Abstract

Title of Document:	THE EFFECTS OF ENVIRONMENTAL STRESSES ON THE RELIABILITY OF FLEXIBLE AND STANDARD TERMINATION MULTILAYER CERAMIC CAPACITORS
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Flexible termination capacitors were designed to reduce stresses transmitted to the ceramic dielectric of a capacitor and thereby prevent flex cracking. Two studies were conducted to examine the reliability of flexible termination multilayer ceramic capacitors (MLCCs) subjected to environmental stresses. The first study used temperature-humidity-bias to compare the effects of termination type (standard vs. flexible), presence of a conformal coating (acrylic coating vs. no coating), and voltage bias level. *In situ* monitoring demonstrated similar failure statistics between the flexible and standard termination capacitors, presence of conformal coating, and voltage bias level. Upon removal from THB conditions recovery occurred only in the standard termination MLCCs. Flexible termination capacitors at the rated voltage bias were found to have more permanent failures after exposure to THB testing as compared to standard termination capacitors. Failure analysis indicated that silver and palladium migration between electrodes was the failure mechanism in the biased flexible termination capacitors.

In the second study flexible and standard termination MLCCs experienced a storage test in which they were exposed to elevated temperature and humidity conditions. It was found that the standard termination MLCCs had a lower reliability with the majority of the MLCCs failing compared to the flexible termination MLCCs where only one MLCC failed. Nearly all failures were for insulation resistance with few capacitors failing for other parameters. Subsequent bake-out of the MLCCs showed some recovery, however more failures were still occurring in the standard termination MLCCs compared to the flexible termination MLCCs. X-ray photoelectron spectroscopy and cross-sectioning were used to examine the failure mechanisms of the capacitors. A bulk migration of silver into the dielectric was determined to be one of the failure mechanisms in the capacitors.

THE EFFECTS OF ENVIRONMENTAL STRESSES ON THE RELIABILITY OF FLEXIBLE AND STANDARD TERMINATION MULTILAYER CERAMIC CAPACITORS

By

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Dedication

This thesis is dedicated to my family for their unconditional love and support. You have provided me with opportunities I could never have dreamed.

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I would like to first thank Dr. Michael H. Azarian for all of his help and guidance throughout this project. This project would not have been possible without his advising. I would like to thank Dr. Michael Pecht for his guidance and support throughout the project as well as his advising. Thank you to Dr. Donald Barker for all of his help with the finite element research as well as his helpful insights throughout the project. I would also like to thank Dr. Barker and Dr. Patrick McCluskey for serving on my committee and reviewing my research.

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1 Introduction

Multilayer ceramic capacitors (MLCCs) are a vital component to the electronics industry. MLCCs serve as an important passive component used for coupling and decoupling in many circuits. For example, it has been estimated that by 2011, 30% of all cell phones will contain upwards of 400 MLCCs each [1]. It was also estimated that the ceramic capacitor industry would see a $46 million benefit just from the United States economic stimulus plan [2]. With increased use of MLCCs has come an increased concern about their failures.

1.1 MLCC Construction

MLCCs are composed of alternating layers of ceramic and metal electrodes. Layers of ceramic dielectric are stacked with electrodes being deposited in between. A layered composition of ceramic and metal is created with is then fired at over 1000°C to create a block of ceramic and metal electrodes. Metal is than added to the ends with the exposed electrodes to create terminations. On the top, bottom and sides of the capacitor there can be a block of ceramic called a cover layer which does not contain any electrodes. The basic structure of an MLCC can be seen in Figure 1.

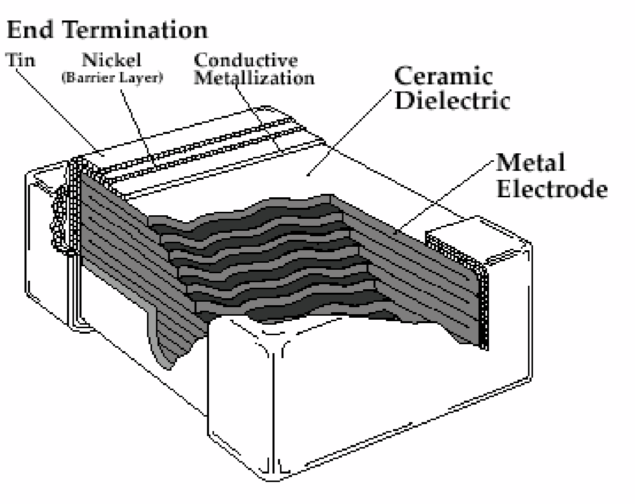


Figure 1: Basic structure of a standard termination MLCC [3]

1.2 Flex Cracking

"Flex" cracking has been a major problem since the inception of MLCCs. This occurs when stress is applied to the printed circuit board (PCB) upon which the capacitor is mounted. This stress is transmitted through the circuit board, and into the MLCC. If this stress exceeds the strength of the ceramic dielectric in the capacitor a crack can form. An illustration demonstrating flex cracking is shown in Figure 2.

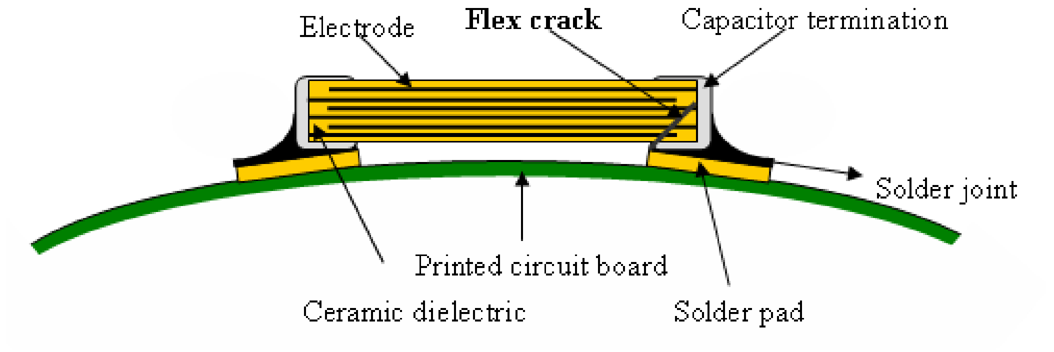


Figure 2: Flex cracking of a capacitor due to printed circuit board bending [4]

Flex cracks typically have the same origin. They start at the end of the termination on the board side of the capacitor and propagate up into the dielectric and electrode layers. Various factors, such as ceramic dielectric type, capacitor dimensions and the solder fillet shape can influence cracking of the capacitor. A photo of a flex crack is shown in Figure 3.

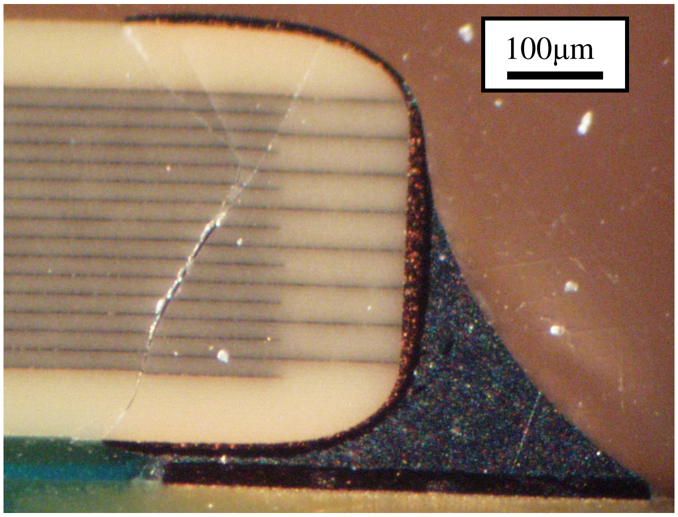


Figure 3: Flex crack in standard termination MLCC

Flex cracks are of particular concern given the propensity for circuit failure when the capacitor cracks. The circuit can have an open or a short in place of the capacitor with the crack occurs. A short is of great concern since it can cause over heating and lead to a dangerous situation.

1.3 Capacitor Terminations

Currently there are two types of terminations which can be used in MLCCs. Standard termination capacitors have been used since the capacitors creation. Due to their propensity for flex cracking the flexible termination capacitors were created. A further description of each type is shown below.

1.3.1 Standard Termination Capacitors

Standard termination capacitors are created with metal deposited in direct contact with the layers of ceramic and electrodes. The metal that is in direct contact with the dielectric is usually either copper for base metal electrode capacitors or silver for precious metal electrode capacitors. This metal is coated by a layer of nickel and tin to improve solder ability for attachment of the component to the circuit. A cross section of a standard termination MLCC is shown in Figure 4.

