Miniaturization of High Voltage BME X7R Multi-Layer Ceramic Capacitors for use in Automotive Applications

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Abstract

The need for smaller case size, high voltage capacitors has driven the development of a new range of surface mountable, multi-layer ceramic capacitors (MLCC) for use in Automotive Applications. These X7R type capacitors, with 0603 and 0805 case sizes, have voltage ratings of 500, 630 and 1000VDC. They employ designs that prohibit arcing allowing higher capacitances to be realized in these smaller sizes. The development of this technology is reviewed and the challenges associated with smaller terminal to terminal separations are discussed. Test data is presented to help understand the impact of smaller pad separations on high voltage performance. The impact of board flexure on reliability is evaluated for different termination types using a custom accelerated test procedure as a guide to field performance. AEC Q200 reliability data will be presented.

Introduction

High voltage multi-layer ceramic capacitors (MLCCs) rated ≥ 500VDC have been manufactured for over 20 years using serial designs. These designs, also known as “floating electrode” or “cascade designs” consist of 2 or more active overlap volumes in series so the voltage across the terminals of the capacitor is split between these capacitors. Unfortunately this results in the capacitance being reduced also. MLCCs made with high capacitance X7R dielectrics were developed in 2006 that employed a patented “shield” design [1] prohibiting surface arcing so allowing a single overlap to be used for ratings up to 1000VDC. These precious metal electrodes (PME) MLCCs were promoted for use in implantable medical technology to reduce component size [2]. The mechanisms associated with voltage breakdown in these capacitors was thoroughly documented using CSAM, cross-sections and high speed cameras [3]. Since this time the MLCC have been successfully employed in many applications including automotive. In 2008 KEMET Corporation began the development of higher capacitance, high voltage shielded electrode MLCCs using X7R with nickel base metal electrodes (BME). These were qualified in accordance AEC Q200 and introduced in 2011 for case sizes 0805to1812 in rated voltages of 500, 630 and 1000VDC [4]. Some data on accelerated stress testing of board flexure resistance is presented for reference with respect to reliability of the assembled MLCC. These patented MLCC designs [5] allow even higher capacitance values to be realized. MLCC with “shield” designs are compared with “serial” MLCC [6]. Further miniaturization of MLCC by reducing case size has many potential benefits. Compared to 1206 the smaller 0805 and 0603 require 44% and 75% less board space respectively. In addition to less circuit board area the smaller MLCC use less material so cost less, the component weight is lower and so there are environmental benefits. To realize these benefits the small case high voltage MLCC must have high capacitance as well as being very reliable. Evaluations of terminal-to-terminal and pad-to-pad arcing are presented together with voltage breakdown and reliability measurements with respect to extending the capacitance range of 0805 and miniaturizing high voltage X7R MLCC to 0603 case size.

Development of High Voltage X7R MLCC

A 200VDC rated standard MLCC cross-section is shown in Figure 1.

Figure 1. Cross-section of a standard 200VDC rated X7R MLCC

This has a large capacitor overlap volume with a large the overlap area (A) between opposing electrodes separated by dielectric. The capacitance (C) of the MLCC can be calculated by Equation 1.

$$C = \epsilon \, \epsilon_0 An/t \qquad \textbf{Equation 1.}$$

In this case t is the thickness of the dielectric and n the number of these active layers. The capability of the dielectrics to store electric charge is given by ϵ and dimensionless material constant and ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m) that is a constant that represents the charge that would be stored in a vacuum between the electrodes with no dielectric present. To achieve adequate performance for dielectric breakdown at this active thickness must be much higher than the rated voltage.

To achieve higher voltage performance ≥ 500VDC serial MLCC designs where developed where the inner electrodes are arranged such that a number of capacitors (N) are between the terminals as shown in Figure 2.

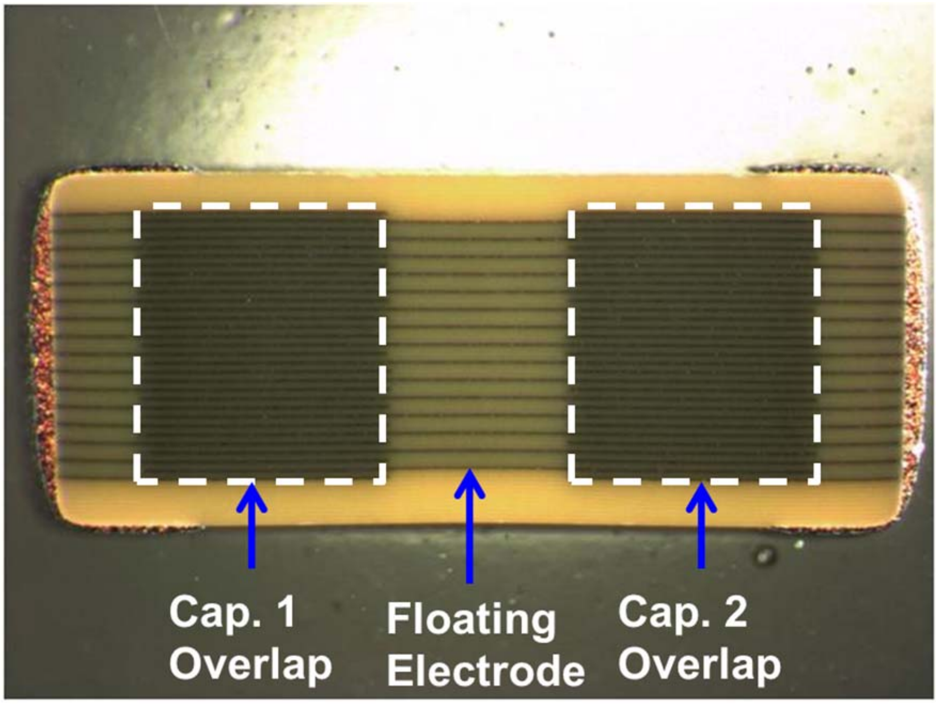


Figure 2. Cross-section of a 2-serial MLCC

In this way the acting voltage on each capacitor is reduced by the reciprocal of the number of capacitors (1/N). These are also known as "floating electrode", because of the unconnected electrodes connecting the 2 capacitors or "cascade" designs. However, there is a capacitance penalty in designing MLCC with 2 or more capacitors in series, the effective capacitances (C_{Eff}) is lowered by the sum of the reciprocal capacitances as shown in Equation 2.

$$1/C_{Eff} = \Sigma 1/C_N \qquad \textbf{Equation 2.}$$

Although very effective at achieving high voltage capability this approach limits the available capacitance. For this reason "shield" designs were developed with a large non-serialized active area [4], as shown in Figure 3.

