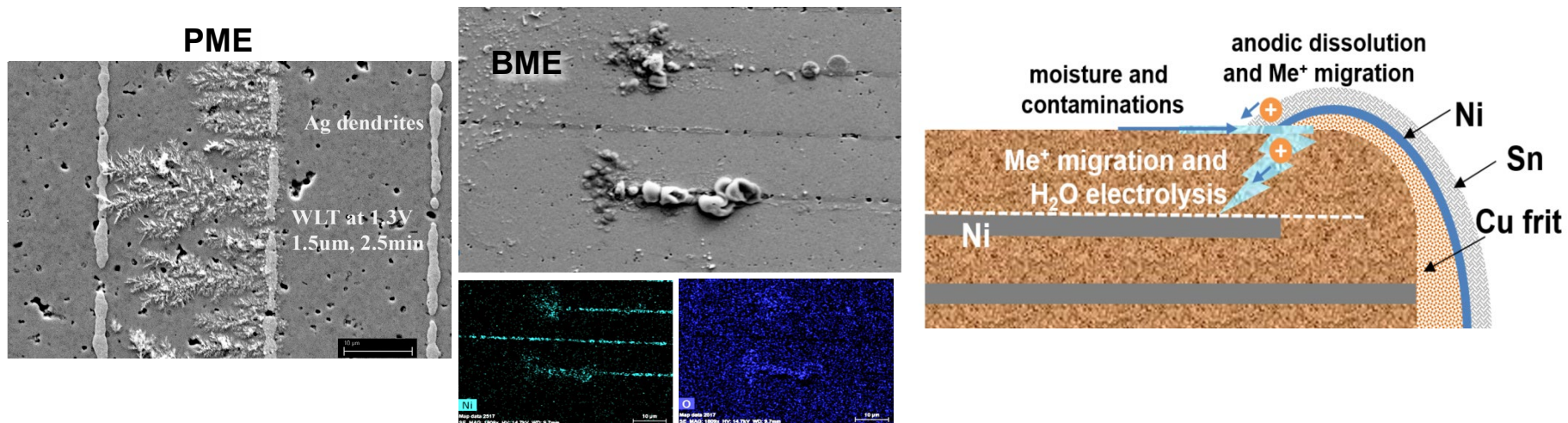
Effect of Hydrogen

- ❑ On-orbit anomalies with CDR35 capacitors after several months of operation.
 - ❑ Delamination might be due to generation of H_2 during electroplating that:
 - decreases the fracture toughness;
 - removes PdO barrier on Ag/Pd electrodes;
 - reduces the volume of electrodes;
 - weakens Me/ceramic interface;
 - facilitates electromigration of Ag.
 - ❑ Higher CTE of termination materials compared to ceramic creates tension stresses facilitating delamination.
- ✓ Failures were likely due to anomalies of electroplating processes.
 - ✓ Manual soldering accelerated failures in a lot with pre-existing defects.
 - ✓ Delamination in failed MLCCs might have been revealed by SAM examinations.



