Development of High Capacitance, High Voltage BME X7R Multi-Layer Ceramic Capacitors

John Bultitude, Jim Magee, Lonnie Jones,
Mark Laps, Bill Sloka and Abhijit Gurav

KEMET Electronics Corporation
2835 KEMET Way, Simpsonville, SC 29681, USA
Tel: +01-864-228-4052, Fax: +01-965-582-4707, e-mail: billsloka@kemet.com

Abstract

The need for high capacitance coupled with high voltage performance has driven KEMET's development of a new range of surface mountable, multi-layer ceramic capacitors (MLCC). These X7R capacitors with nickel inner electrodes are designed for voltage ratings of 500, 630, and 1000VDC. In order to achieve higher capacitance instead of 2 or more capacitors in series within an MLCC these new devices employ shield electrodes; as an added benefit these shield electrodes also prevent arcing. The overlap area within an MLCC is increased to achieve higher capacitance. The prevention of arcing allows higher breakdown voltages to be achieved compared to non-shielded MLCC and these are shown to be reliable through extensive life testing. The effect of ramp rate on breakdown performance is analyzed. Measurements of insulation resistance under various voltages and temperatures are presented together with characteristic ESR/ Impedance with frequency measurements. Combining these MLCC with flexible terminations allows them to withstand excessive board flexure compared to standard terminations. Load humidity testing after flexure of flexible and standard terminated MLCC is evaluated with respect to trying to quantify robustness.

Introduction

High voltage electronic circuits continue to develop and reducing size is a critical design consideration. To reduce size without compromising performance creepage distances are maintained using techniques such as slotted circuit boards and folding of flexible circuits; also surface arcing can be minimized by conformal coating. However, the size required by the components also has to be considered. The development of higher capacitance, high voltage BME X7R MLCC is described that will allow further miniaturization of circuits to be realized. Since surface arcing is prevented in these designs, no conformal coating is required.

Design Considerations

By placing a number of capacitors (N) in series, the acting voltage on each capacitor is reduced by the reciprocal of the number of capacitors (1/N). This principal has been applied by high voltage circuit designers for many years and to MLCC for almost as long. In addition to being known as "serial" capacitors MLCC with this arrangement are also known as "floating electrode", because of the unconnected electrodes connecting the two capacitors or "cascade" designs. However, there is a capacitance penalty in designing MLCC with two or more capacitors in series; the effective capacitances (C_{Eff}) is lowered by the sum of the reciprocal capacitances as shown in Equation 1.

$$1/C_{Eff} = \Sigma 1/C_N \qquad \textbf{Equation 1.}$$

Although very effective at achieving high voltage capability this approach limits the available capacitance. Furthermore on examining the cross-section of a typical 2-serial MLCC design (Figure 1.) the volume available for the active area is limited.

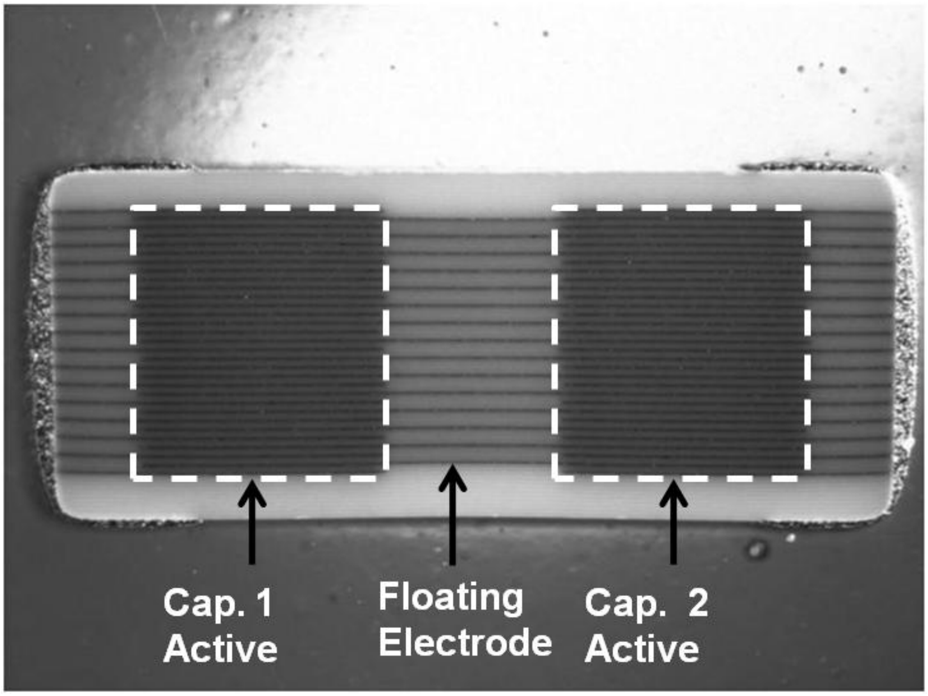

Figure 1. Cross-section of a 1500Vrated 2-serial, 1206, 10nF X7R MLCC

The active volume is the overlap area (A), thickness between opposing electrodes (t) and the number of active layers of dielectric (n). These are related to the capacitance (C) by the permittivity of the dielectric material (Є) and the permittivity of free space ($Є_0 = 8.854 \times 10^{-12}$ F/m) according to Equation 2.