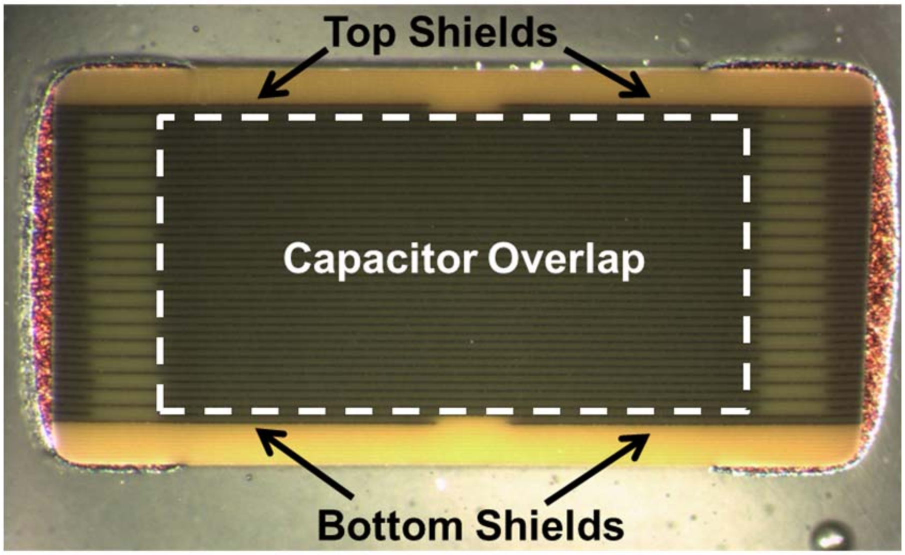


Figure 3. Cross-section MLCC with addition of Top & Bottom Shields

In the case of this “shield” MLCC the active volume is large similar to that of the standard MLCC design shown previously in Figure 1. The increase in the available overlap area significantly increases the capacitance even though the thickness between opposing electrodes (t) has to be increased to avoid voltage breakdown since this is much higher than in the serial designs. Using the “shield” design approach capacitance can be increased by up to 4 x higher than using a 2-serial design for a given X7R dielectric and case size. To understand how these “shield” MLCC work make this possible we must first consider the failure modes exhibited by capacitors with standard overlap and no shields. In many cases when an overvoltage condition occurs a terminal-to-terminal arc is seen as shown diagrammatically in Figure 4.

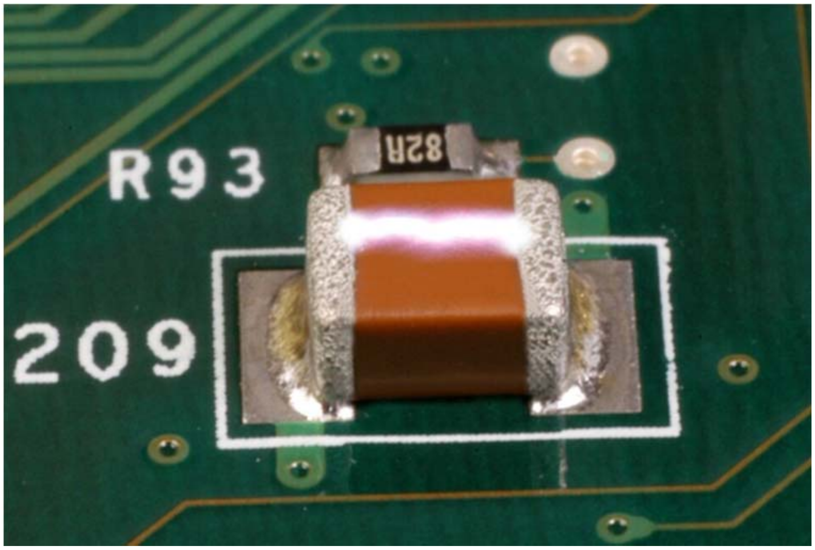


Figure 4. Surface Arcing in an MLCC

Recently a minimum breakdown of 327V at 7 micron in air at 1 atmosphere, calculated using Paschen’s equation, has been correlated to failures induced by cracking of lower voltage rated MLCC, 6.3to 100VDC ratings [7]. This work was undertaken to study and potentially improve the effectiveness of voltage screening. There was some indications that surface arcing can occur at lower voltages than those predicted by this equation although at electrode (thickness) separations > 50 microns (0.002inch) the breakdown voltages were > 650V. This is far shorter than the terminal-to-terminal or pad-to-pad distances evaluated later in this paper. Surface arcing in higher voltage MLCC happens over longer distances and the influence of the electric fields at the surface must be considered. In MLCC without shield electrodes the air is ionized between the terminals as shown in cross-section in Figure 5.