Failures in the Presence of Moisture

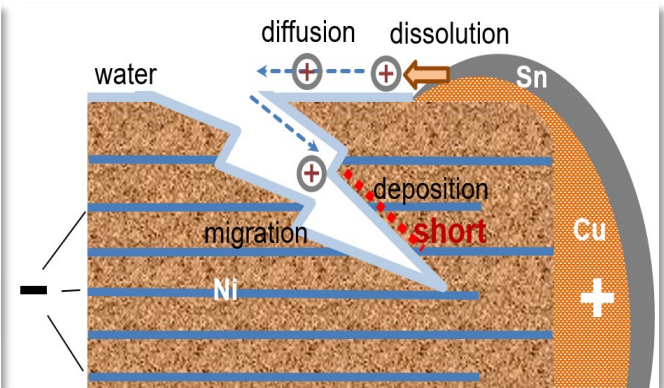
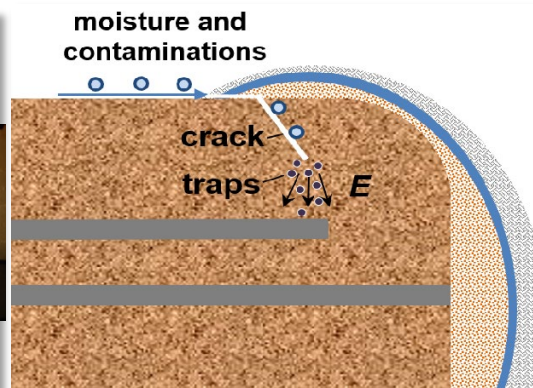
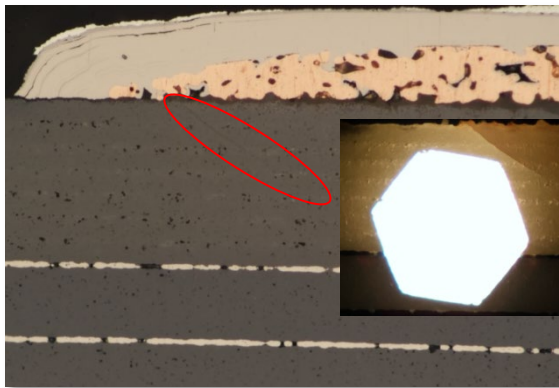
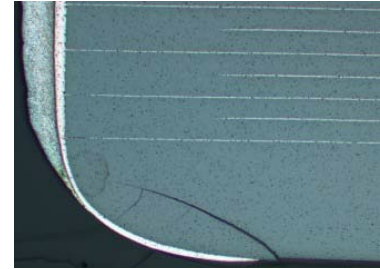
- ❑ The difference between PME and BME MLCCs is due to the specific electrochemical behavior of Ni and Ag/Pd electrodes and formed products (conductive Ag-based deposits for PME and isolative Ni/C/O compositions for BME).
- ❑ Anodic dissolution of Sn or Cu from terminations may result in conductive deposits or dendrites in cracks.
- ❑ Post-THB delamination might be due to hydrogen generated by electrolysis of water penetrated through cracks.



- ✓ The probability of failures for PME capacitors with cracks is greater than for BME capacitors due to a high susceptibility of Ag electromigration.

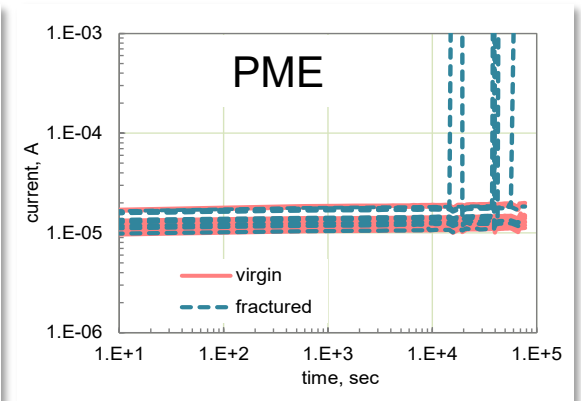
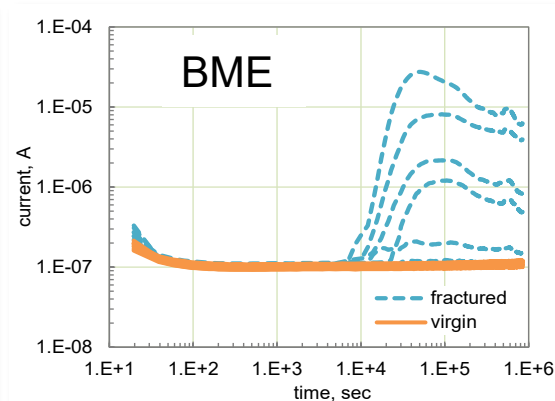
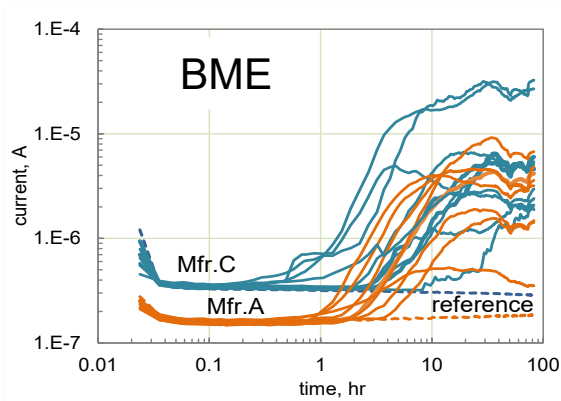
Effect of Corner Cracks