$$C = Є\, Є_0 An/t \qquad \textbf{Equation 2.}$$

In the last several years, alternate MLCC designs have been developed[1] to increase capacitance. These designs work on the principle of a partial Faraday cage that prevents arcing in air. By prohibiting surface arc-over, low voltage surface breakdown associated with this failure mode in standard type overlap designs are eliminated. In its simplest form “shield electrodes” are added to the top and bottom of the active electrodes in the capacitors. The cross section of a standard overlap MLCC with 40 active electrodes is shown in Figure 2 and can be compared to a similar MLCC with the same number of actives (n) of the same thickness (t) as well as overlap area (A) to which an additional top and bottom shield electrodes were added as shown Figure 3.

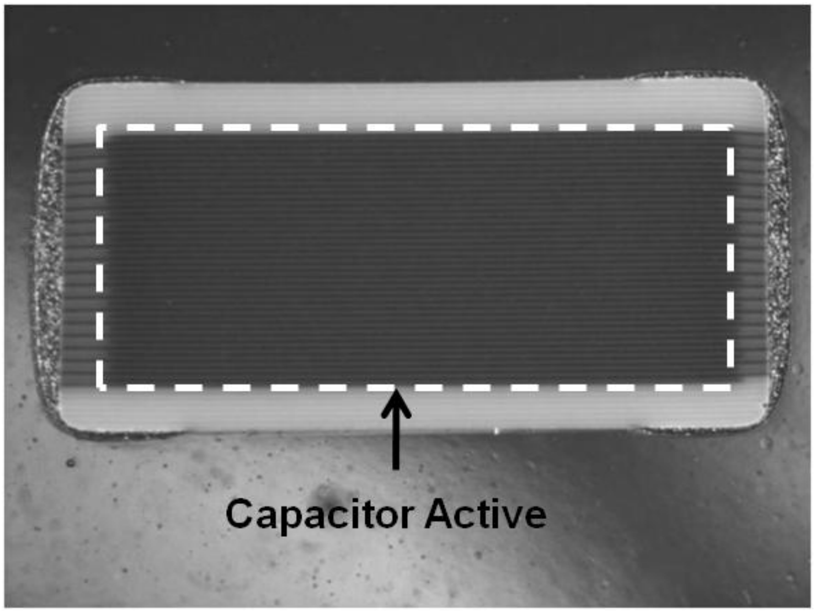

Figure 2. Cross-section MLCC with Standard Overlap

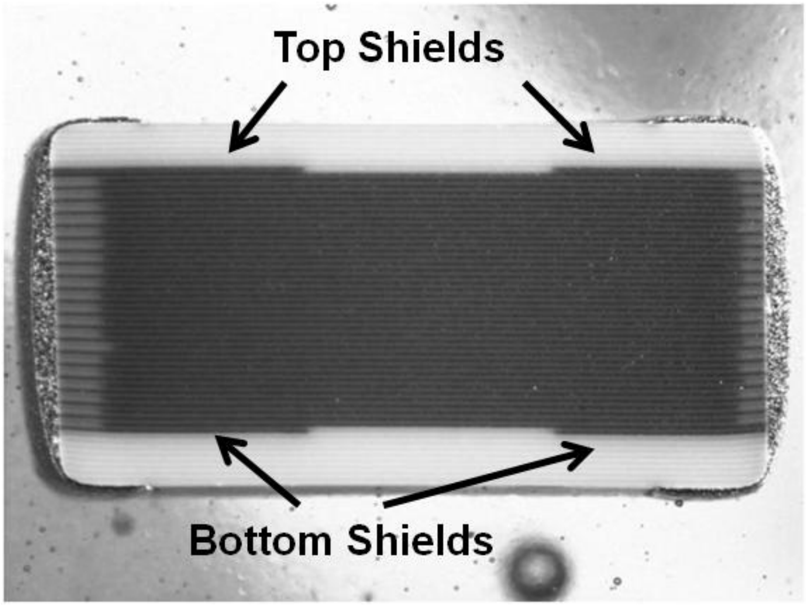

Figure 3. Cross-section MLCC with addition of Top & Bottom Shields

The 1206 case size MLCCs shown in Figures 3 and 4 were made with the same BME X7R material system. The benefit of the addition of the simple shield electrodes can be appreciated by comparing the capacitance, dissipation factor and voltage breakdown in air of these as summarized in Table 1.

MLCC Design	Capacitance and Dissipation Factor - 50pcs					Voltage Breakdown in Air - 50 pcs (VDC)			
	48 hr Cap Mean (nF)	Cap Std Dev (nF)	Cap % Std Dev	48 hr DF Mean (%)	DF Std Dev (%)	Avg.	Max.	Min.	Std. Dev.
Standard Overlap	137.48	0.86	0.63%	1.42	0.039	972	1350	730	146
Top/Bottom Shields	141.00	1.44	1.02%	1.48	0.024	1347	1720	1060	156

Table 1. Electrical Characteristics Standard Overlap Vs Top/Bottom Shield MLCC

The addition of the shields adds slightly to the capacitance and DF is slightly higher. The voltage breakdown in air measured at a ramp rate (dV/dt) of 300V/sec is higher for the MLCC with the shields. The standard overlap design had a minimum breakdown at 730V; the lowest breakdown increased to 1060V by adding shields. The average breakdown increased from 972V for the standard overlap to 1347V for the MLCC with shield electrodes.