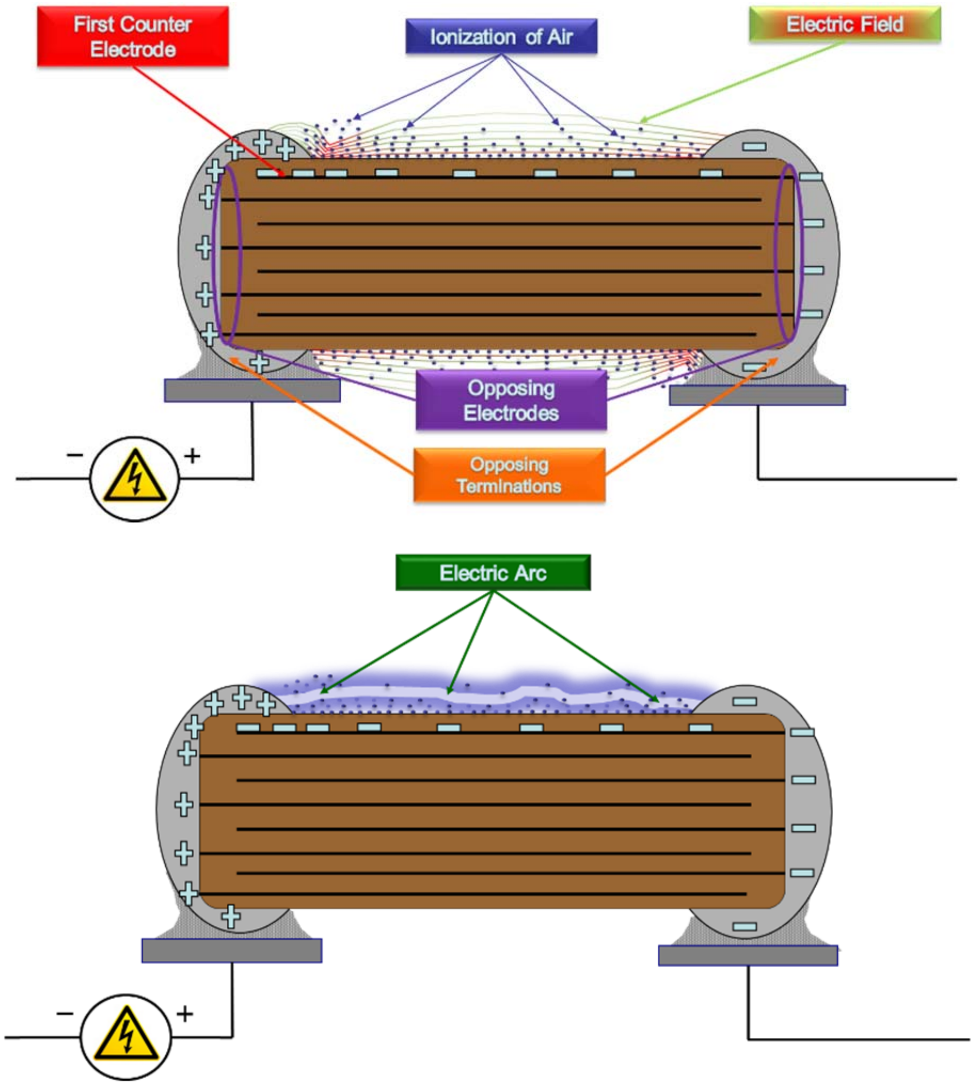


Figure 5. Cross-section of Surface Arcing in an MLCC with no shield electrodes

Coating of the MLCC prior or post assembly can prohibit surface arcing by preventing the ionization of the air. Apart from the expense associated this has some important limitations can compromise the voltage handling capability such as any damage to the pre-coated component and coating under MLCCs after assembly may not be 100% effective. Furthermore, the coatings may not be compatible with secondary assembly processes. When MLCCs are not coated arcing can leave a carbon trace with low IR at the surface of the MLCC. However, what is less well documented is that this arcing will eventually cause failures by terminal-to-active arcing. This failure mechanism has been studied using CSAM and high speed cameras [3] but examination of failures often shows these are located adjacent to the terminal as shown in Figure 6.

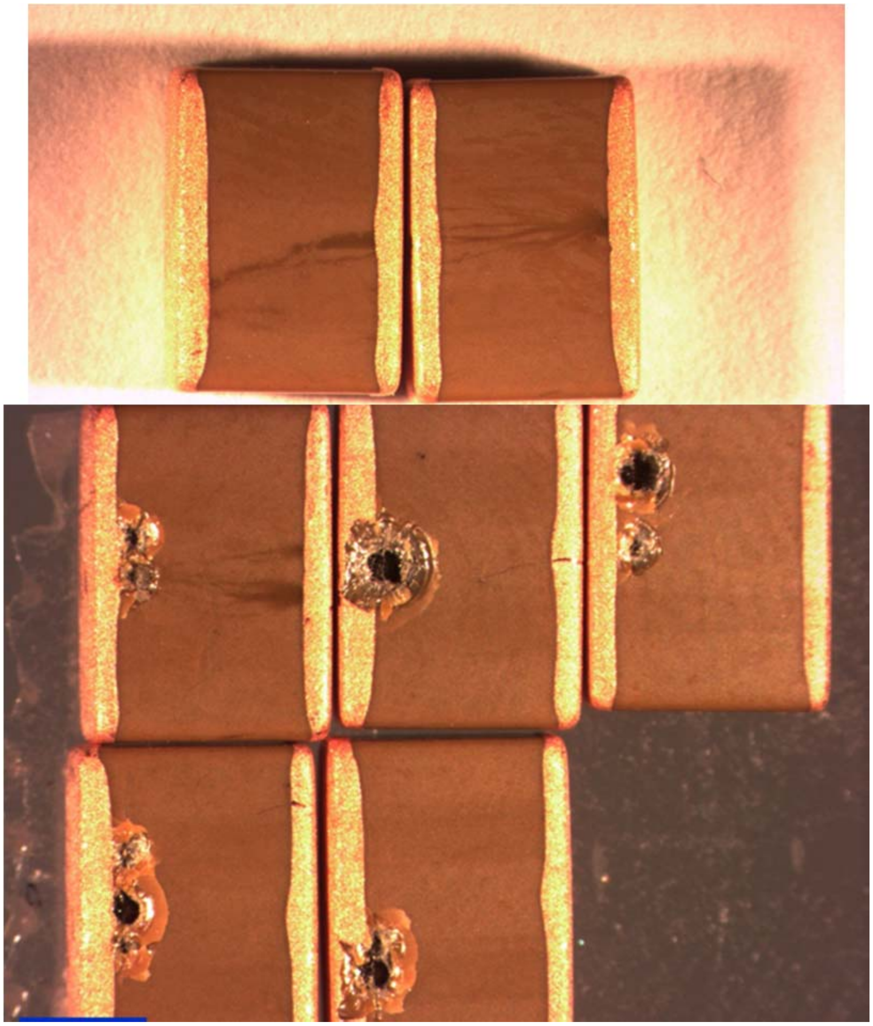


Figure 6. Carbon traces formed on 1825 Case size X7R MLCC and voltage breakdown failures in air

The presence of the “shield” electrodes prohibit this failure mode by creating a barrier between the termination and active of opposed polarity. This also increases the energy barrier between with respect to terminal-to-terminal arcing as shown in the diagrams of Figure 7.