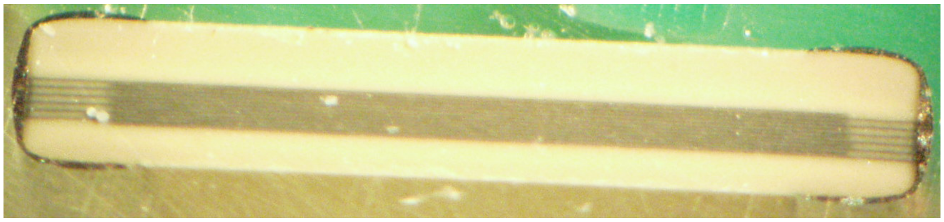
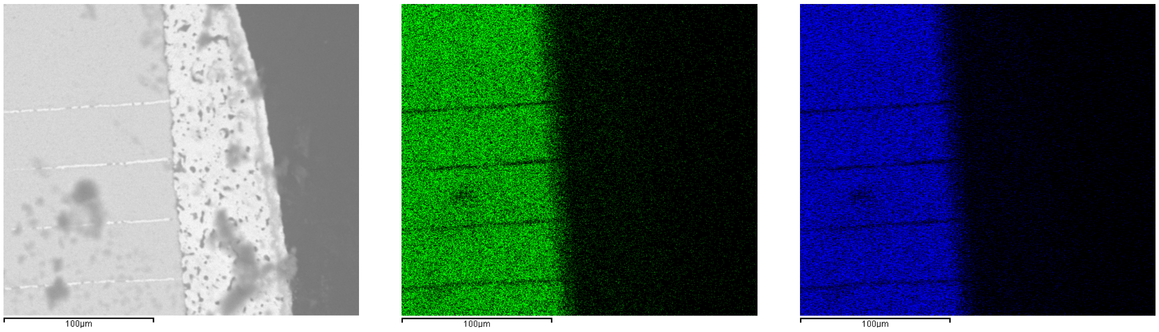
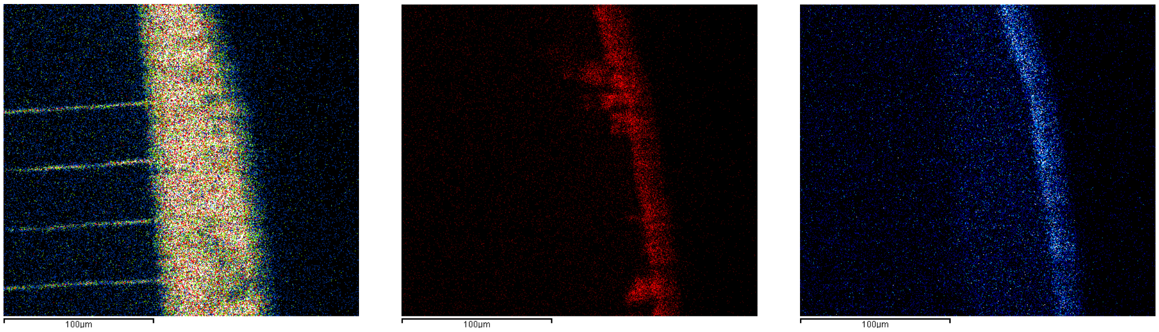


Figure 4: Cross section of a standard termination capacitor.

An electron dispersive spectroscopy (EDS) map is shown in Figure 5. From this mapping it is evident that the electrodes are made of silver, while the ceramic is barium titanate. One point of note is that the electrodes shown are only showing silver, when in fact they are silver palladium. The palladium is therefore believed to be in a very low concentration.



Original Area **Ti** **Ba**



Ag **Ni** **Sn**

Figure 5: EDS map of standard termination capacitor.

1.3.2 Flexible termination capacitors

Flexible termination capacitors were developed to dissipate the stresses transmitted to the brittle ceramic dielectric of the MLCC [5]-[9]. Variations to the flexible terminations exist between differing companies. A compliant silver polymer is placed in the end termination which is able to deform and reduce the amount of stress transmitted to the ceramic dielectric. This polymer is conductive and is coated with a layer of nickel and tin to aid in solder ability. This polymer also creates a differing geometry for the flexible termination capacitors when compared to the standard termination. A cross-section of one of the flexible termination capacitors used in this set of experiments is shown in Figure 6.

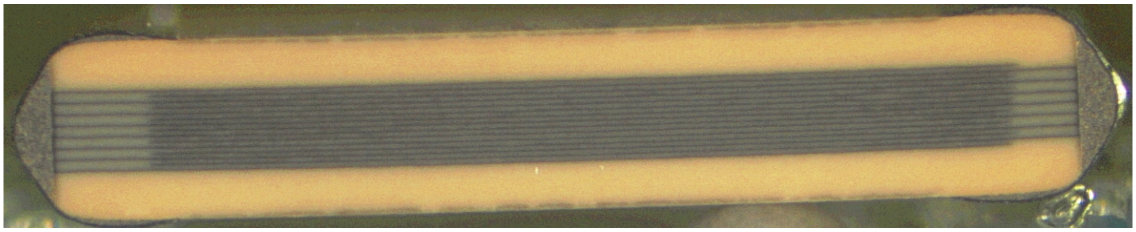


Figure 6: Cross section of a Syfer flexible termination MLCC.

The composition of the polymer in the termination is something that has been of debate during this project. An EDS map shows that there is a large amount of silver present, but is inconclusive as to the other materials present. A scanning electron microscope (SEM) image of the silver polymer in the end termination is shown in Figure 7.

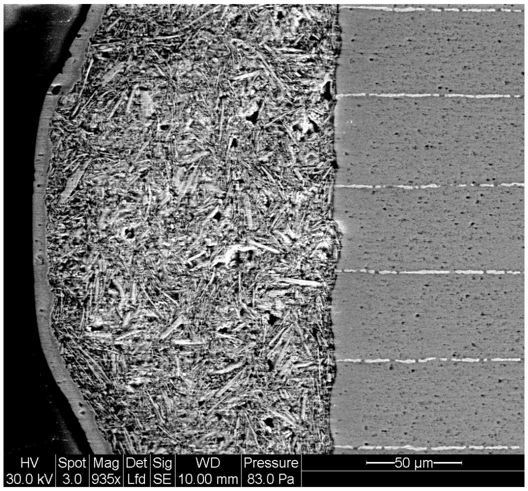


Figure 7: SEM image of a flexible termination MLCC

1.4 Electrodes

There are currently two types of electrodes which are used in MLCCs. Precious metal electrodes have been used in MLCCs since their creation, however due to the high cost of the metals base metal electrodes were developed. Base metal electrodes consist of nickel which is deposited inside the dielectric of the MLCC. Base metal electrodes are currently more common, as compared to precious metal, given the low cost of construction. Precious metal electrodes are made using a combination of silver and palladium. The amount of palladium has a major impact on the reliability, as a larger amount of palladium reduces the propensity of silver migration. However a balance is needed due to the high cost of palladium.

1.5 Ceramic Dielectric

MLCCs are composed of alternating layers of ceramic and dielectric. This dielectric must have properties which allow it to have a high dielectric constant and high resistance. Currently the majority of capacitors are composed of titanium dioxide compositions, such as barium titanate. Different dopants are often added to the ceramic to achieve a better dielectric constant or resistance. The electronics industry association (EIA) classifies MLCCs into four classes (I, II, III, IV) based on their characteristics at varying temperatures [10]. The results displayed in this thesis used class II capacitors.

1.6 Literature Review

Kobayashi et al [11] described two failure mechanisms that are prominent in multilayer ceramic capacitors. The first was punch through, which occurs when a buildup of energy occurs inside the layers of the capacitors and it is released all at once breaking the ceramic. This can also cause a burn to occur inside the ceramic and will appear as charring. The second mechanism is silver migration which is described as occurring on the surface of the capacitor in THB conditions. It is visible through stains on the ceramic surface. Their studies showed that dissipation factor was the first to change for a silver migration failure and also that the presence of a conformal coating (epoxy or silicon paste) would prevent a silver migration failure.

Brennan [12] completed a series of tests demonstrating that insulation resistance failures were accelerated by low voltage. The MLCCs were found to fail at 1/10th their rated voltage at room temperature, however many capacitors recovered as the voltage was increased. Prior to testing the capacitors experienced a voltage conditioning at 100V and 125°C for 100 hours. These failures were believed to be caused by voids, delaminations and other dielectric defects. It is recommended that capacitors undergo a high temperature and low voltage screening if the capacitors are intended for low voltage applications.

Donahoe et al [13] completed testing on moisture induced degradation in multilayer ceramic capacitors. A comparison between base metal and precious metal electrodes exposed to an autoclave (121°C/ 100%RH) was completed. It was determined that the precious metal electrode MLCCs followed a well known aging mechanism, while the base metal electrode MLCCs degraded below their specification limits. It was hypothesized that the difference could be due to oxidation or corrosion of the nickel plates or chemical changes in the barium titanate dielectric.

There has been a lot of research into cracking of standard termination capacitors. Recently, there has been work by Keimasi et al [4],[14] to examine the differences between the standard and flexible termination capacitors, as well as eutectic tin-lead and lead-free solders. In these tests it was found that the flexible termination capacitors had a greater resistance to cracking than the standard termination capacitors. It was also found that capacitors assembled with lead-free solders were more resistant to cracking than capacitors assembled with tin-lead solder. Finally it was determined that capacitor size and dielectric composition played a role in cracking reliability, with smaller MLCCs having a greater resistance to cracking and C0G capacitors showing a resistance to cracking, while X7R capacitors were failing.

Minford [15] completed research to examine the degradation of insulation resistance under high temperature and high voltage situations. Capacitors were exposed to 2x and 8x the rated voltage at temperatures of 85°C and 170°C. It was determined that the times to failure followed a lognormal distribution with a standard deviation of approximately 0.5. It was found that having a capacitor at 150°C and 3 times the rated voltage for 80 hours would be the same as having a capacitor exposed to 85°C and 50V for 500,000 hours.

Farag et al [16] completed a study comparing the failure mechanisms of capacitors in a power distribution system installed and operated from 1980 through 1990. In this test there were several failures which were found to occur in the capacitors. It was found that 92% of the failures were caused by a loss of insulation resistance in the composite dielectric.

Chan and Yeung [17] reported the reliability of 0805 surface mount MLCCs with X7R dielectric in THB conditions. The temperature and humidity were cycled and capacitance, dissipation factor and insulation resistance were all used to determine failure. Silver and tin migration on the surface of the capacitor led to failure. At higher voltage bias levels there was less of a recovery of the capacitor parameters upon completion of the test.

Nie et al [18] and Gu et al [19] performed a prognostics analysis using data from flexible termination capacitors in THB conditions. In this test the majority of the failures occurred in the capacitors tested at the rated voltage. A large disparity was also found between the numbers of failures between manufacturers. One of the biggest findings was the difference in total failures between the standard and flexible termination MLCCs, with more flexible termination MLCCs failing.