- ❑ Corner cracks are common and often disregarded.
- ❑ Multiple LT failures of BME 250V capacitors occurred under corner terminations.
- ❑ Moisture and contaminations can accumulate in the cracks over time at room conditions, and to a greater degree during humidity testing.
- ❑ Electric field at the tip of cracks may be higher than between electrodes, resulting in TDDDB.



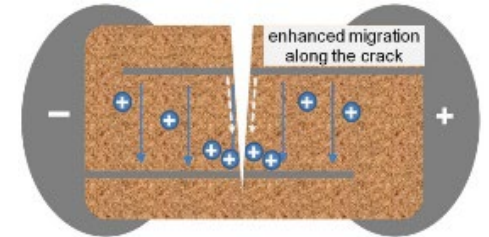
- ✓ Requirements for margins in MIL secs are less stringent than manufacturers' requirements for AEC-Q200 parts - need for a revision.

Failures in Dry Conditions



❑ Degradation in BME is due to a faster migration of V_O^{++} along the surface of cracks or near defects. It occurs gradually and energy generated at the defect can be balanced by heat dissipation.

❑ Degradation in PME is due to generation of traps in the dielectric. The breakdown occurs when concentration of defects reaches the critical level resulting in adiabatic release of energy and catastrophic failures.



✓ Defects that can cause thermal runaway failures in BME MLCCs during HALT may never happen at lower voltages. => The risk of overstressing thin dielectric BME capacitors during MIL-spec testing.