Previous work has shown the voltage breakdown in inert fluid for non-shielded standard overlap designs are equivalent to the shielded design since the early arc-over failures are prevented[2]. This is indicative of another way of preventing arc-over by using conformal coatings[3, 4]. Conformal coating is relatively expensive and difficult to achieve for surface mounted MLCC because the terminations must be free of coating to allow subsequent assembly. As a result conformal coating is more commonly applied to the assembled boards. In either case complete coverage by the conformal coating over the MLCC surface must be achieved to be effective. Also typical coatings are not capable of subsequent thermal processing so once coated the boards cannot be assembled into power supplies using IR reflow processing or other processes that reach temperatures beyond the coating capability.

By applying the shield design principal and optimizing both the overlap area of the active electrodes and the dielectric formulation, high capacitance was achieved with BME X7R MLCC whilst retaining high voltage performance without the aforementioned compromises required of conformal coatings. This work is described in the following section.

High Voltage Performance

As described in the previous section voltage breakdown data is typically used as an indicator of design merit for high voltage capacitors. Although it is a useful gauge with respect to capability, the long term reliability has to also be assessed as noted in previous work in this area[5]. Life test data for 1206 X7R BME MLCC with shield designs was measured at 125°C at 2 different test voltages, 500V and 1000V. The Top and Bottom shield design described in the previous section was tested and compared to a Modified shield design. The results are shown in Table 2.

MLCC Design	Voltage Breakdown in Air - 50 pcs (VDC)				Life Test @ 500V & 125°C			Life Test @ 1000V & 125°C	
	Avg.	Max.	Min.	Std. Dev.	250 hrs	500 hrs	1000 hrs	250 hrs	500 hrs
Top/Bottom Shields	1347	1720	1060	156	0/77	0/77	3/77	16/77	41/77
Modified Design	1712	2140	1120	224	0/77	0/77	0/77	2/77	2/77

Table 2. Voltage Breakdown and Life Test data for 2 different Shield Designs

Although the Modified design has a higher average voltage breakdown, the lowest failure that occurred was only 60V higher than the previous design. The life test results at 500V are slightly better for the Modified design but at 1000V this has far fewer failures. By life testing parts a greater appreciation of the impact of design on performance can be acquired and using this approach the design rules to achieve reliable performance were developed.

In addition to refining the designs the dielectric formulation was also optimized. In Figure 4 voltage breakdown data is compared for the Original X7R and the New formulation made with the same MLCC shield designs.