Ling and Jackson [20] demonstrated that silver migration can cause a short between the electrodes of precious metal electrode capacitors which are exposed to temperature-humidity-bias (THB) conditions. In their tests MLCCs were exposed to a temperature humidity bias. It was found that the failure rates were dependent on the quality of the parts from the manufacturer, as well as if the capacitors were barrel plated. Cross sections showed large voids present in the ceramic that were believed to be caused by burning of the shorts, which in turn destroyed the dielectric. In experiments in which the electrodes were exposed to the THB conditions it was found that silver was able to migrate several hundred microns after less than 1000 hours of exposure. They concluded that the silver would be able to migrate along grain boundaries and voids leading to failures.

Sato et al. [21] demonstrated a method for metal migration in MLCCs. The first step was the creation of a microscopic crack in the dielectric. Salt contaminants the get into the space where the crack is present. If moisture is then present it is possible to have electrolysis. Electromigration of the electrodes is then present if they are made of silver or palladium, which can in turn lead to failure of the MLCCs.

Lee and Su [22] demonstrated that the proportion of silver to palladium has a large impact on the migration of the metal. If more palladium was present there was a greater reliability than if there was less palladium in the mixture. Tests were run using combinations of silver to palladium of 90/10, 95/5, 97/3 and 99/1. The MLCCs were exposed to 140°C and 200V with insulation resistance being measured until failure. A linear extrapolation between the life time and the silver to palladium content was able to be created. A capacitor which had 10% palladium would last 100 hours in these conditions, compared with less than 20 hours for a capacitor with 1% palladium.

Naguid and MacLaurin [23] completed tests to determine silver migration in MLCCs. It was found that unencapsulated Ag base conductors were subject to silver migration in THB environments. It was found that the rate of Ag migration decreases with increased palladium and that Ag migration is the main failure mode in dielectric crossover structures. An abrupt change in capacitor and insulation resistance was found to occur with silver migration.

Zou et al [24] studied the effects of silver migration of the dielectric properties and reliability of relaxor based MLCCs. It was It was determined that silver migration causes grain growth, changes in dielectric properties and also decreases the insulation resistance. This was thought to possibly be due to the low melting point of silver.

1.7 Motivation

The creation of flexible termination capacitors has relieved much of the concerns over flex cracking; however there are now concerns over the reliability of the flexible termination capacitors. Flexible termination capacitors were created for the purpose of high reliability applications where failures are not acceptable. There has been research evaluating the effectiveness of the termination in dissipating stresses and preventing flex cracking, however there is little published data on the reliability of flexible termination MLCCs exposed to environmental conditions. Manufacturer testing conditions are often limited, consisting of 168, 500 or 1000 hours. Manufacturers also do not report using *in situ* testing nor do they have much information other than the total failures. These tests were conducted to examine and compare the reliability of standard and flexible termination MLCCs *in situ*, and for longer test durations.

2 Temperature Humidity Bias (THB) Test

To evaluate the reliability and create a comparison between the standard termination and flexible termination capacitors a temperature-humidity-bias (THB) test was chosen. In this test capacitors are exposed to elevated temperature and humidity conditions while a bias is applied. Three different bias levels were used to examine the bias effects. Given that the capacitors had precious metal electrodes, it was believed that the bias may promote silver migration, which could in turn lead to failure. Having two separate bias levels allowed for a comparison to examine claims that the high bias level will burn up shorts, while a low bias level is better for promoting silver migration. The unbiased capacitors were meant to serve as a comparison to examine if voltage is having an effect. Finally a conformal coating was applied to some of the capacitors to evaluate if it would have any effect in mitigating degradation.

2.1 Experimental Setup and Procedures

MLCCs with flexible and standard terminations, both of size 1812 and from the same manufacturer, were the subject of this study. The MLCCs had precious metal electrodes and X7R dielectric material. The nominal capacitance was 100nF with a tolerance of 10 %. Twenty four capacitors were mounted on each PCB, which was composed of high glass transition temperature (Tg = 170°C) FR4 material. All capacitors were attached with eutectic tin-lead solder. An acrylic conformal coating was applied to two of the four boards used in this study. An image of one of the boards is shown in Figure 8.

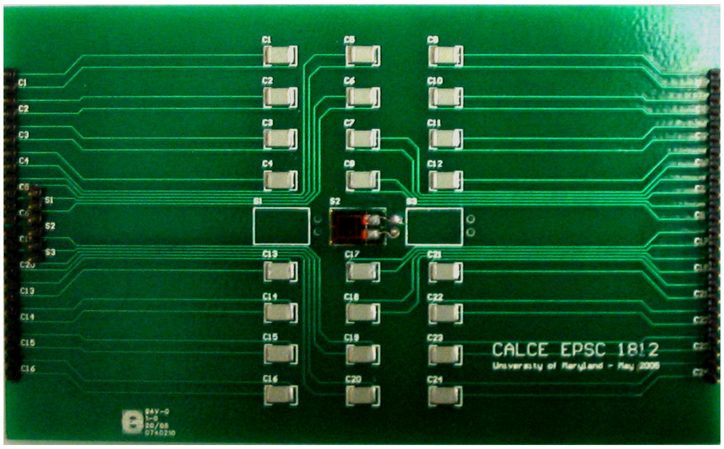


Figure 8: Circuit board used for THB testing

The capacitors were tested to determine the effects of end termination type (standard vs. flexible), and the effect of the presence or absence of the conformal coating when exposed to THB conditions. The capacitance, dissipation factor (DF) and the insulation resistance (IR) were measured in situ. The full test matrix is shown in Test matrix for THB testTable 1.

Board #	Termination	Bias	Conformal Coating	Total Capacitors
1	Standard	50	None	10
1	Standard	1.5	None	10
1	Standard	Unbiased	None	4
2	Flexible	50	None	10
2	Flexible	1.5	None	10
2	Flexible	Unbiased	None	4
3	Standard	50	Acrylic	10
3	Standard	1.5	Acrylic	10
3	Standard	Unbiased	Acrylic	4
4	Flexible	50	Acrylic	10
4	Flexible	1.5	Acrylic	10
4	Flexible	Unbiased	Acrylic	4

Table 1: Test matrix for THB test

The failure criterion used for measurements made outside the chamber was taken from the IEC 60384-22 standard [25]. This criterion is a 15% change in capacitance, a rise above 0.1 for dissipation factor or a drop below 0.25 GΩ for insulation resistance. Due to the effects of temperature and humidity on the electrical parameters it was necessary to adopt a different set of failure criteria for the in situ measurements. Following introduction into the environmental chamber, temporary fluctuations in electrical parameters were found to have stabilized by 89 hours. A baseline was taken from approximately the 89th hour in THB conditions until the 105th hour from which a factor of 10 drop for IR, change by 10% for capacitance, or doubling of DF was considered failure. The time to failure was identified as the measurement time immediately prior to the first of at least 5 consecutive readings which satisfied one or more of the failure criteria.

On each board there a DC bias of 50V was applied to 10 capacitors, 1.5V was applied to another 10 capacitors, and 4 capacitors had no bias applied. The capacitance and dissipation factor were measured using a voltage of 1 V and a frequency of 1 kHz on the LCR meter. The insulation resistance was measured using a voltage of 10V and a charge time of 120 seconds. Extensive preliminary testing showed that a voltage of 10 V would produce equivalent results to the rated voltage of 50 V, which is the voltage which is usually used in IR measurements. This avoided exposure of the 1.5V and unbiased capacitors to the high voltage, which can affect the occurrence and detection of silver migration. An image of the test setup is shown in Figure 9.

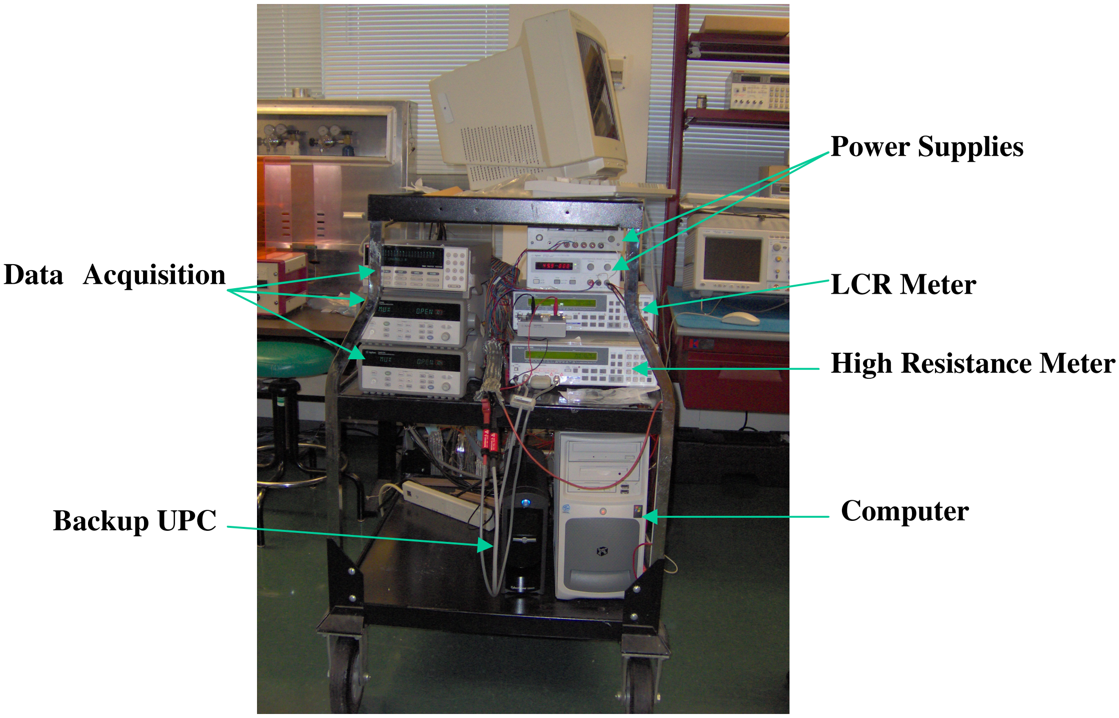


Figure 9: THB test setup

Upon assembly of the boards, an initial measurement of the electrical parameters was performed, along with a visual inspection for any cracks or assembly defects on the board. During the initial electrical testing it was found that two of the capacitors had already experienced a failure. Both of these capacitors had standard terminations without the conformal coating and were among those that would be subjected to a 50V bias. Both of these capacitors were removed from all analysis and failure statistics. The boards were then preconditioned by temperature cycling from -55°C to 125°C at a 5°C/min ramp rate and 15 min. dwell time for 20 cycles. After preconditioning the electrical parameters were again measured to screen out any premature failures. This yielded a third failure on the same board as the prior failures, which was also removed from all analysis and failure statistics. These capacitors which failed prior to testing were found to have failed due to cracks in the ceramic dielectric. Preconditioning did not produce a significant change in any of the other capacitors.