Revealing Defects during S&Q

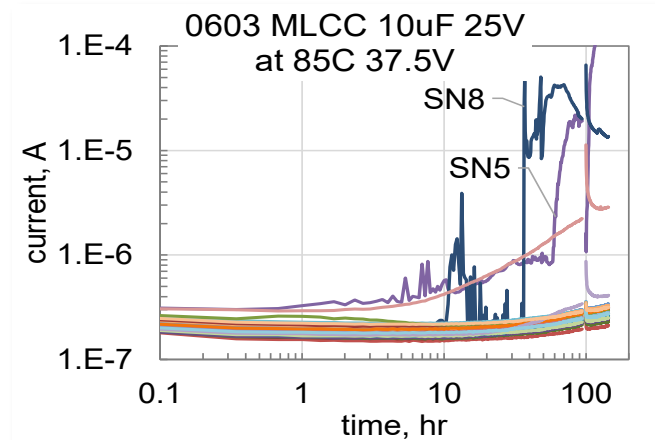
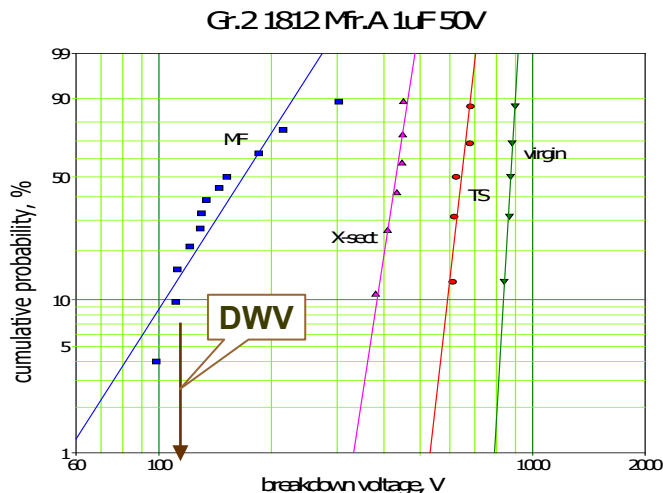
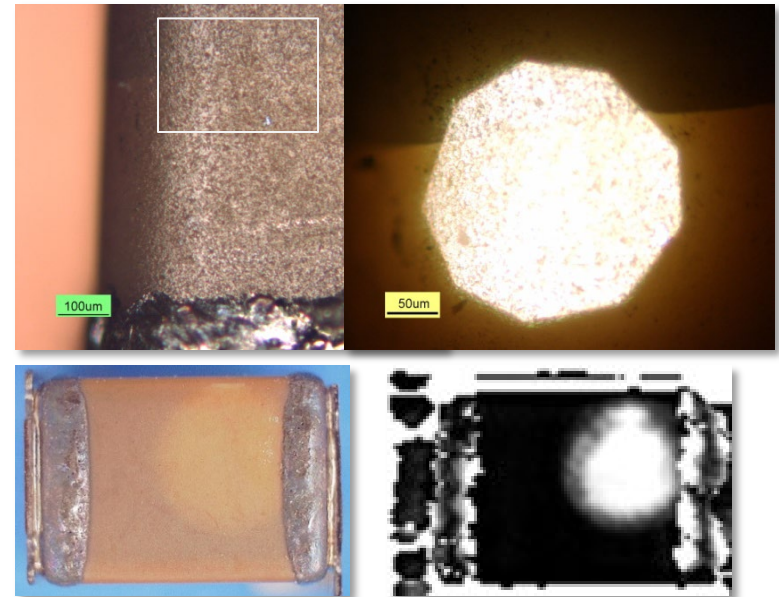
- ❑ Several cases of system-level failures were caused by cracks/delamination in PME MLCCs manufactured per M55681 or SCD specifications.

Test	M123 (ER)	M55681 (ER)	M32535T
Visual exam.	✓	✓	✓
C, DF, IR, DWV	✓	✓	✓
Burn-In	125C/168hr/2VR	T _{max} /100hr/2VR	125C/168hr/2VR
SAM	Before termination	-	Before and after termin. size ≥0805
Life Test (gr.B)	1000hr, 2×VR, 125C	-	1000hr, (1.5-2)×VR, 125C
VBR (gr.B)	-	-	VBR ≥ 6×VR /1200V
THB (gr.B)	M202 TM106 (50V during 10c)	-	12(0) pcs., 85C, 85% RH, 96hr, VR
HSSLV (gr.B)	240hr, 1.3V, +85°C/85%RH 12(0)	-	-

- ✓ Failures of CDR capacitors may have been prevented by better S&Q tests.
- ✓ HSSLV has not been required for MIL-grade parts since 2010.

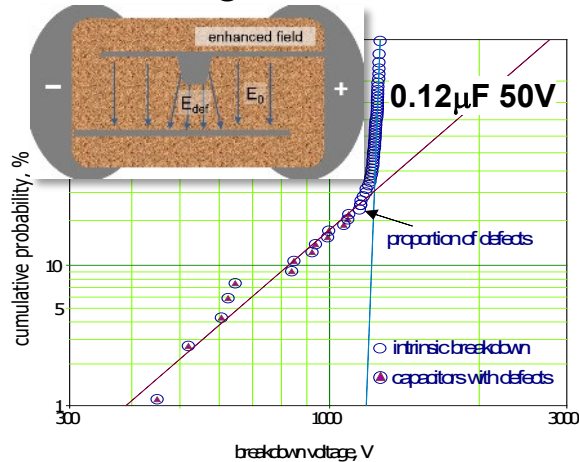
Deficiencies of the Existing S&Q

- ❑ Visual examination → vicinal illumination.
- ❑ AC (C, DF) and DC (IR, DWV) characteristics: insufficient sensitivity to cracks.
- ❑ SAM: not used for all MIL-grade capacitors, effect of terminations.
- ❑ BI, LT, THB: currents are not monitored.