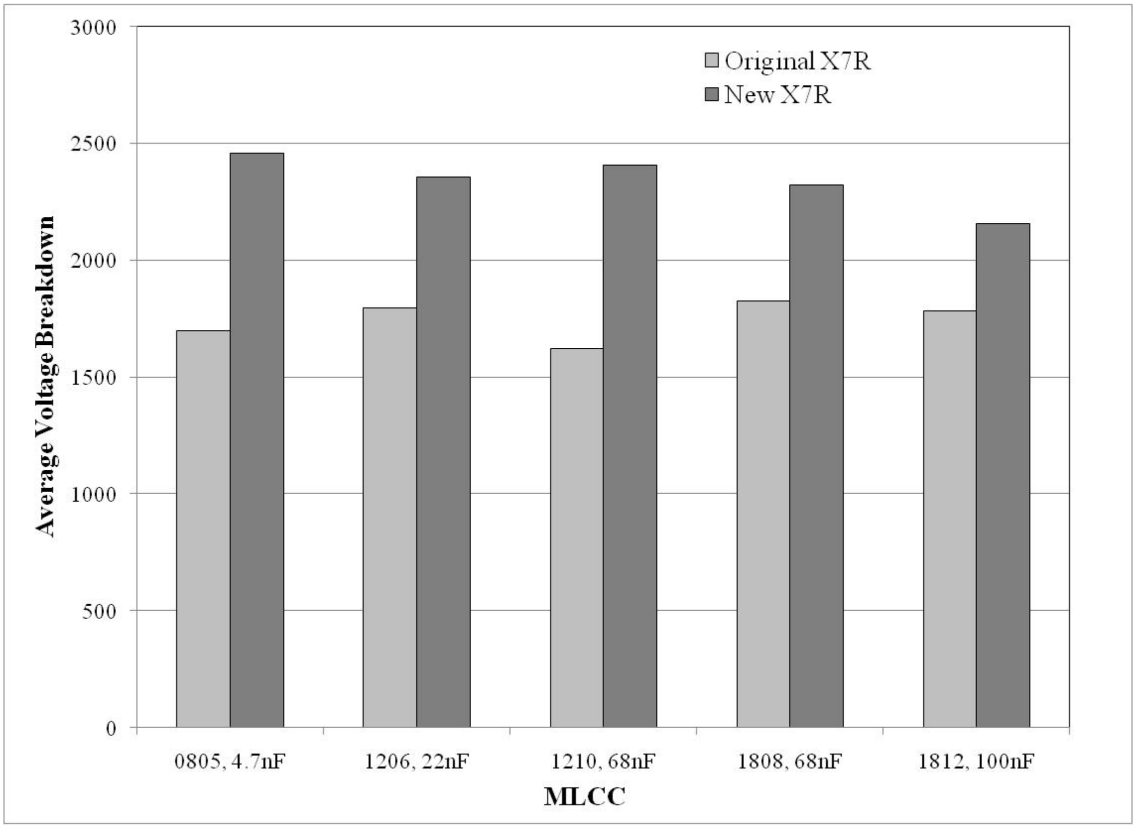

Figure 4. Average Voltage Breakdown for Original and New X7R Formulations

This data shows that for the New X7R formulation the average breakdown voltage increased by approximately 20% at these active thicknesses. A cross-section of a 1206, 68nF, 500V rated MLLC made with this new formulation and optimized design is shown in Figure 5.

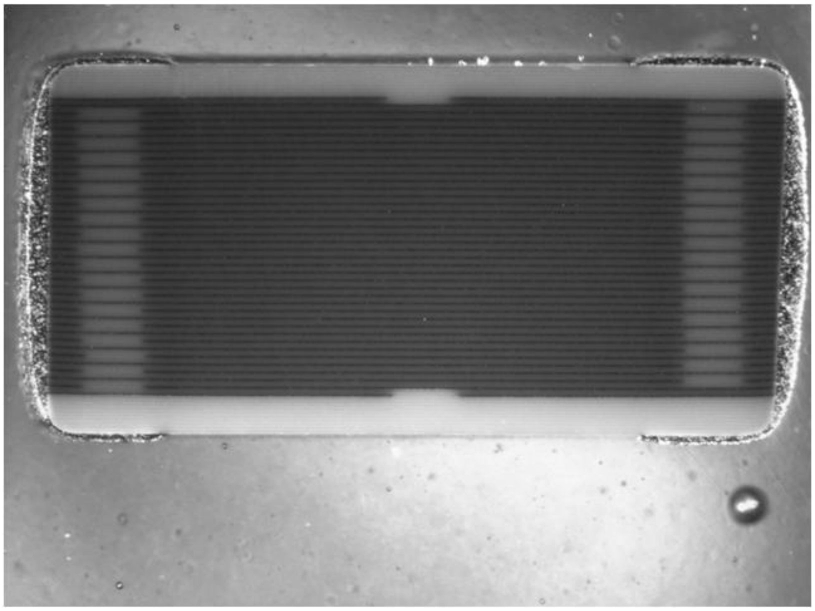

Figure 5. Cross-section of 1206, 68nF, 500V MLCC made using new X7R formulation and optimized design

Electrical Properties and Reliability

A range of X7R BME MLCC with higher capacitance values rated at 500V, 630V and 1000V in EIA case sizes from 0805 to 1812 was developed. Electrical and reliability data for some selected parts is summarized in Table 3.

KEMET Part Number	Voltage Rating	Average Capacitance (nF)	Average DF (%)	TCC (%)		IR (GΩ)		Average Voltage Breakdown in Air (VDC)	Life Test 1000 hr @ 1.2Vr, 125°C	Biased Humidity 1000 hr @ 200V, 85°C/85%RH
				-55°C	125°C	25°C	125°C			
C0805P123ACRAC	500	12.61	1.24	-8.72	-12.18	77.5	7.7	2138	0/77	0/77
C0805P822ABRAC	630	8.19	1.18	-9.56	-11.45	168.2	14.3	2276	0/77	0/77
C0805P472ADRAC	1000	4.75	1.10	-9.61	-10.79	400.4	25.8	2458	0/77	0/77
C1206P683ACRAC	500	71.96	1.14	-9.27	-13.51	12.6	1.3	2026	0/231 *	0/231 *
C1206P333ABRAC	630	33.31	1.03	-9.40	-11.91	40.4	3.5	2290	0/231 *	0/231 *
C1206P223ADRAC	1000	22.51	0.98	-9.37	-9.71	74.4	5.8	2271	0/231 *	0/231 *
C1210P154ACRAC	500	164.41	1.17	-8.79	-12.20	5.7	0.7	1913	0/77	0/77
C1210P104ABRAC	630	108.24	1.05	-9.46	-11.64	12.9	1.1	2152	0/77	0/77
C1808P154ACRAC	500	158.48	1.18	-13.22	-9.16	5.8	0.7	1908	0/77	0/77
C1808P104ABRAC	630	104.38	1.07	-12.03	-9.58	13.3	1.1	2072	0/77	0/77
C1808P683ADRAC	1000	72.18	1.04	-10.80	-9.80	28.7	1.8	2239	0/77	0/77
C1812P334ACRAC	500	340.00	1.14	-13.12	-9.07	2.7	0.5	1802	0/231 *	0/231 *
C1812P154ADRAC	630	158.59	1.14	-8.66	-11.13	8.7	0.8	1984	0/231 *	0/231 *

*** 3 batches tested 77 pcs each**

Table 3. Electrical & Reliability data for higher capacitance X7R BME MLCC with shield designs.