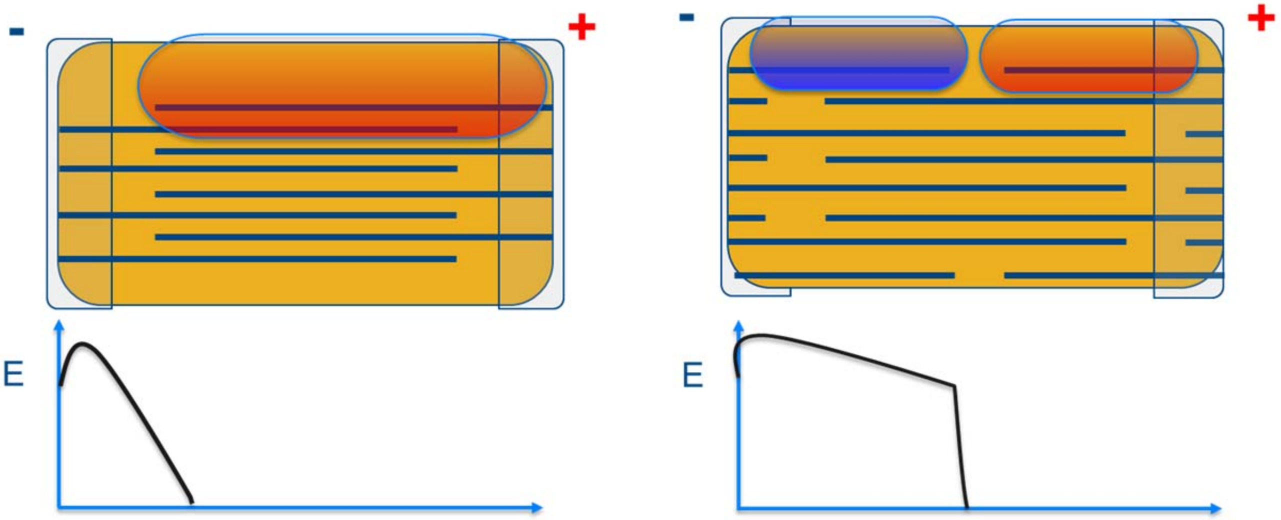


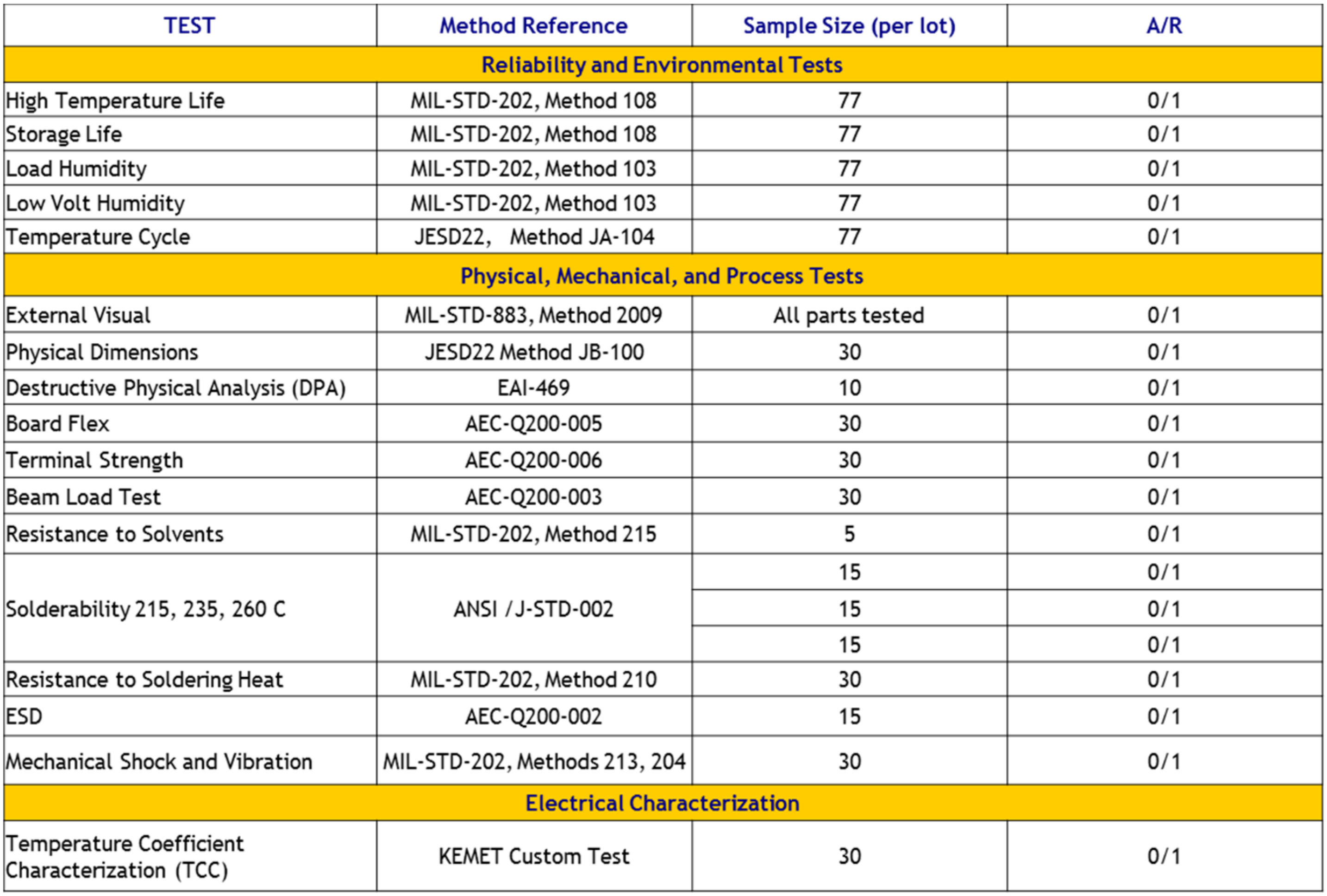
Figure 7. “Shield” electrode designs for prohibiting arcing