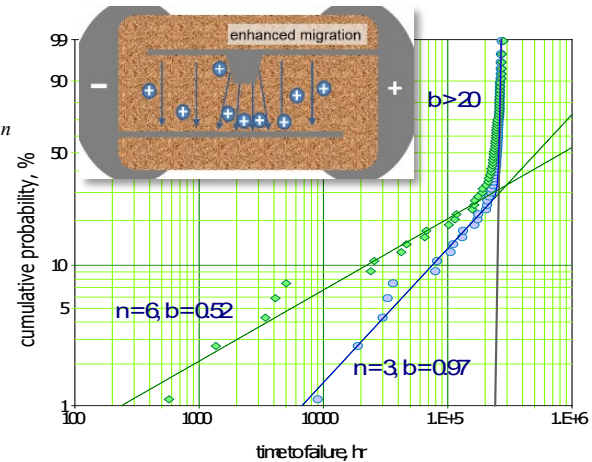


Deficiencies of the Existing S&Q, cont'd

- ❑ VBR testing can be used to screen out defects.



$$TTF = TTF_0 \times \left(\frac{VBR_d}{VBR_i} \right)^n$$

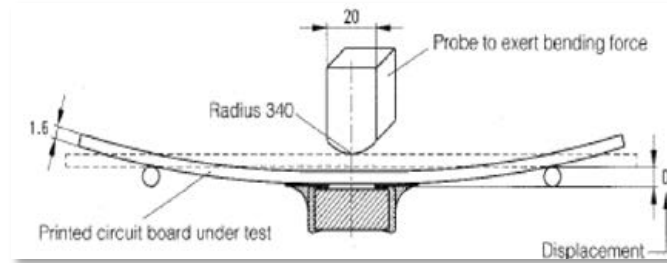


- ❑ Qualification testing are often carried out using loose parts.
- ❑ RSH (qual test) – less stressful than for COTS, no tests for manual soldering.
Manufacturers often use wave solder testing without preheating to assess quality of their production. The maximum temperature during this test is 280° C for automotive industry capacitors and 235° C for military capacitors. Solder iron testing is not used.
- ❑ Sample size for gr.B tests.

At the proportion of defective samples P_f , the number of samples that must be tested with a zero-failure result can be calculated as:

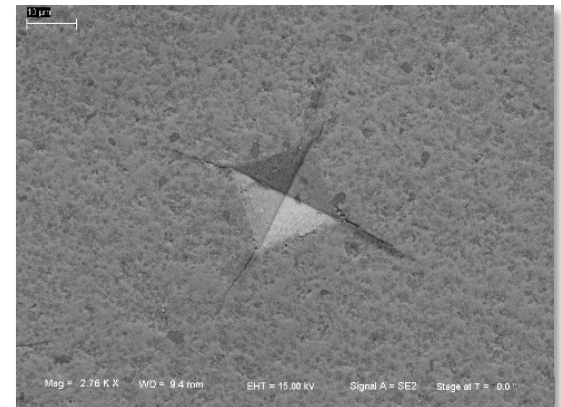
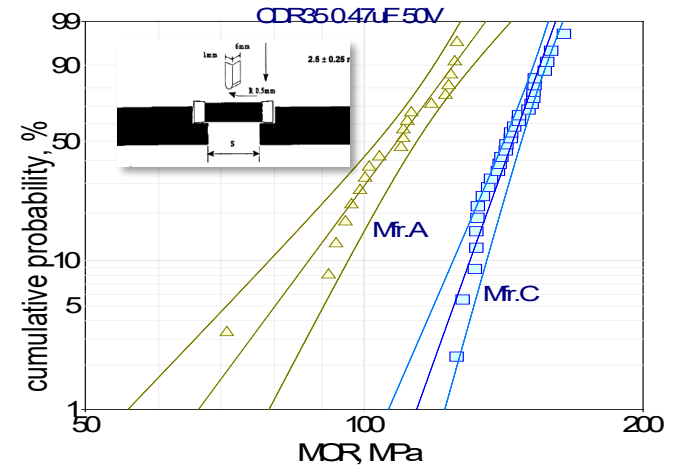
$$N(P_f) \approx -\ln(1-c.l.)/P_f, \text{ at } P_f = 0.1\% \text{ and } c.l. = 60\% \text{ calculations yield } N \approx 1000.$$