The life test and biased humidity results confirm these parts have acceptable long term durability. The insulation resistances (IR) were measured at 500V after 60 second charge time. To test the effect of higher voltage and temperature on IR some selected parts were measured at 1000V at 3 temperatures 25°C, 85°C and 125°C using a 60 second charge time. The results are shown in Figure 6.

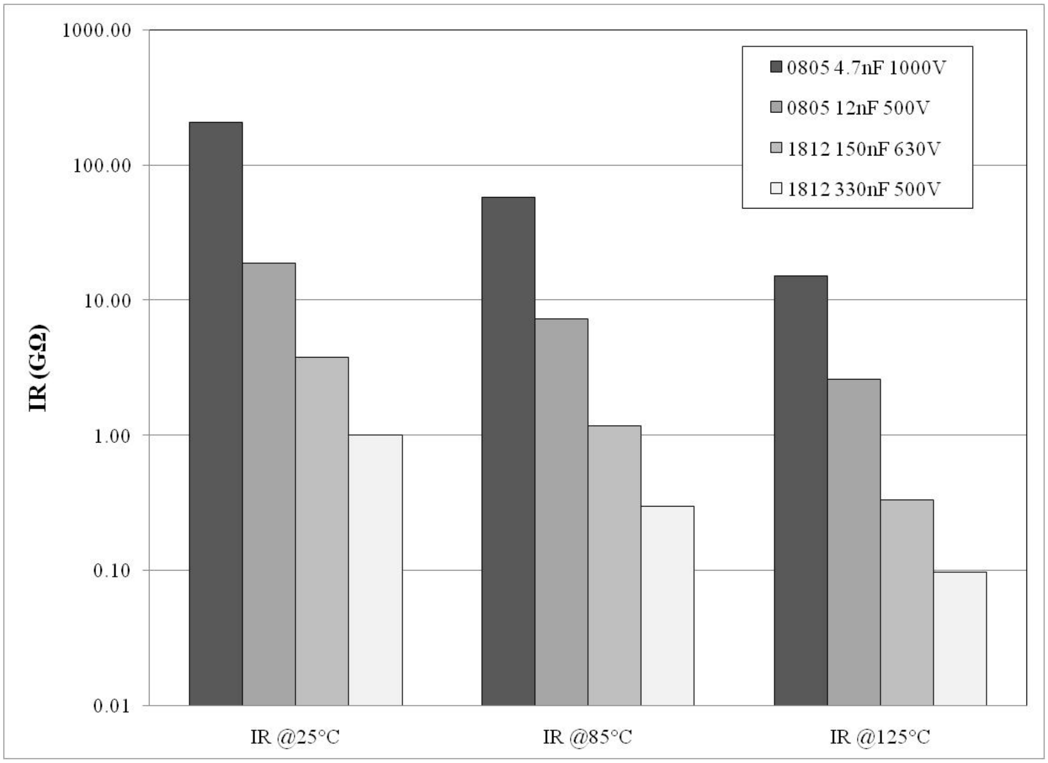

Figure 6. Insulation Resistance of X7R BME MLCC at 1000V

Even at 1000V and 125°C the IR remains around 100MΩ for the 330nF 1812. In all cases the RC factors at this temperature and voltage were ≥ 30ΩF.

The ESR and Impedance with frequency of these same types were also measured as shown in Figures 7 and 8.