The screened boards were placed in an environmental chamber set at 85°C and 85% relative humidity and kept in the chamber for 1766 hours. Electrical parameters were continuously measured *in situ*. Following the THB test the boards were removed and the electrical parameters were again measured after cooling. The boards were then baked at 85°C for 24 hours, allowed to cool to room temperature and measured again in a desiccator and then in the laboratory conditions. Failure analysis was then conducted to determine the failure mechanisms present in the MLCCs. A flow chart of the entire test procedure is shown in Figure 10.

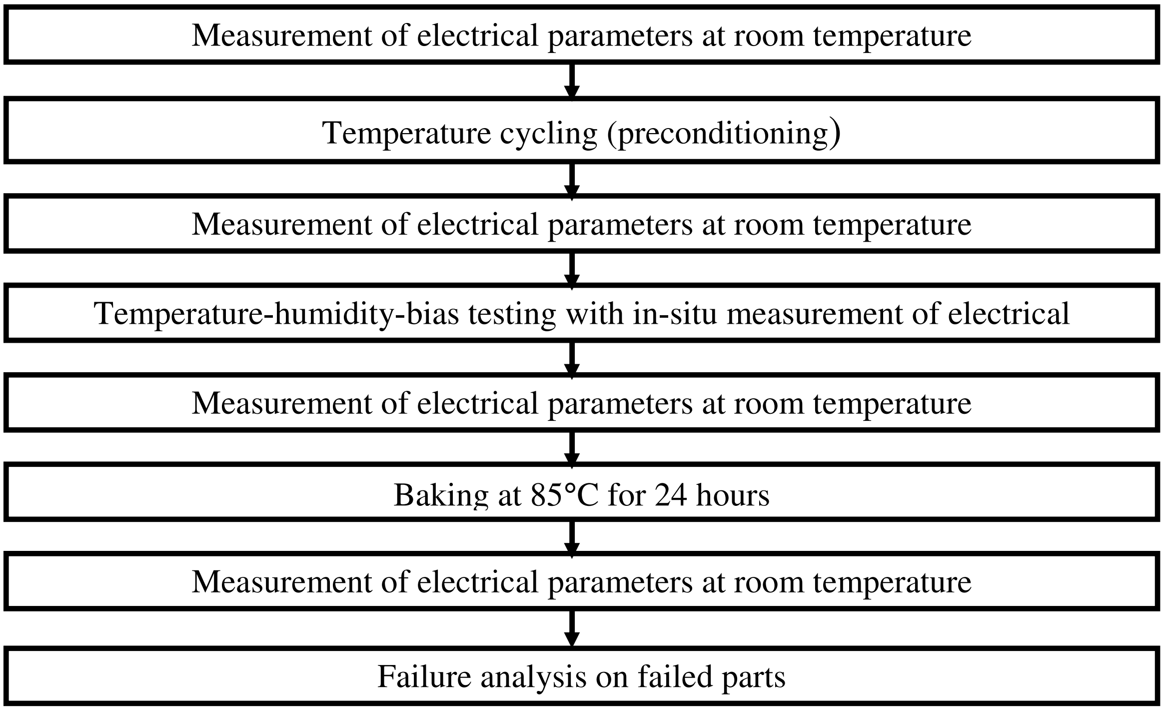


Figure 10: Flow chart of procedure for THB test

2.2 Results

At the completion of the test there were 11 capacitors which had experienced a failure of at least one parameter while being measured in situ. Of these capacitors there were 6 which had a flexible termination and 5 which had a standard termination. Six of the failed capacitors had been conformally coated whereas five had not. The results for the times to failure, as well as the parameter which failed, are displayed in Table 2.

					Time to Failure (Hours)		
Termination	**Bias Voltage**	**Conformal Coating**	**Total Capacitors Tested**	**Total Failures**	**Insulation Resistance**	**Capacitance**	**Dissipation Factor**
Standard	50	No	7	2	1017	-	1416
					1028	-	-
Standard	50	Yes	10	1	1064	-	-
Standard	1.5	No	10	0	-	-	-
Standard	1.5	Yes	10	1	-	-	814
Standard	unbiased	No	4	0	-	-	-
Standard	unbiased	Yes	4	1	-	-	964
Flexible	50	No	10	2	581	-	774
					1569	-	1569
Flexible	50	Yes	10	1	1154	-	1193
Flexible	1.5	No	10	0	-	-	-
Flexible	1.5	Yes	10	1	964	1316	1316
Flexible	unbiased	No	4	1	1656	-	-
Flexible	unbiased	Yes	4	1	1686	-	-

Table 2: Times to failure for in situ monitored capacitors from THB test

(- indicates no failures for that parameter)

The presence of the voltage bias level had little effect on the number of in situ failures. The most failures occurred in the 50 V bias groups, with 6 failures occurring out of the 37 parts in the group. However the highest percentage of failures occurred in the unbiased group, with 3 failures occurring in only 16 samples. The 1.5V biased group showed the fewest failures, with only 2 failures occurring out of the 40 MLCCs in this group. Among the unbiased failures it should be noted that 2 out of the three failures occurred very close to the end of the test, while the majority of the failures for the biased capacitors occurred around 1000 hours in THB conditions. The sole permanent failure among the unbiased parts was a flexible termination capacitor.

The majority of failures were due to drops in insulation resistance. There were two capacitors which failed for dissipation factor and did not fail for any other parameter. Other capacitors which failed for dissipation factor either failed for insulation resistance at the same time or had previously failed for insulation resistance. It should also be noted that the only capacitors which failed solely for dissipation factor were both standard termination capacitors. One capacitor failed for capacitance. This capacitor first failed for insulation resistance and then failed for both capacitance and dissipation factor a few hundred hours later.

Throughout the testing there were some capacitors which experienced an intermittent failure, with a capacitor failing at one instance, but subsequently recovering. An example of a permanent and an intermittent failure for insulation resistance is shown in Figure 11. The behavior of insulation resistance for these capacitors is similar to that observed in the experiments reported by Nie et al [18] and Gu et al [19].

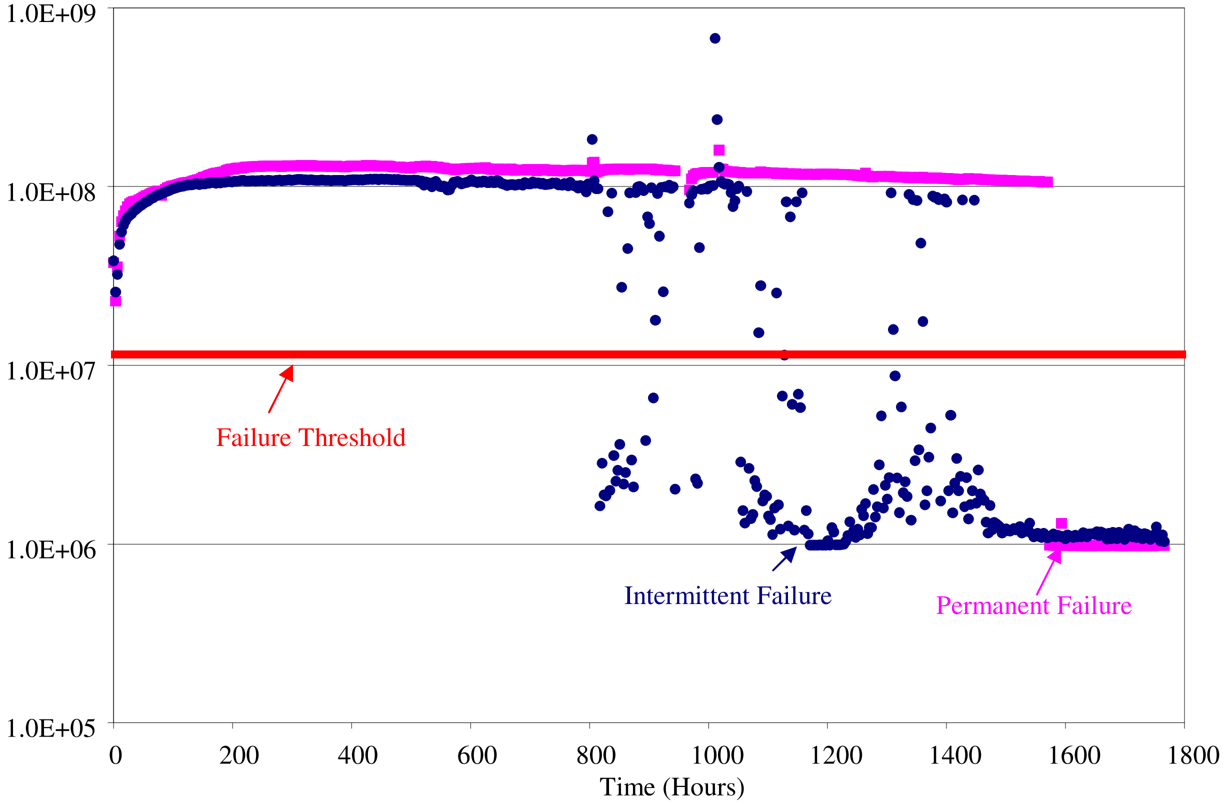


Figure 11: Examples of permanent and intermittent IR failures

The three parameter Weibull distribution was used to model the failure time of the difference sets of capacitors. The probability density function for the Weibull distribution is:

$$f(t) = \beta\eta^{-\beta}(t-\gamma)^{\beta-1}e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

In this distribution the shape parameter is represented by β, the scale parameter is represented by η, and the location is represented by γ, with t representing the time in THB conditions. The parameters for all of the different conditions can be seen in Table 3. It was found that the location parameter for all capacitors, except the unbiased group, was negative. This signals that there is no failure free period for the capacitors at the beginning of the test. It was also found that the characteristic life for all of the capacitors was similar, being around 5000 hours, with the exception of the 1.5V bias group which had a characteristic life that was about 3500 hours longer than the other groups. A comparison of the flexible vs. standard termination Weibull distributions can be seen in Figure 12.