In-Situ Mechanical Tests



- ❑ Flex testing.
- ❑ The flexural strength ("Beam Load Test" per AEC-Q200).
- ❑ Vickers Hardness Testing.
- ❑ Indentation Fracture Toughness (IFT).

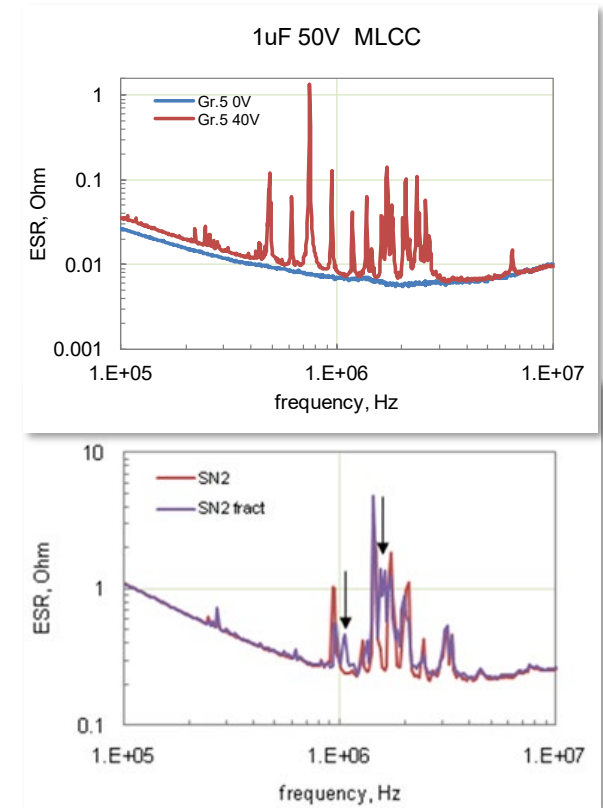
- ✓ Problems: accuracy and failure criteria.
- ✓ IFT might be useful for relatively large size capacitors with thicknesses of the cover layers exceeding the size of the introduced cracks.



Test Methods for Revealing Cracks

- ☐ Electro-mechanical resonance.
- ☐ Resonant ultrasound spectroscopy (RUS).
- ☐ Tone-burst excitation.
- ☐ Acoustic emission.
- ☐ Laser interferometry.
- ☐ Time Domain Reflectometry (TDR).

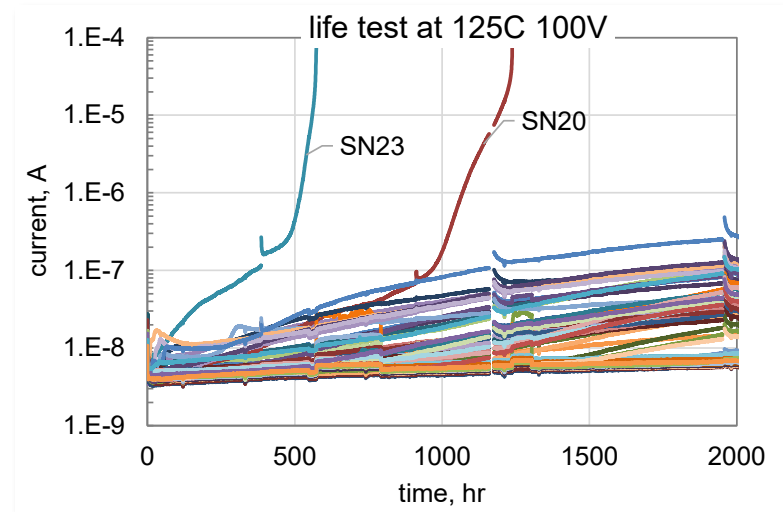
✓ None of the techniques are universal and can detect defective parts reliably.