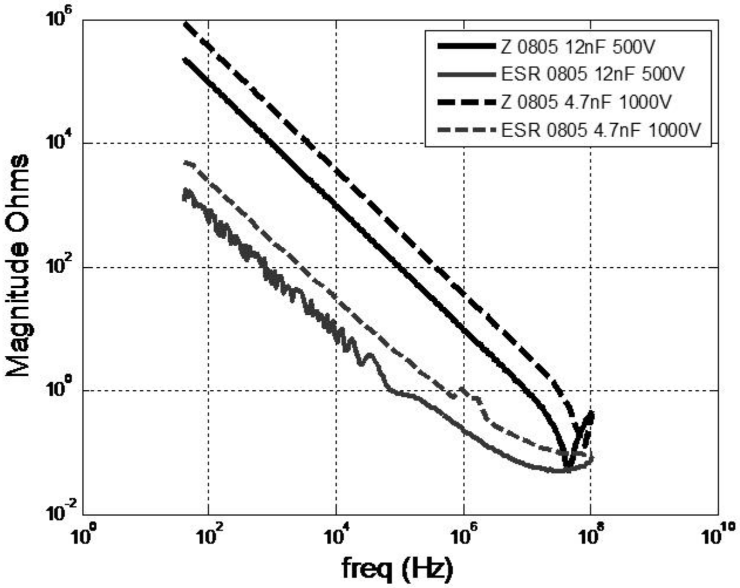

Figure 7. Impedance (Z) and ESR of 0805 12nF 500V & 4.7nF 1000V MLCC

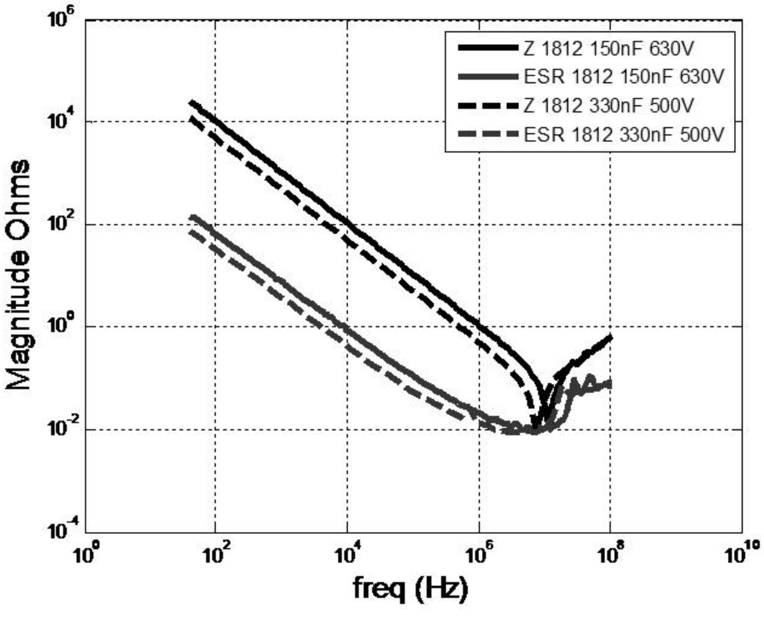

Figure 8. Impedance and ESR of 1812 330nF 500V & 150nF 630V MLCC

The 0805, 4.7nF 1000V MLCC has the highest self resonant frequency (SRF) ~100MHz with the highest ESR ~ 100mΩ. This is consistent with standard capacitor designs where the lowest capacitance has the lowest SRF and the fewest electrodes result in the highest ESR. Conversely the 1812, 330nF, 500V has the lowest SRF ~10MHz with the lowest ESR ~ 10mΩ.

As mentioned previously the voltage breakdown performance measurements were at 300V/sec ramp rate. To test the effect of different dV/dt on the voltage breakdown samples were tested with voltage applied at 4 different rates, 300V/sec, 600V/sec, 900V/sec and 1200V/sec in both air and inert fluid. The voltage breakdown (UVBD) failure distributions in 10V increments are shown for each ramp rate in Figures 9 to 12.