Condition	Total Capacitors	Total Failures	Shape Parameter (β)	Scale Parameter (η: Hours)	Location Parameter (γ: Hours)
All MLCCs	**93**	**11**	**5.05**	**5194**	**-1685**
Standard Termination	**45**	**5**	**3.19**	**5510**	**-1063**
Flexible Termination	**48**	**6**	**6.22**	**4770**	**-1685**
Acrylic Conformal Coating	**48**	**6**	**4.82**	**5228**	**-1685**
No Conformal Coating	**45**	**5**	**5.11**	**5266**	**-1655**
50V Bias	**37**	**6**	**4.40**	**4924**	**-1668**
1.5V Bias	**40**	**2**	**2.42**	**8445**	**-963**
Unbiased	**16**	**3**	**2.18**	**2335**	**639**

Table 3: Weibull distribution parameters for THB results

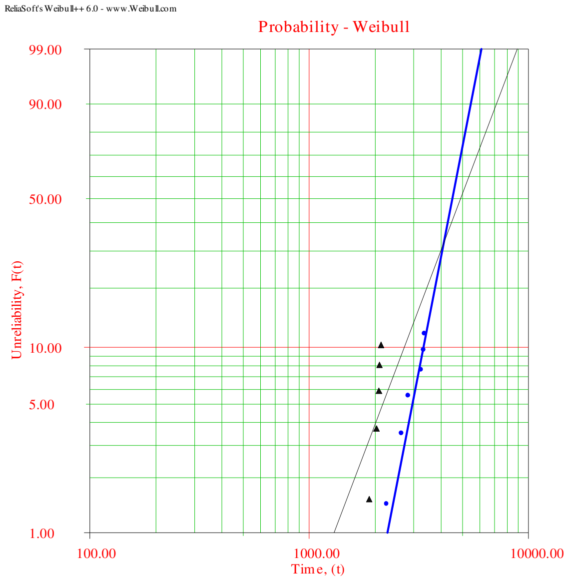


Figure 12: Weibull plot for THB test comparing terminations (Blue line and markers are flexible termination MLCCs, Black line and markers are standard termination MLCCs)

Once the MLCCs were removed from the THB conditions their electrical parameters were measured in laboratory conditions. The MLCCs were then baked at 85°C for 24 hours, and upon removal from the oven were kept in a desiccator while they were re-measured. The MLCCs were then removed from the desiccator and measured again after equilibrating to laboratory conditions. Each set of measurements produced a change in the total number of failures for each termination type. After removal from the THB chamber, fewer failures were identified among standard termination capacitors than during the THB portion of the test, whereas more flexible termination capacitors satisfied the failure criteria. As previously noted, these criteria were different for the in situ and laboratory measurements. There was a near equal distribution of failures between the conformally coated and uncoated boards. The distribution of failures for each set of measurements can be seen in Table 3.

Three of the standard termination capacitors recovered once they were removed from the elevated temperature and humidity conditions. Alternatively one additional flexible termination failure was recorded upon removal from the THB conditions. Baking the MLCCs led to the recovery of one part when placed in the desiccator and another part when removed from the desiccator. It should be noted that the latter two recovered capacitors had IR values that were only slightly above the failure criterion of 0.25 GΩ. All of the capacitors which remained as failures after the final bake-out failed for insulation resistance.

Degradation of IR was also observed during post-bake out measurements in many of the non-failed flexible termination MLCCs. These MLCCs exhibited IR values in the range of 10^8 Ω, but did not reach the failure threshold. The degradation was not as great in the standard termination MLCCs. The MLCCs were measured again after 15 weeks of storage in laboratory conditions with the number of failures remained unchanged.

The acrylic conformal coating did not mitigate the degradation to the capacitors. It is believed that the coating became saturated quickly in THB conditions and therefore was no longer able to keep moisture away from the capacitors. This would account for the similarity in failure rates between the coated and uncoated capacitors.

				Cumulative Failures			
Termination	**Bias Voltage**	**Conformal Coating**	**Total Capacitors Tested**	**During Test**	**After Removal from Environmental Chamber**	**After 85°C Baking (Cooled in Desiccant)**	**After Removal from Desiccant**
Standard	50	No	7	**2**	**1**	**1**	0*
	50	Yes	10	**1**	**1**	**1**	**1**
	1.5	No	10	0	0	0	0
	1.5	Yes	10	**1**	0	0	0
	None	No	4	0	0	0	0
	None	Yes	4	**1**	0	0	0
Flexible	50	No	10	**2**	**2**	**2**	**2**
	50	Yes	10	**1**	**2**	**2**	**2**
	1.5	No	10	0	0	0	0
	1.5	Yes	10	**1**	**1**	**1**	**1**
	None	No	4	**1**	**2**	**2**	**1***
	None	Yes	4	**1**	**1**	0	0

Table 4: Cumulative failures after completion of test.

*Recovering capacitors were only slightly above the failure threshold.

2.3 Failure Analysis

Failure analysis was conducted on the failed capacitors from the THB test. First a set of electrical measurements were taken followed by a visual inspection to determine any possible defects. Optical microscopy was then used still yielding no defects which would have been indicative of a failure. It was determined that the conduction path creating the low insulation resistance was likely internal to the capacitor and cross sectioning would need to be employed. The procedures used for these cross sections, along with the results, are described in the coming sections.

2.3.1 Procedure

To determine the failure mechanisms present in the THB tested capacitors a method of cross sectioning while monitoring resistance was used. The low IR failures were believed to be caused by silver migration between the electrodes, which would cause a short inside the capacitor. Cross sectioning while monitoring resistance would allow for a short to be found through the removal of material until a spike is resistance was found.

The first step was to measure the resistance and ensure that it was low enough such that it could be measured by an ohmmeter. The resistance has to be measured continuously and therefore a high resistance meter cannot be used. Wires were then soldered to each end of the capacitor, such that the IR, capacitance and DF of the capacitor could be measured through that set of wires. From here a diamond saw was used to cut the board around the capacitor, ensuring that there was a large amount of PCB around the capacitor to allow for mounting.

The next step was to coat the capacitor and piece of PCB in a thin layer of epoxy. The epoxy was placed only around the capacitor and the board was tilted several times to try and ensure epoxy was under the capacitor. This was necessary since the cross sectioning process creates metallic particles, which can in turn build up under the capacitor giving a false resistance reading. Once the epoxy had solidified it was then possible to begin cross sectioning of the capacitor.

Cross sectioning was completed using a Buehler MPC 2000. This machine allows for precision cross sectioning, with up to 1 micron resolution. To find the short inside the capacitors a 9 micron lapping film was placed on the machine and the capacitor was mounted on a fixture using a bonding wax. The wires, which had previously been attached to each of the capacitor terminations, were then attached to an Agilent multi-meter. A 1 kΩ resistor was added in series to ensure that any shorts inside the capacitor would not be destroyed by a current surge. The capacitor was cross sectioned from the side in 1 micron intervals. Once a spike in resistance was found the cross sectioning process was immediately stopped. The capacitor was then observed using optical and electron microscopy to determine if a short was present. A diagram of the setup can be found in Figure 13.

Figure 13: Cross sectioning equipment setup

2.3.2 **Results**

Failure analysis has been conducted on the flexible termination capacitors biased at the rated voltage with a metallic bridge between two electrodes in two of the permanently failed capacitors being identified. The failed capacitor in figure 2 was a flexible termination capacitor without a conformal coating and with a 50V applied bias. This capacitor had a resistance of approximately 15 kΩ at the start of the cross sectioning. A sudden rise in the resistance indicated a short was present and a visual inspection produced a metallic conduction path bridging the 2nd and 3rd electrodes from the bottom of the capacitor. An optical image of the short is shown in Figure 14.

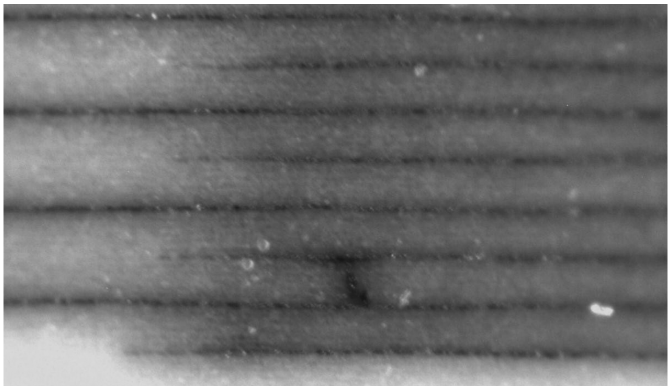


Figure 14: Metallic short in flexible termination capacitor

Scanning electron microscopy (SEM) was used to examine the area of the short. It was found that the short consisted of metal which had penetrated into voids present in the ceramic between the 2nd and 3rd electrodes from the bottom of the capacitor. This metal was only present in one area of the capacitor and was not found in any of the voids in the surroundings ceramic. A SEM image, showing the short (in the red box) and the surrounding dielectric with no metal in the voids, is shown in Figure 15.