- *Inverse piezoelectric effect results in acoustic waves in polarized capacitors.*
- *EMR may cause mechanical damage and result in failure.*

Can we use BME MLCCs that Fail LT?

- ❑ AEC-Q200 BME 0805, X7R, 10nF, 50V for use in 5V lines at 65 °C max.
- ❑ 300 samples passed monitored BI at 125 °C/100V/160hr with zero failures.
- ❑ Monitored LT: 60 samples soldered onto test PWB tested at 125 °C/100V/2000hr after 10 TS -55 °C to 125 °C.
- ❑ Two life test failures.



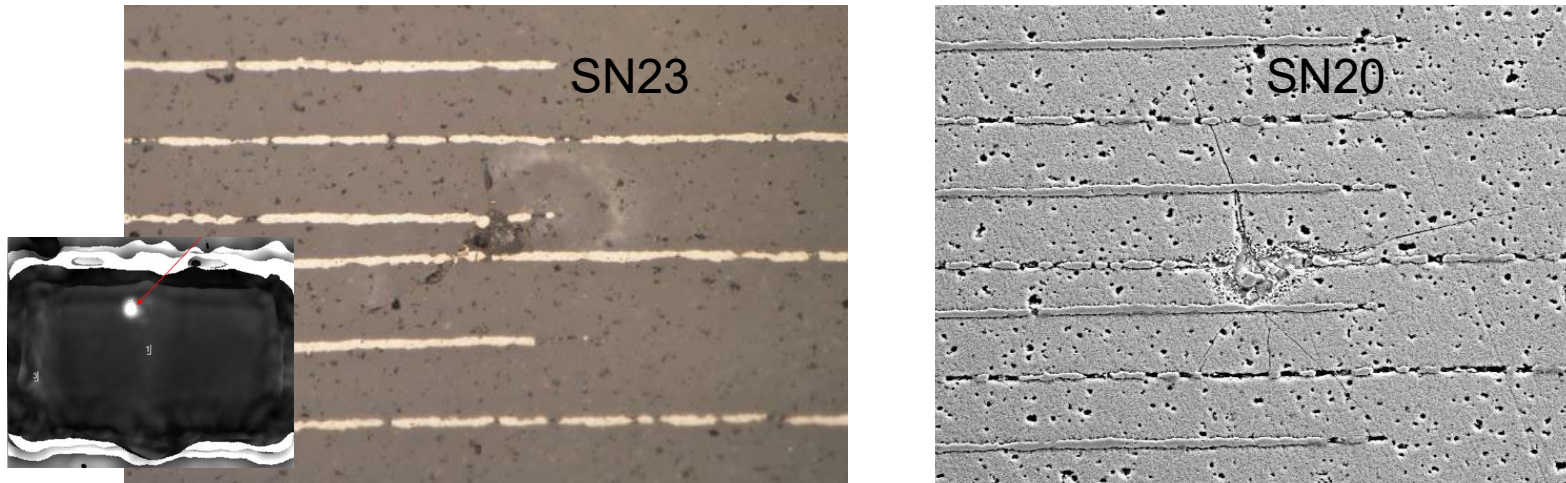
If a COTS part fails MIL spec life testing, can it still be used? If not, then:

- A. Relax requirements in the MIL spec (IDC capacitors, hybrids)?
- B. Assess acceleration factors and determine the probability of failure during the mission.