The standard electrode design on the left has a low energy barrier between the terminal and the electric field of opposed polarity compared to the “shield” design. Although depicted in 2 dimensions to be effective the electric fields must be controlled in all 3 dimensions and this can be thought of in terms of a Faraday cage with a gap to avoid shorting. Using this principal a range of X7R “shield” MLCC were developed with nickel BME [4] that prohibit arcing without coating. These high capacitance MLCC designs are patented [5] and a range of case sizes from 1812 to 0805 with voltage ratings of 500, 630 and 1000VDC were launched in September 2011. Some typical electrical data for these parts together with voltage breakdown in air, life at 1.2 x rated voltage (Vr) and biased humidity testing are shown in Figure 8.

KEMET Part Number	Voltage Rating	Average Capacitance (nF)	Average DF (%)	IR (GΩ)		TCC (%)		Average Voltage Breakdown in Air	Life Test 1000hr @ 1.2Vr 125°C	Biased Humidity 1000hr @ 200V 85°C/85%RH
				25°C	125°C	-55°C	125°C			
C0805V123KCRAC	500	12.61	1.24	77.5	7.7	-8.72	-12.18	2138	0/77	0/77
C0805V822KBRAC	630	8.19	1.18	168.2	14.3	-9.56	-11.45	2276	0/77	0/77
C0805V472KDRAC	1000	4.75	1.10	400.4	25.8	-9.61	-10.79	2458	0/77	0/77
C1206V683KCRAC	500	71.96	1.14	12.6	1.3	-9.27	-13.51	2026	0/231	0/231
C1206V333KBRAC	630	33.31	1.03	40.4	3.5	-9.40	-11.91	2290	0/231	0/231
C1206V223KDRAC	1000	22.51	0.98	74.4	5.8	-9.37	-9.71	2271	0/231	0/231
C1210V154KCRAC	500	164.41	1.17	5.7	0.7	-8.79	-12.20	1913	0/77	0/77
C1210V104KBRAC	630	108.24	1.05	12.9	1.1	-9.46	-11.64	2152	0/77	0/77
C1808V154KCRAC	500	158.48	1.18	5.8	0.7	-13.22	-9.16	1908	0/77	0/77
C1808V104KBRAC	630	104.38	1.07	13.3	1.1	-12.03	-9.58	2072	0/77	0/77
C1808V683KDRAC	1000	72.18	1.04	28.7	1.8	-10.80	-9.80	2239	0/77	0/77
C1813V334KCRAC	500	340.00	1.14	2.7	0.5	-13.12	-9.07	1802	0/231	0/231
C1813V154KDRAC	630	158.59	1.14	8.7	0.8	-8.66	-11.13	1984	0/231	0/231

Figure 8. Electrical & Reliability data for higher capacitance X7R BME MLCC with shield designs.

In all cases the capacitance was on target and the dissipation factor (DF) and TCC were as expected for BME X7R dielectric as were the insulation resistances (IR) measured at 500V after 60 second charge time. The life tests at 20% higher voltage than required by AEC and the biased humidity results confirm these parts have acceptable long term durability. In the cases where 231 part data are shown these represent 3 different test batches (3 x 77pcs). Internal qualification tests were performed for these part numbers based on AEC Q200 Rev. D guidelines per Table, 1, 2 & 2A. The test methods sample size and accept/reject (A/R) criteria are shown in Figure 9.



TEST	Method Reference	Sample Size (per lot)	A/R
Reliability and Environmental Tests			
High Temperature Life	MIL-STD-202, Method 108	77	0/1
Storage Life	MIL-STD-202, Method 108	77	0/1
Load Humidity	MIL-STD-202, Method 103	77	0/1
Low Volt Humidity	MIL-STD-202, Method 103	77	0/1
Temperature Cycle	JESD22, Method JA-104	77	0/1
Physical, Mechanical, and Process Tests			
External Visual	MIL-STD-883, Method 2009	All parts tested	0/1
Physical Dimensions	JESD22 Method JB-100	30	0/1
Destructive Physical Analysis (DPA)	EAI-469	10	0/1
Board Flex	AEC-Q200-005	30	0/1
Terminal Strength	AEC-Q200-006	30	0/1
Beam Load Test	AEC-Q200-003	30	0/1
Resistance to Solvents	MIL-STD-202, Method 215	5	0/1
Solderability 215, 235, 260 C	ANSI / J-STD-002	15	0/1
		15	0/1
		15	0/1
Resistance to Soldering Heat	MIL-STD-202, Method 210	30	0/1
ESD	AEC-Q200-002	15	0/1
Mechanical Shock and Vibration	MIL-STD-202, Methods 213, 204	30	0/1
Electrical Characterization			
Temperature Coefficient Characterization (TCC)	KEMET Custom Test	30	0/1

Figure 9. Typical AEC Q200 Test Result

Flexible terminations were also qualified. In addition to the AEC board flex testing select MLCCs with standard and flexible terminations were compared using an accelerated failure test. This combined excessive flexure with bias 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 100 pieces 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 92hours at 200V to accelerate any failures due to cracks. The samples were tested for shorts and results are summarized in Figure 10.