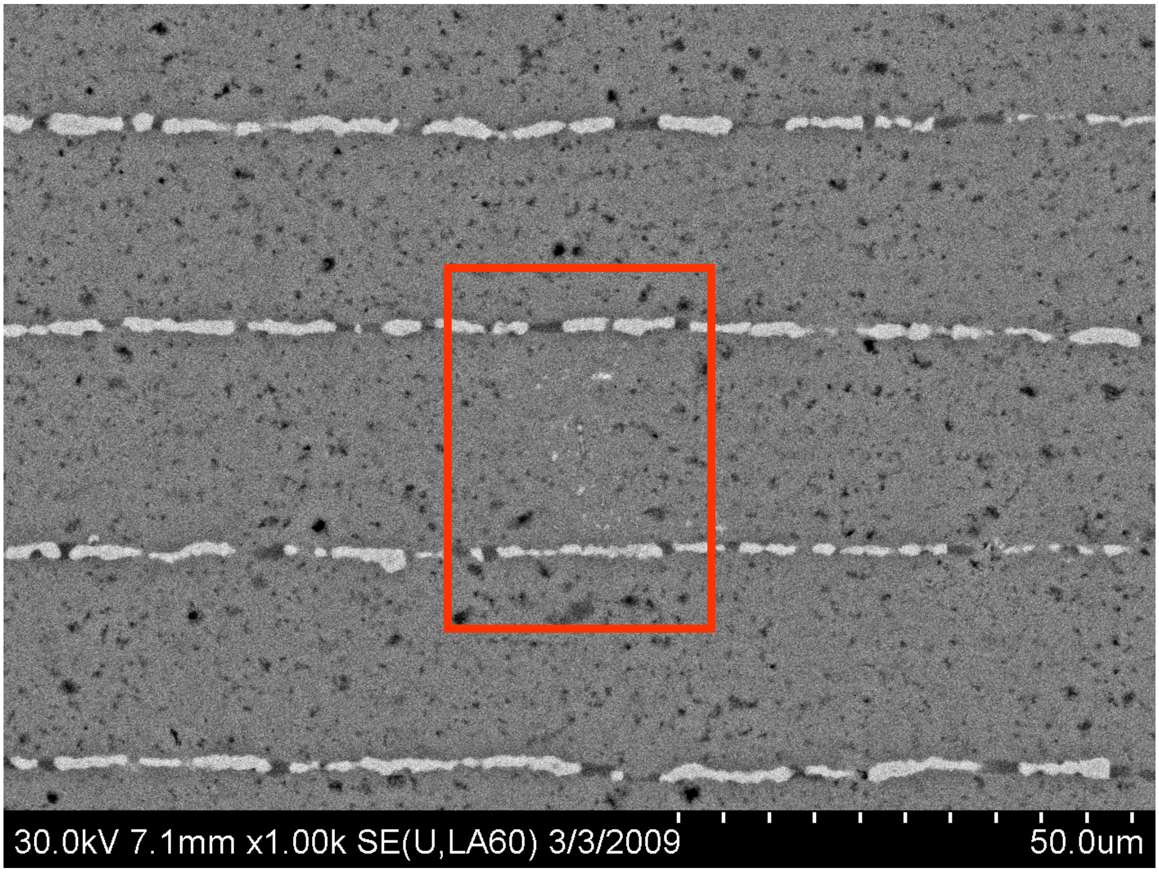


Figure 15: SEM image of the short present in biased THB tested MLCC

Energy dispersive spectroscopy (EDS) was used to determine the material compositions of the metallic shorts. It was found that the shorts were caused by a migration of silver and palladium into voids in the dielectric. Given that palladium was also present in the voids, the metal is therefore coming from the electrodes and not the end termination. A line scan demonstrating the elevated levels of silver and palladium between the electrodes is shown in Figure 16.

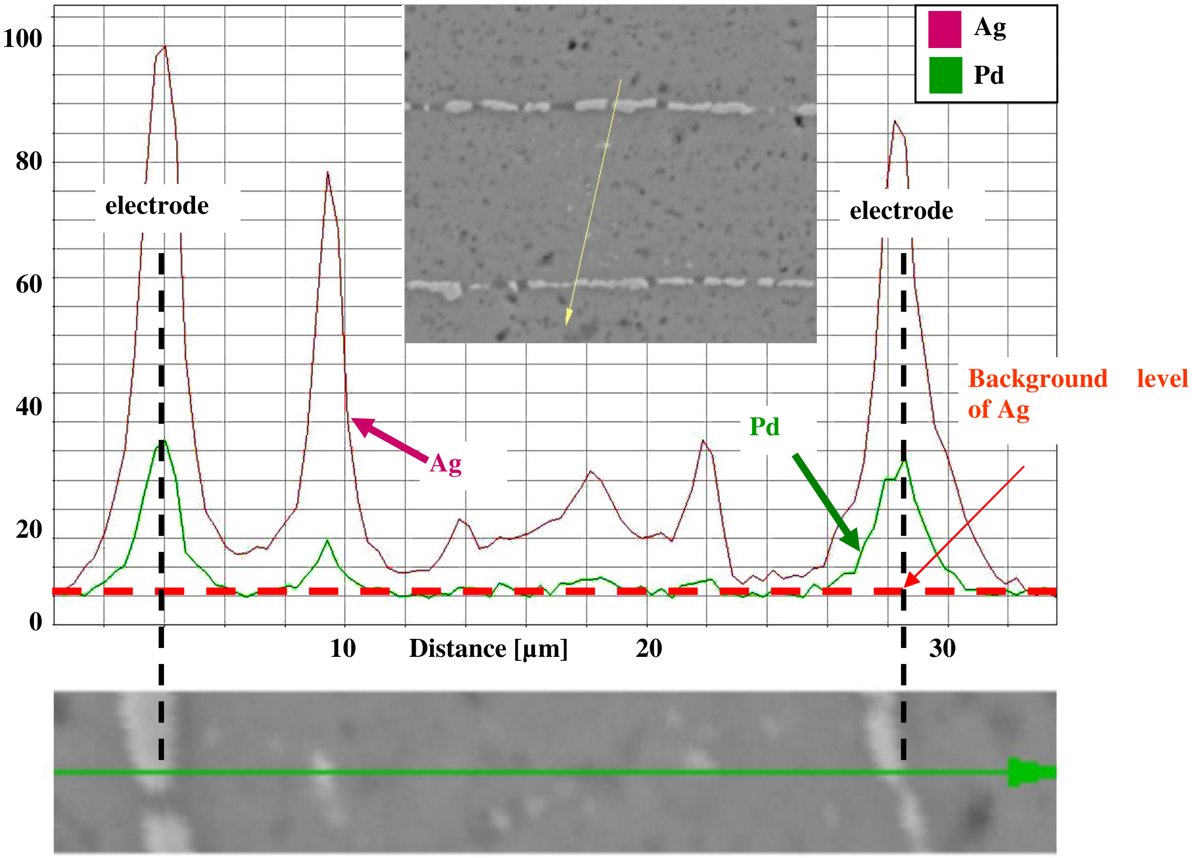


Figure 16: EDS line scan of metallic short

Failure analysis on the sole permanent 1.5V failure indicated the failure mechanism was a metallic short; however no visual confirmation could be made. The resistance value for this capacitor, while still well below the failure criteria, was approximately 2 orders of magnitude greater than the failed capacitors biased at the rated voltage level. Cross sectioning was completed until a spike in resistance occurred. The spike was so dramatic that the short was completely ground away. It is believed that the short was approximately 1 micron in width; given this is the approximate amount of material removed when the spike occurred.

The biased flexible termination capacitors are experiencing silver and palladium migration which is causing a short, appearing as a low insulation resistance value. The metal migrates along grain boundaries or voids present in the dielectric. This corresponds with publications by Ling and Jackson [15] as well as Brennan [12], showing silver migration as the failure mechanism for MLCCs in THB conditions. The unbiased capacitors are believed to be experiencing an overall degradation of insulation resistance leading to failure. The possibility also exists that the periodic voltage bias applied for IR measurement could be causing failure in the unbiased capacitors, however their insulation resistance is too high for use of the cross sectioning method in finding a short. The failed standard termination MLCC also had an insulation resistance which was too high for cross sectioning to be effective in determining if a short was present. It is believed that it also experienced a short, similar to the flexible termination biased MLCCs.

2.3.3 **Data Comparison**

A data comparison was created to compare to *in situ* data trends to the failure mechanisms found. It was determined that in the biased capacitors there were a few different failure mechanism present. If the capacitor experienced an avalanche, or sudden failure, the failure mechanism was silver and palladium migration. This occurred in all but one of the biased flexible termination capacitors. The other biased flexible termination capacitor had a data trend in which the insulation resistance slowly dropped, which is believed to be ceramic degradation; however there is currently not a failure analysis method to conform this.