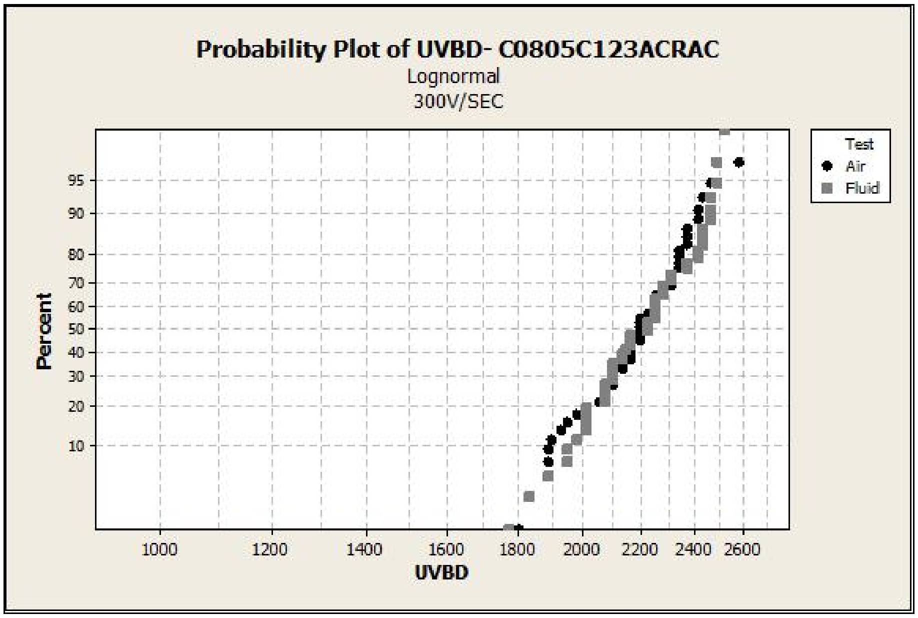

Figure 9. Voltage Breakdown Distribution at 300V/sec in Air and Fluid

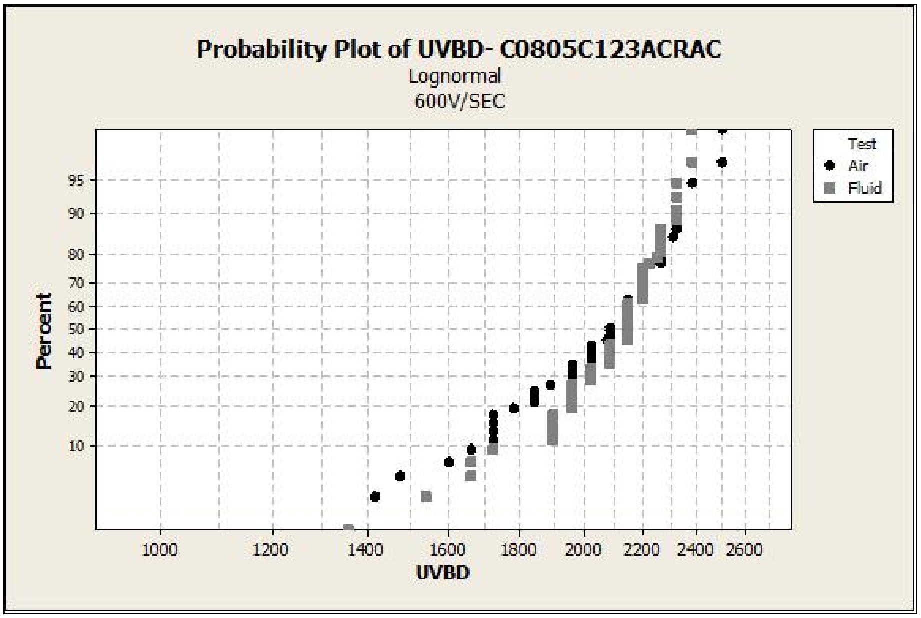

Figure 10. Voltage Breakdown Distribution at 600V/sec in Air and Fluid

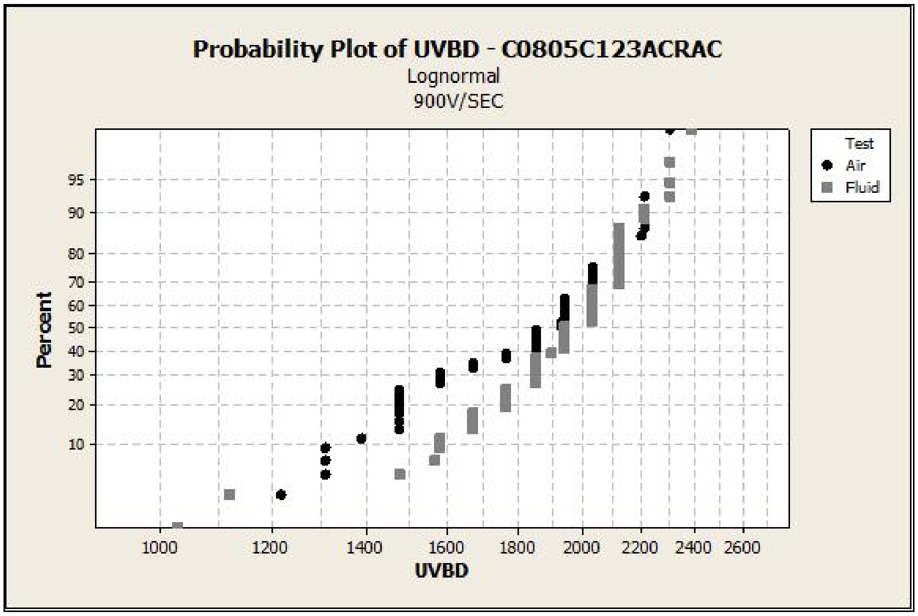

Figure 11. Voltage Breakdown Distribution at 900V/sec in Air and Fluid

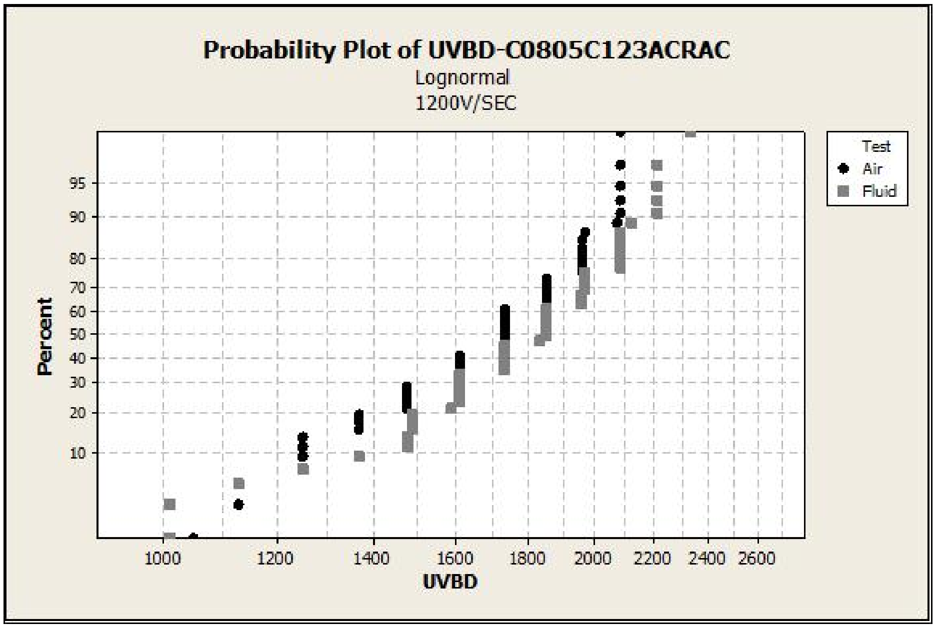

Figure 12. Voltage Breakdown Distribution at 1200V/sec in Air and Fluid

The 0805, 500V MLCC have the lowest voltage rating combined with the shortest distance between terminals making it more favorable to surface arcing. If this failure mode increased with raising dV/dt to 1200V/sec we would expect to see a significant divergence between the results in air and fluid since the fluid prevents surface arcing. As shown in Table 1. for a standard overlap 1206 MLCC at 300V/sec some failures occurred below 1000V. For the 0805, 500V in both air and fluid as the dV/dt increased to 1200V/sec breakdown occurred at lower voltages but in all cases the lowest voltage failures occurred in fluid. At 1200V/sec the breakdown in air occurred at > 1000V. This indicates that for ramp rates to 1200V/sec the failure mechanism in air was dielectric breakdown not surface arcing.