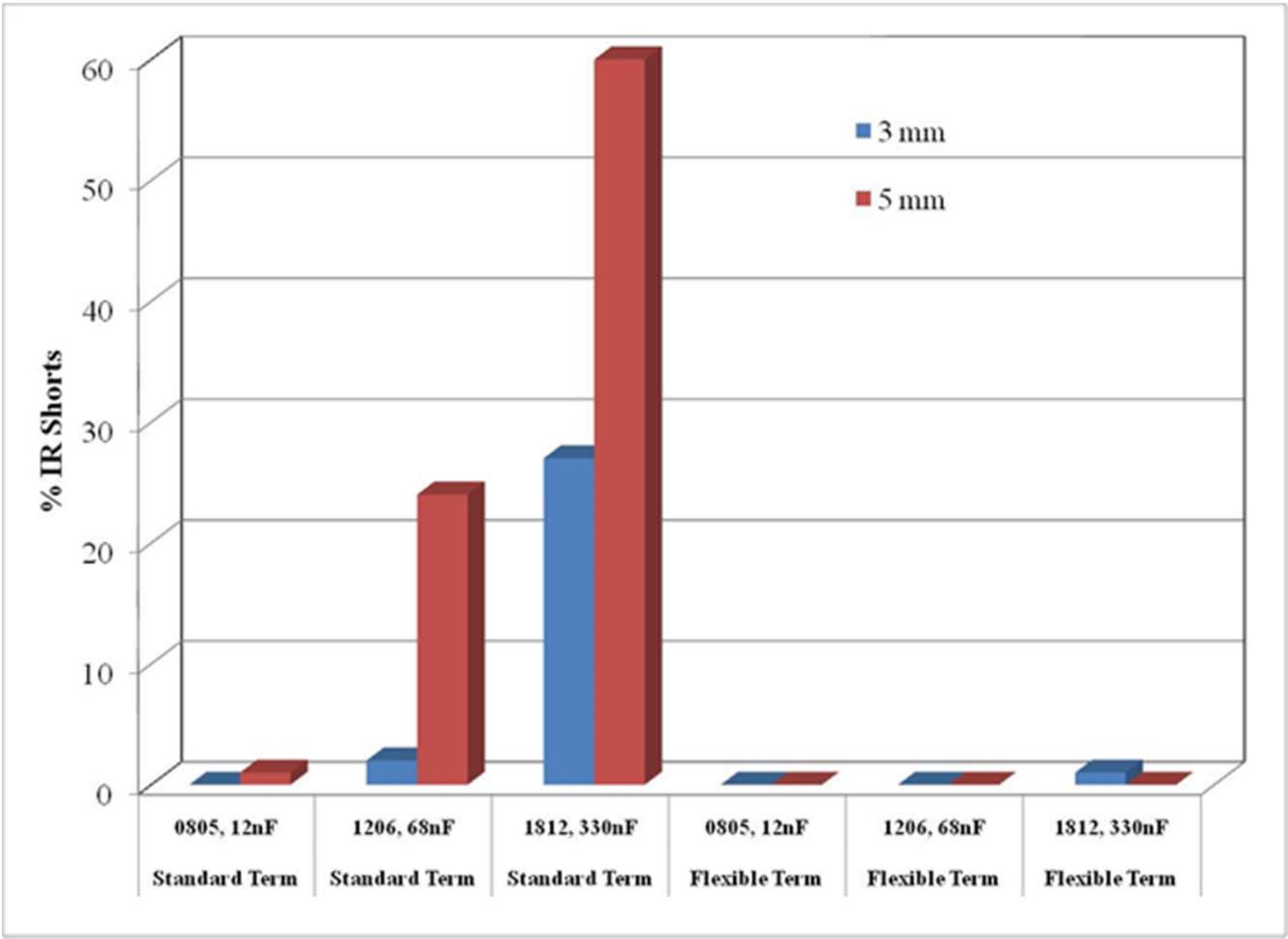
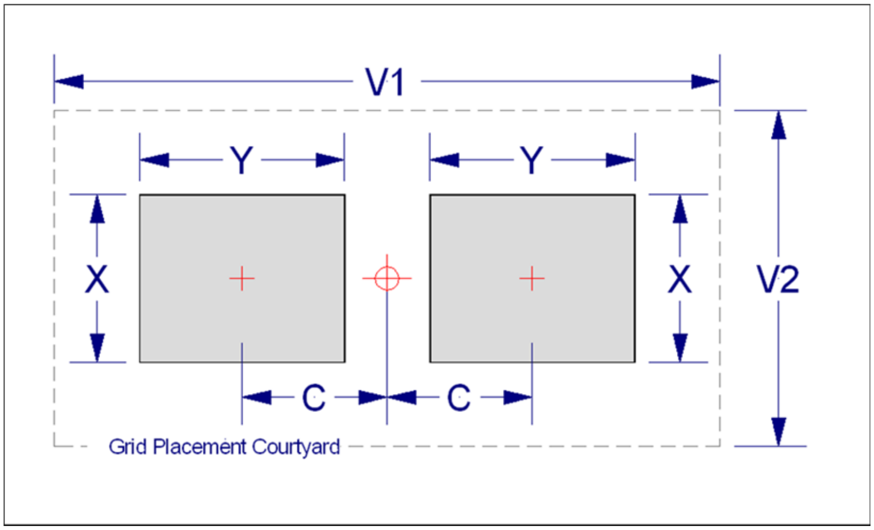


Figure 10. Results of Flex Termination Robustness, Accelerated Failure Test

As expected as the flexible terminations are very effective at mitigating failures due to board flexure, and the smaller the case size the lower the susceptibility to this failure mode.

Miniaturization down to 0603 Case Size

The performance of 0805 circuit boards in addition to 0805 “shield” MLCC has been previously reported [6]. The studies were conducted at different voltage ramp rates as well as under 85^{o}C/85% Relative Humidity, since it has been well documented that humidity can decrease arcing distance so increasing the breakdowns associated with assembly of high voltage MLCC [8]. A comparison of 0805 and 0603 circuit board designs tested is shown in Figure 11.