The standard termination capacitors experienced many intermittent failures with only one capacitor failing after removal from THB conditions. The standard termination MLCC which failed *in situ* but not after removal from THB conditions was found to have a crack present. It is believed that this crack allowed a path for moisture penetration which is the reason for the *in situ* failures. Once removed from THB conditions there was no longer moisture present in the crack and therefore there was not a conduction path. The failure mechanism of the other standard termination MLCC could not be determined since the resistance was too high for cross sectioning while monitoring resistance. It is believed that it is caused by silver and palladium migration, given that it also had a 50V bias applied. The capacitor also had a similar data trend with many intermittent failures, but the insulation resistance finally settling at 1 MOhm, the value of the series resistor. A graph showing the insulation resistance over time for the failed biased capacitors in the THB test can be found in Figure 17. It should be noted that the peaks occurring at approximately 800 and 1000 hours were due to chamber problems, and are not indicative of the true nature of the capacitors.

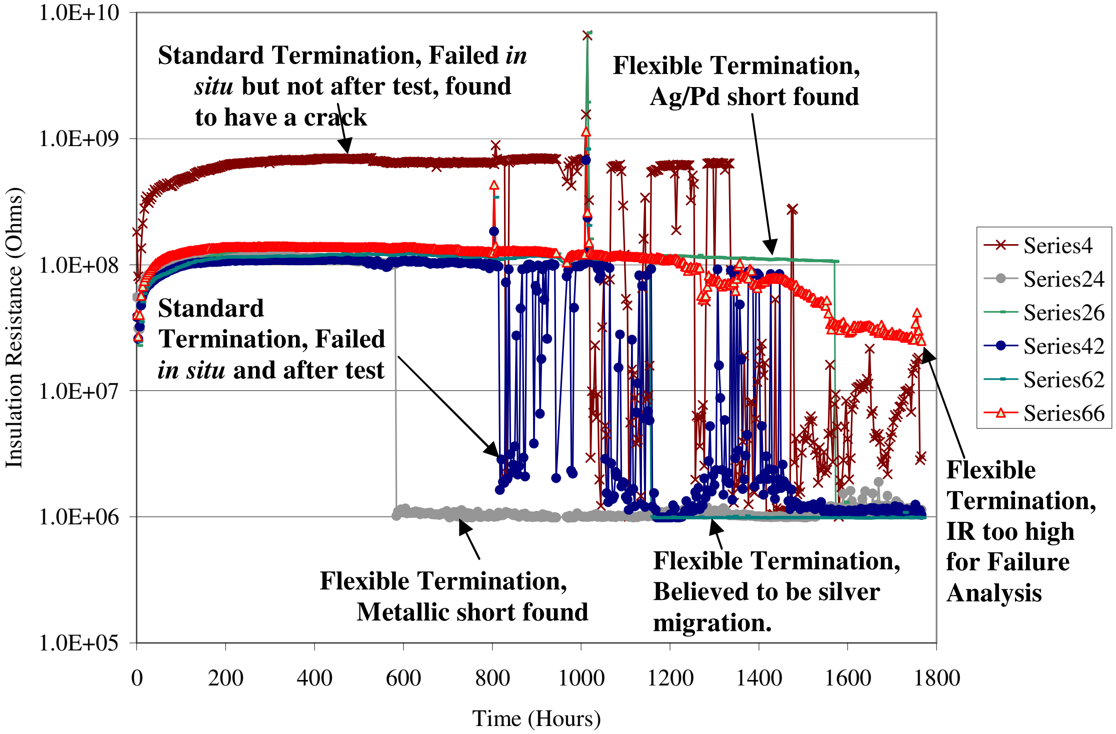


Figure 17: IR over time for the failed biased THB tested capacitors

The failed unbiased MLCCs had a different trend from the biased MLCCs. Around 1400 hours in THB conditions the failed capacitors were found to start experiencing a slow degradation. The insulation resistance gradually dropped to and below the failure threshold. Only one capacitor ever reached the value of the series resistor (1 MOhm) and this was an intermittent failure. Only one of the failed unbiased capacitors was a failure after removal from the chambers. Due to the gradual reduction of insulation resistance, it is believed that there is a degradation of the ceramic dielectric occurring which is leading to failure of the MLCCs. Currently there is not a failure analysis method which can conclusively say degradation of the ceramic has occurred, therefore this is only speculation from the data trends. The IR over time for the three failed unbiased capacitors is shown in Figure 18. It should be noted that the peaks occurring at approximately 800 and 1000 hours were due to chamber problems, and are not indicative of the true nature of the capacitors.

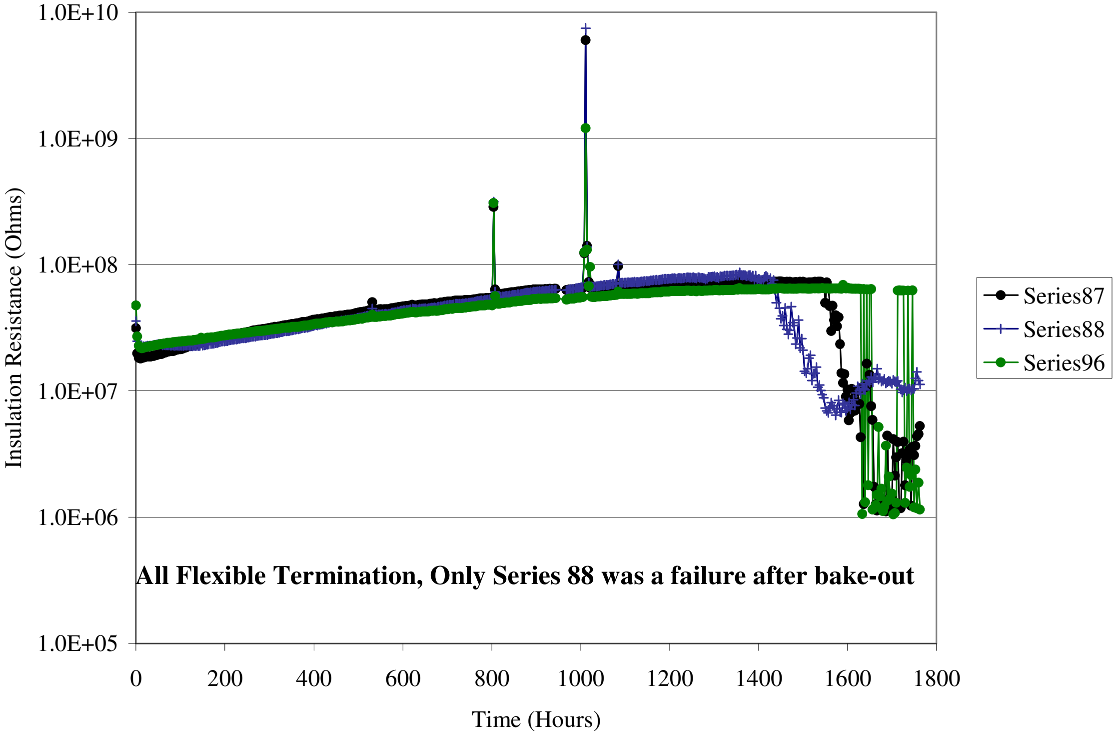


Figure 18: IR over time for the failed unbiased MLCCs in the THB test

2.4 Discussion

This study demonstrated that flexible termination capacitors experienced a lower reliability compared with the standard termination capacitors after 1766 hours in THB conditions. The majority of capacitors failed for insulation resistance, with a few MLCCs failing for dissipation factor only. The capacitors also experienced both permanent and intermittent failures while in THB conditions. This indicates that there are likely multiple failure mechanisms present. Upon removal from THB conditions it was found that the capacitors which had failed solely for dissipation factor had recovered for all electrical parameters.

The flexible termination capacitors experienced a greater number of failures compared with the standard termination capacitors once removed from the THB conditions. In the flexible termination capacitors there is a silver polymer which is in direct contact with the dielectric, while the standard termination capacitors have pure silver against the dielectric. Since the shorts are a combination of silver and palladium it is believed that the metal is coming from the electrodes, which are a mix of the two metals. It is hypothesized that the silver polymer in the flexible termination capacitors may be providing a path for moisture to enter the capacitor and also could be causing the dissipation factor failures for the flexible termination capacitors. The standard termination capacitors would therefore not experience the same problems since no polymer is present.

MLCCs which failed during in situ testing yet recovered in laboratory conditions, as well as intermittent failures in the in situ data, are hypothesized to have failed by moisture penetration into voids in the capacitor. Moisture penetration would create a loss of insulation resistance in the capacitor which could disappear when the capacitor was removed from a high humidity environment. This is believed to be the mechanism for the MLCCs which experienced a recovery upon removal from THB conditions.

Research by Lee and Su [22] demonstrated that the proportion of silver to palladium has a large impact on the migration of the metal. If more palladium was present there was a greater reliability than if there was less palladium in the mixture. This demonstrates that both metals can still migrate as was found in this THB study. It also suggests that a larger amount of palladium in the electrodes would prevent the migration in the flexible termination electrodes.

This test indicates that manufacturer testing may not be adequate for determining differences in the reliability of the flexible and standard termination MLCCs. In situ monitoring and longer test durations are needed better determine the reliability of the MLCCs. It was found that as of 1000 hours there were 4 capacitors which had failed for at least one parameter. Three of the four capacitors had failed after 800 hours and two were dissipation factor failures which were not present after removal from THB conditions. Had the test been stopped at 1000 hours it is believed that only 1 or 2 of the capacitors would have been failures outside the THB conditions, which is similar to that reported by manufacturers. Completing testing for 766 more hours showed six failures in the flexible termination capacitors, compared with one in the standard termination MLCCs. This difference in the number of hours in THB conditions is believed to be the cause of the reliability difference.

In situ testing also had a major impact. This allowed for knowledge about the degradation and intermittent failures of the capacitors. Many capacitors experienced intermittent failures and would quickly recover. These failures might not be found by manufacturers not using in situ monitoring therefore not giving an accurate reading of the reliability.