✓ Paradigm shift: confirming that a lot has acceptable reliability at application conditions instead of compliance with MIL-level requirements.

Failure Analysis

- ❑ Failed samples had resistances of 28k for SN20 and 2k for SN23.
- ❑ No external defects.
- ❑ Acoustic microscopy and cross-sectioning were used to reveal damage.



FA by Ron Weachock

- ✓ In both cases, the damage was due to a local breakdown.
- ✓ Failures were associated with a manufacturing defect: thinning of the dielectric from 13 μm in normal areas down to 5-7 μm at the failed sites.
- ✓ HALT was used for additional reliability analysis.

Reliability Assessments

□ AF per the Prokopowicz-Vaskas model:

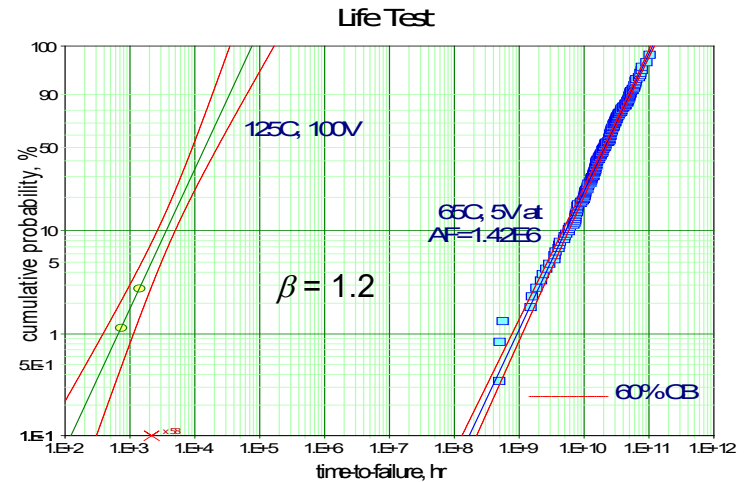
$$AF = AF_T \times AF_V, \quad AF_T = \exp \left[\frac{E_a}{k} \left(\frac{1}{T_{op}} - \frac{1}{T_{test}} \right) \right] \quad \text{and} \quad AF_V = \left(\frac{V_{test}}{V_{op}} \right)^n,$$

E_a is from 1 to 1.6 eV and n is varying from 3 to 9.

HALT for this lot showed $n = 3.5$, $E_a = 1$ eV.

$T_{test} = 125C$	$V_{test} = 100V$	
$T_{op} = 65C$	$V_{op} = 5V$	
$AF_{T_min} = 177$	$AF_{V_min} = 8E3$	$AF_{min} = 1.4E+06$
$AF_{T_max} = 3951$	$AF_{V_max} = 5.1E+11$	$AF_{max} = 2.0E+15$

For conservative estimations, $AF = 1.4E6$



- ✓ The time to failure inceptions (0.1%) increases from 120 hours for life test conditions to 19,000 years for use conditions.
- ✓ The probability of failure during a 20-year mission is $8.7E-8$, so the risk of failures during operation is small.
- ✓ According to the thermal run-away model for capacitors with defects, some parts that fail catastrophically HALT might never fail at low voltages.

Conclusion

- ❑ LL are necessary to improve the S&Q system.
- ❑ Failures due to cracking may happen at the system-level during I&T period, and even in space.
- ❑ Cracking-related problems:
 - Difficulties in revealing cracks.
 - Difficulties in failure predictions (modeling).
 - Derating might not work.
- ❑ The susceptibility to cracking is lot-related.
- ❑ Possible solutions for cracking problems:
 - Improvements in the S&Q process (monitoring leakage currents, SAM, TSD350, etc.)
 - Replacing large size PME with smaller size BME capacitors.
- ❑ Application of MIL requirements for COTS MLCCs is not justified.
 - A paradigm shift for BME COTS: analysis of the probability of failure at the mission conditions based on HALT and AFs instead of following MIL requirements.