Case Size	**C** (inch)	**Length Y** (inch)	**Width X** (inch)	**Spacing** (inch)
0603	0.0315	0.0374	0.0394	0.0256
0805	0.0354	0.0453	0.0571	0.0256

Figure 11. 0805 and 0603 Circuit Board Designs

The spacing between the pads is very similar for 0805 and 0603 but we evaluated the arcing breakdown for 0603 FR4 boards with these pad dimensions at 25°C and at 85°C/85% relative humidity. The results were compared to the earlier testing on the 0805 circuit boards as shown in Figure 12.

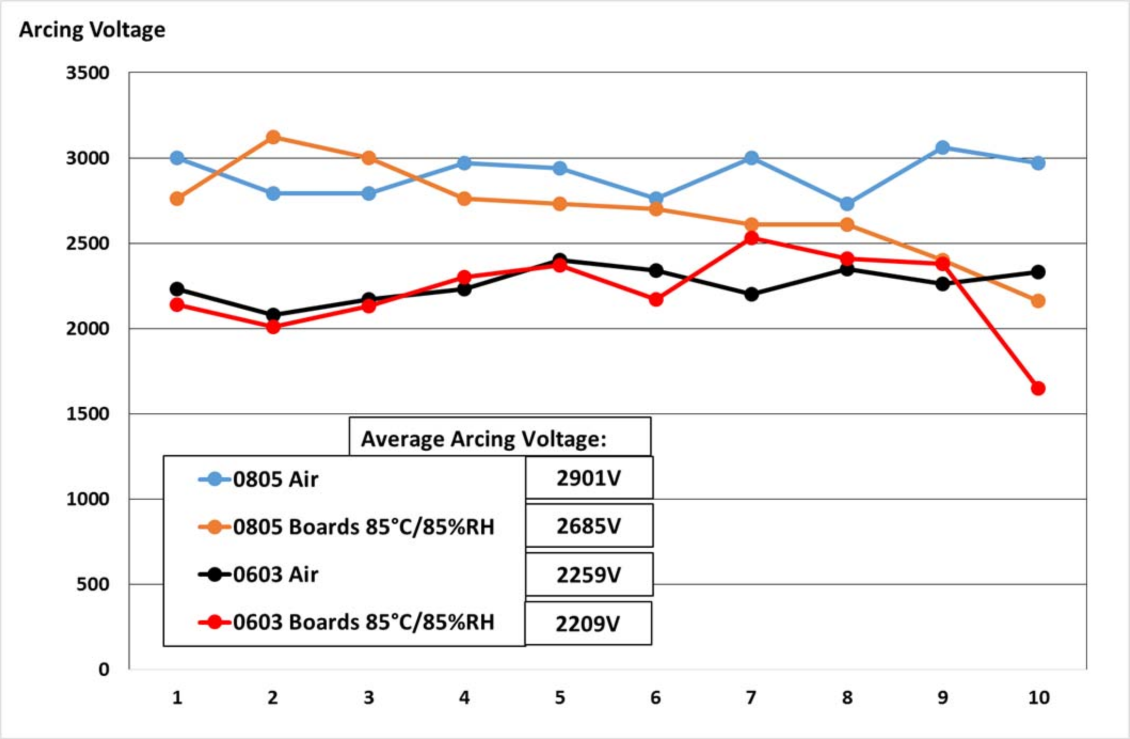


Figure 12. Circuit Board Arcing Voltage in Air and 85°C/85% Relative Humidity

Despite having the same gaps between the pads the 0603 boards showed a lower arcing voltage on average. The reason for this decrease is not clear at the time but the FR4 circuit boards were not subject to any special degreasing or cleaning. The arcing voltage was lower at high humidity for both case sizes and for one 0603 board an arc occurred at 1650V.

Another experiment was undertaken to understand if the terminal-to-terminal gaps in the smaller 0603 case size can lower the arcing voltage below the 1000VDC being considered for miniaturization. In this case 25 X7R MLCC were made without any inner electrodes in case sizes 0603, 0805, 1206 and 2220. Terminations were applied using our standard process then the average, minimum and maximum arcing voltages were measured as shown in Figure 13.