Board Flexure Robustness

In addition to their high voltage capability “serial” or “floating electrode” designs fail open after board flexure[6]. This open failure mode does not occur with these “shield electrode” designs with standard fired termination. However, by using a “soft” or “flexible” termination open failures can result on board flexure. To test the effectiveness of standard Vs flexible terminations an accelerated failure test was performed by combining flexure with low voltage humidity testing to accelerate any cracks to failure. MLCC samples rated at 500V of different case sizes, 1812, 1206 and 0805 were terminated both ways. Samples of 100pieces of each type were soldered onto flex test boards. The standard termination resists cracking at 2mm flexure so in this accelerated test the samples were flexed to 3mm and 5mm. These samples were then exposed to 85^{o}C/85%Relative Humidity for 92hrs at 200V to accelerate any failures due to cracks. The samples were tested for shorts and results are summarized in Figure 13.

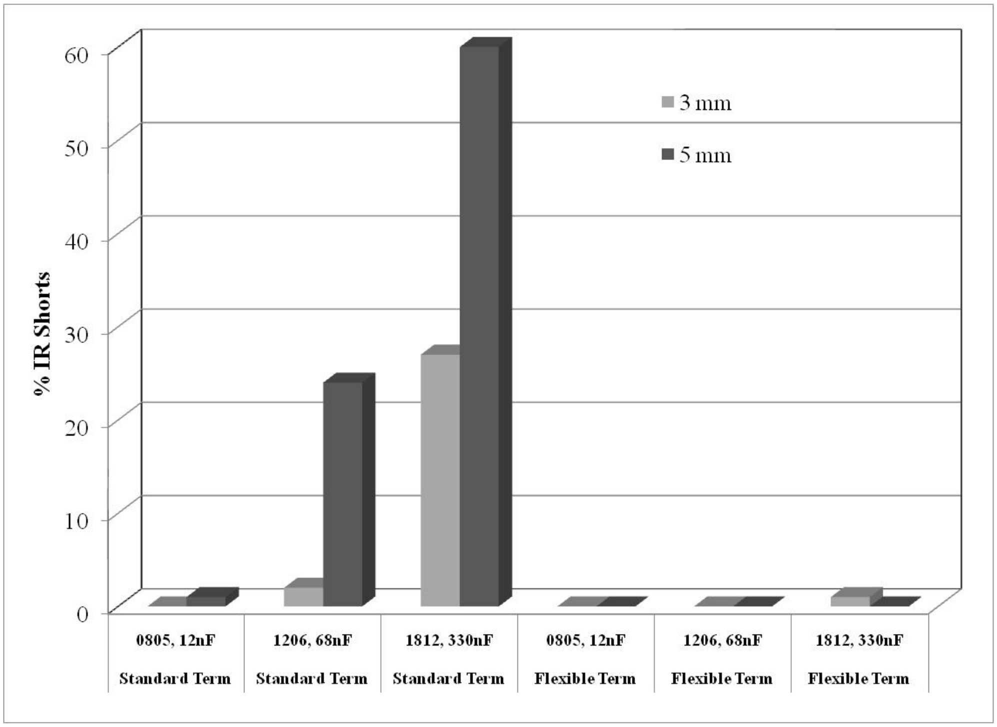

Figure 13. Results of Flex Termination Robustness, Accelerated Failure Test

Only one (1) IR short was detected in the 1812 Flexible Termination sample flexed at 3mm. All the samples with standard terminations had some level of IR shorts except for the 0805 flexed to 3mm. The standard termination flexed to 5mm had a higher failure rate than at 3mm and the larger the case size the higher the failure rate. In applications where mechanical stresses are high, making flexure issues more likely, the flexible termination is therefore recommended.

Summary

A range of higher capacitance, high voltage BME X7R MLCC have been developed using shielded designs that will allow further miniaturization of circuits to be realized. Since surface arcing is prevented in these designs no conformal coating is required. Voltage breakdown and life testing were used to verify these MLCC designs. Reliability was confirmed in subsequent life and humidity testing. Voltage breakdown testing in high dV/dt (1200V/sec) in air and fluid confirmed that in the 0805, 12nF, 500V MLCC the failures were not associated with surface arcing but were breakdown related. Impedance and ESR showed similar trends to standard MLCC designs. An accelerated failure test for board flexure demonstrated that MLCC with flexible termination are more robust with respect to IR shorts and so preferred in applications where high mechanical stresses are expected.

Acknowledgements
The authors would like to acknowledge the support of their colleagues, Wanda Andrews, Kevin Lynn and Bobby Gentry.

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