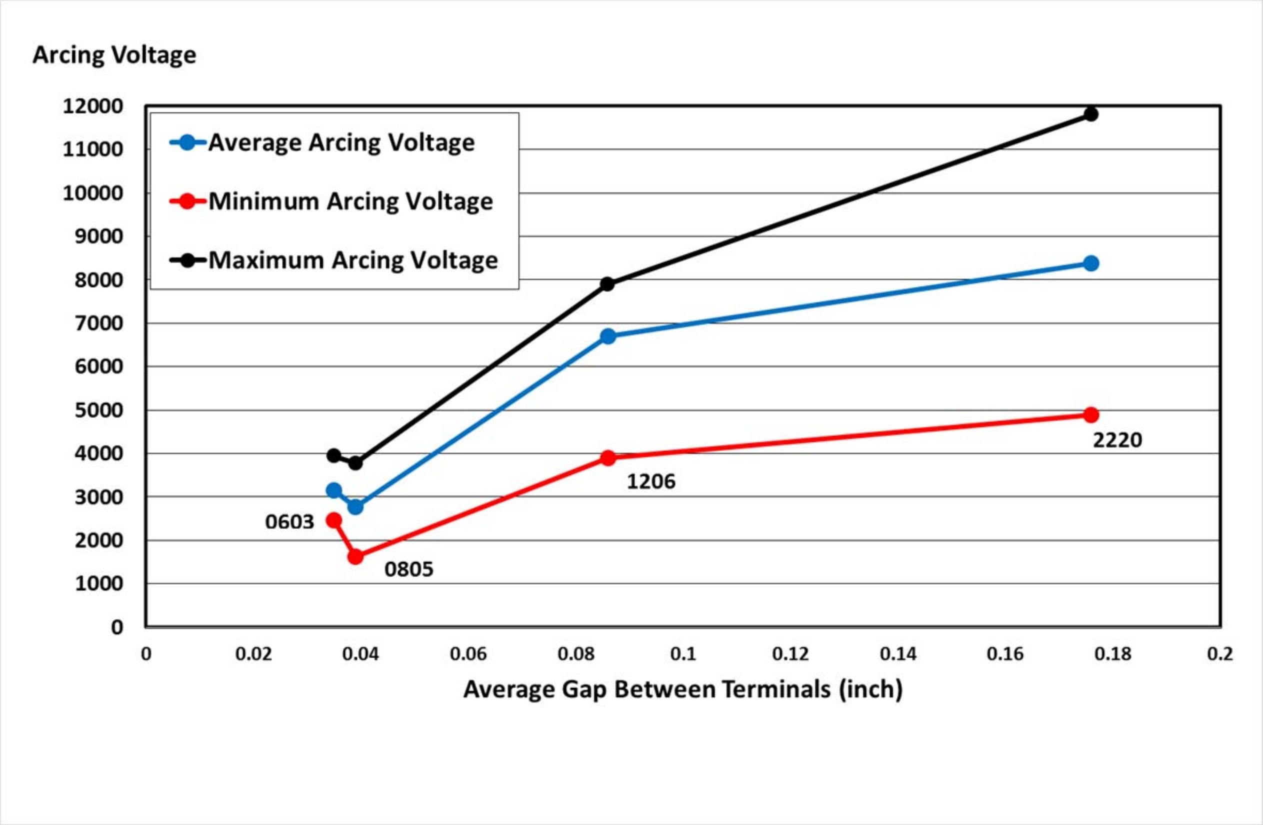


Figure 13. Terminal-to-terminal Arcing Voltages for Different MLCC Sizes

Arcing occurs over a broad range of voltages for each different MLCC size. The average arcing voltages are lowered as the gap size is reduced. However, in the 0805 case size tested in this condition all the arcing voltages are lower than for the 0603 with a smaller gap. The shape of the termination may have affected the charge density in this case. Nevertheless arcing still remains > 1500V even for the smaller case sizes. It is important to note that in this experiment there were no internal electrodes influencing the arcing so this is a test of the potential for arcing between terminals only. To test the effect of electrode on surface arcing 1206 MLCC were manufactured with a single electrode 0.006" below the opposite termination and the average arcing voltage decreased to 1500V. This confirms the influence of the electric field associated with the outer electrodes with respect to terminal-to-terminal arcing as shown previously in Figure 7.

Since the circuit board pad-to-pad and terminal-to-terminal arcing tests of 0603 and 0805 remained above 1500V we manufactured and tested extended capacitance values rated 500, 630 and 1000VDC. A summary of some electrical properties and the life testing performed are shown in Figure 14.

KEMET Part Number	Voltage Rating	Mean Capacitance (pF)	Mean DF (%)	IR (GΩ)		Mean Voltage Breakdown	Life Test @ 1.2Vr 125°C		
				25°C	125°C		250hrs	500hrs	1000hrs
C0603V392KCRAC	500	4,100	1.24	77	8.2	2100	0/300	0/300	0/300
C0603V392KCRAC	500	4,200	1.23	80	8.5	2000	0/77	0/77	0/77
C0603V152KBRAC	630	1,400	1.08	394	34.1	2900	0/77	0/77	0/77
C0603V152KBRAC	630	1,500	1.08	469	37.6	2600	0/77	0/77	0/77
C0603V102MDRAC	1000	900	1.01	805	67.0	3100	0/77	0/77	0/77
C0603V102KDRAC	1000	1,000	1.04	815	66.1	3100	0/77	0/77	0/77
C0805V223MCRAC	500	20,300	1.09	23.3	2.2	2600	0/77	0/77	0/77
C0805V223MCRAC	500	20,000	1.09	20.7	2.2	2300	0/77	0/77	0/77
C0805V123MBRAC	630	11,200	1.16	48.8	4.5	2800	0/77	0/77	0/77
C0805V123MBRAC	630	11,200	1.13	53.8	5.1	2700	0/77	0/77	0/77

Figure 14. Electrical Properties and Life Tests of 0603 and 0805 X7R Shield MLCC

The dissipation factors (DF) and insulation resistances are comparable to the earlier data shown in Figure 8. Despite the miniaturization in the case of 0603 the mean breakdown voltages (n = 20) remain high and comparable to the averages seen for these voltage ratings in larger case sizes. No failures have been seen in life test data on these batches at 125°C for 1000hrs @ 1.2 X the voltage rating.

Conclusion

The development of high voltage, high capacitance "shield" BME X7R MLCC has been reviewed and shown to achieve reliable performance by suppressing surface arcing and the associated failure modes. Flexible terminations significantly lowered the failure rate associated with circuit board flexing using an accelerated test. Circuit board pad-to-pad and terminal-to-terminal arcing experiments indicate it is feasible to reduce the case size of high voltage X7R to 0603 to realize the benefits associated with further miniaturization. Electrical characteristics including voltage breakdown in air and life test data at 1.2 x rated voltage for some 0603 and 0805 high voltage capacitance extensions are promising with no life failures seen after 1000hrs @ 125°C.

Future Work

Full internal qualification testing is being performed per AEC Q200 guidelines on the 0603 and 0805 high voltage extensions rated at 500, 630 and 1000VDC with a product release planned for the end of this summer. This will allow further miniaturization as shown by the maximum capacitance values in Figure 15.

Case Size	1206		0805			0603		
Rated Voltage	Serial	Shield	Serial	Shield	Extension	Serial	Shield	Extension
500	15,000pF	68,000pF	8,200pF	12,000pF	22,000pF	NA	NA	3,900pF
630	10,000pF	33,000pF	3,300pF	8,200pF	12,000pF	NA	NA	1,500pF
1000	10,000pF	22,000pF	3,300pF	4,700pF	NA	NA	NA	1,000pF

Figure 15. Maximum Capacitance of High Voltage X7R MLCC by Case Size

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