2.5 Summary and Conclusions

In this study flexible and standard termination capacitors were exposed to 1766 hours in THB conditions and tested at varying voltage bias levels, some with an acrylic conformal coating. It is concluded that the reliability of flexible termination MLCCs is less than standard termination MLCCs when exposed to THB conditions. The tests demonstrated that the application of the rated voltage in THB conditions creates more failures as compared to a low or unbiased capacitor. The flexible termination failures were also permanent while many standard termination capacitors experienced intermittent failures. Acrylic conformal coatings were found to have no effect in mitigating degradation to the MLCCs exposed to THB conditions. Capacitors with the acrylic conformal coating had similar failure statistics to the uncoated capacitors.

Failure analysis has demonstrated migration of silver and palladium as the failure mechanism in the biased flexible termination capacitors. Silver and palladium were found in voids which were present in the dielectric between the upper or lower electrodes in the capacitors. The shorting was found to always occur near the end of one set of electrodes close to the end termination. It is believed that the polymer in the flexible termination capacitors is creating a moisture path which is allowing the metal migration to occur.

These experiments also show similarities between the results and the manufacturer results up to 1000 hours in THB conditions. However after 1000 hours this test shows differences between the flexible and standard termination capacitors. The current testing conditions, up to 1000 hours may therefore not be sufficient to determine differences in the reliability of the different terminations. More extensive testing, with longer test intervals, indicates differences between the reliability of the standard and flexible terminations.

3 Storage Test of MLCCs

A storage test was also conducted to determine the effects of temperature and humidity without the presence of a voltage bias on MLCCs. This test was conducted to determine if the periodic application of a voltage bias for the measurement of insulation resistance in the THB test could be causing the failures which were occurring. For this test capacitors were placed in an aluminum tray directly from the reel. The capacitors were exposed to 85°/ 85% RH conditions for 1978 hours.

3.1 Experimental Procedures

The MLCC lots used in this study were size 1812 flexible and standard termination capacitors with an X7R dielectric and precious metal electrodes. The nominal capacitance was 100nF with a tolerance of 10%. Trays were created that would hold thirty capacitors. One was filled with standard termination capacitors and the other with flexible termination capacitors. The initial electrical parameters were measured using an LCR meter and a high resistance meter. The capacitance and dissipation factor were measured using a Vrms of 1 V and a frequency of 1 kHz. The insulation resistance was measured using a voltage of 50V, a long integration time, and a charge time of 120 seconds.

The first and thirtieth capacitor in each tray were removed to serve as controls, which were kept in laboratory conditions. The trays, now containing 28 capacitors each, were placed in the environmental chamber set to 85°C and 85% relative humidity. Each time the parts were placed in the chamber the temperature was slowly risen to 85°C before the application of the 85% relative humidity in an effort to prevent condensation on the capacitors. The MLCCs were removed approximately every 10 days, allowed to reach room temperature, and the electrical parameters were measured. This was completed by removal of the MLCCs from the chamber and waiting approximately 90 minutes for the parts to acclimate to the laboratory environment.

The failure criteria used followed the criteria outlined in the IEC 60384 - 22 [25]. This gives a criterion of a change by 15% of the capacitance from the nominal value, a rise above 0.1 for dissipation factor or a drop below 25 seconds when multiplying the insulation resistance and the nominal capacitance. For the capacitors used in this study the failure criteria would yield a threshold of 0.25 GΩ for insulation resistance.

The MLCCs were kept in the elevated temperature and humidity conditions for 1978 hours. The capacitors were measured and then placed in an oven at 85°C for 24 hours. The electrical parameters were re-measured to determine if the capacitors had recovered. X-ray photoelectron spectroscopy was used to determine the failure mechanisms in the standard termination capacitors. Cross-sectioning was also used in the failure analysis process.

3.2 Results

Prior to placing the capacitors in an elevated temperature and humidity environment the capacitors were all behaving similarly with all capacitors electrical parameters inside manufacturer specified tolerances. Degradation and failures occurred in the standard termination capacitors upon the first measurement but not in the flexible termination capacitors. This trend continued throughout the completion of the test with more standard termination capacitors experiencing degradation and failing, while the flexible termination capacitors where not experiencing any changes. At completion of testing it was found that there were 18 MLCCs which failed at one or more instances which had a standard termination, compared with one failure in the flexible termination MLCCs. The flexible termination MLCC failed for dissipation factor and recovered on a subsequent measurement. An example of the degradation in insulation resistance for a standard and flexible termination MLCCs is shown in Figure 19.

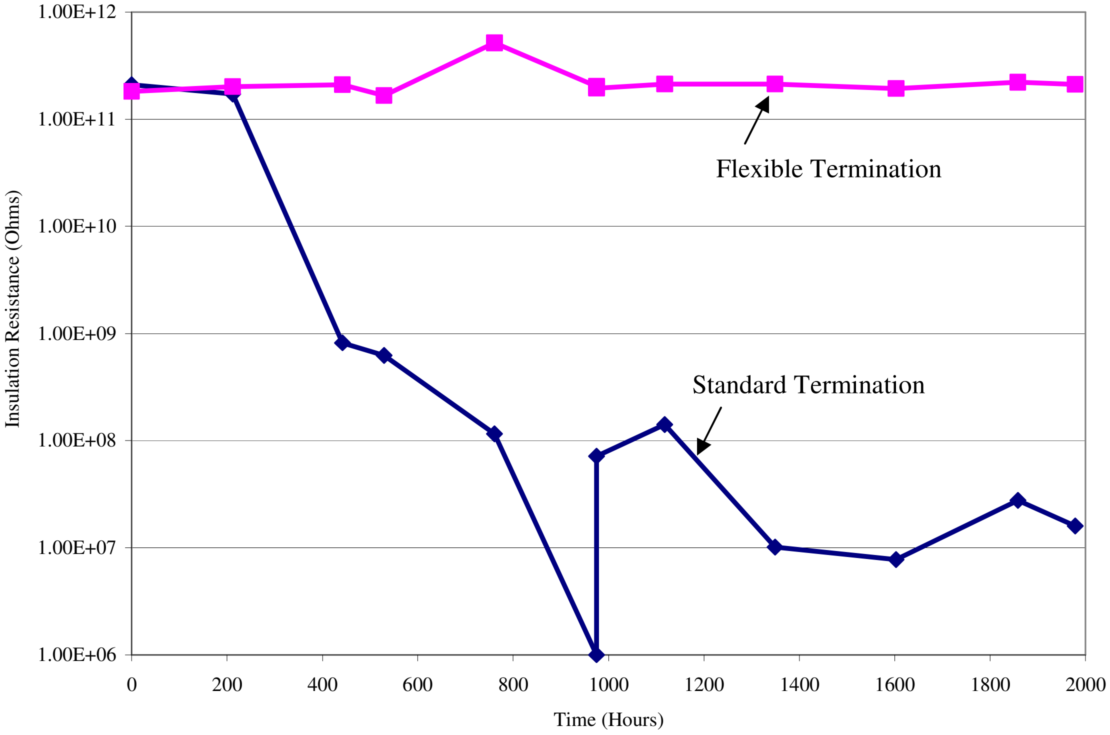


Figure 19: Insulation resistance over time for a standard and flexible termination MLCC

After 975 hours in THB conditions the MLCCs were left in room temperature conditions for an extended period of time. There was a general recovery in approximately half of the standard termination capacitors which were failing in the prior measurement. The two measurements were taken to represent a measurement approximately one month out of the chamber, and a second measurement prior to placing the capacitors back in the chamber, approximately another 1000 hours later. The change in the number of failures demonstrates how recovery occurred as the capacitors were exposed to ambient conditions. Intermittent failures were found to occur in both the standard and flexible termination capacitors throughout testing. This is evident by the fact that the number of capacitors failing at one interval was different from the total capacitors that displayed failure at some point during the test. Table 5 shows interval failures during testing while Table 6 shows cumulative failures during testing.

		Interval Failures at Various Time Intervals (Hours)											
		0	**212**	**442**	**529**	**761**	**975**	**975**	**1118**	**1349**	**1603**	**1858**	**1978**
Standard Termination	Capacitance	0	0	0	0	0	0	0	0	0	0	0	0
	Dissipation Factor	0	0	0	0	0	0	0	0	0	0	2	0
	Insulation Resistance	0	0	0	2	8	5	4	7	14	14	15	14
Flexible Termination	Capacitance	0	0	0	0	0	0	0	0	0	0	0	0
	Dissipation Factor	0	0	0	0	0	0	0	0	0	0	1	0
	Insulation Resistance	0	0	0	0	0	0	0	0	0	0	0	0

Table 5: Interval failures over time

		Cumulative Failures at Various Time Intervals (Hours)											
		0	**212**	**442**	**529**	**761**	**975**	**975**	**1118**	**1349**	**1603**	**1858**	**1978**
Standard Termination	Capacitance	0	0	0	0	0	0	0	0	0	0	0	0
	Dissipation Factor	0	0	0	0	0	0	0	0	0	0	2	2
	Insulation Resistance	0	0	0	2	8	8	8	9	15	16	17	18
Flexible Termination	Capacitance	0	0	0	0	0	0	0	0	0	0	0	0
	Dissipation Factor	0	0	0	0	0	0	0	0	0	0	1	1
	Insulation Resistance	0	0	0	0	0	0	0	0	0	0	0	0

Table 6: Cumulative failures over time

After the completion of the testing with the MLCCs in the elevated temperature and humidity conditions the MLCCs were placed and an oven for bake-out to determine if any parameter recovery would be seen. It was found that the sole failure in the flexible termination parts recovered and was no longer a failure while the standard termination parts had one recovery from the final measurement time. During the there were 18 standard termination capacitors which failed at some point during the test and there were 14 showing failure at the end of the test. Bake out recovered one of these MLCCs giving a final total of 13 failed capacitors after the completion of the test. These results are shown in Table 7.

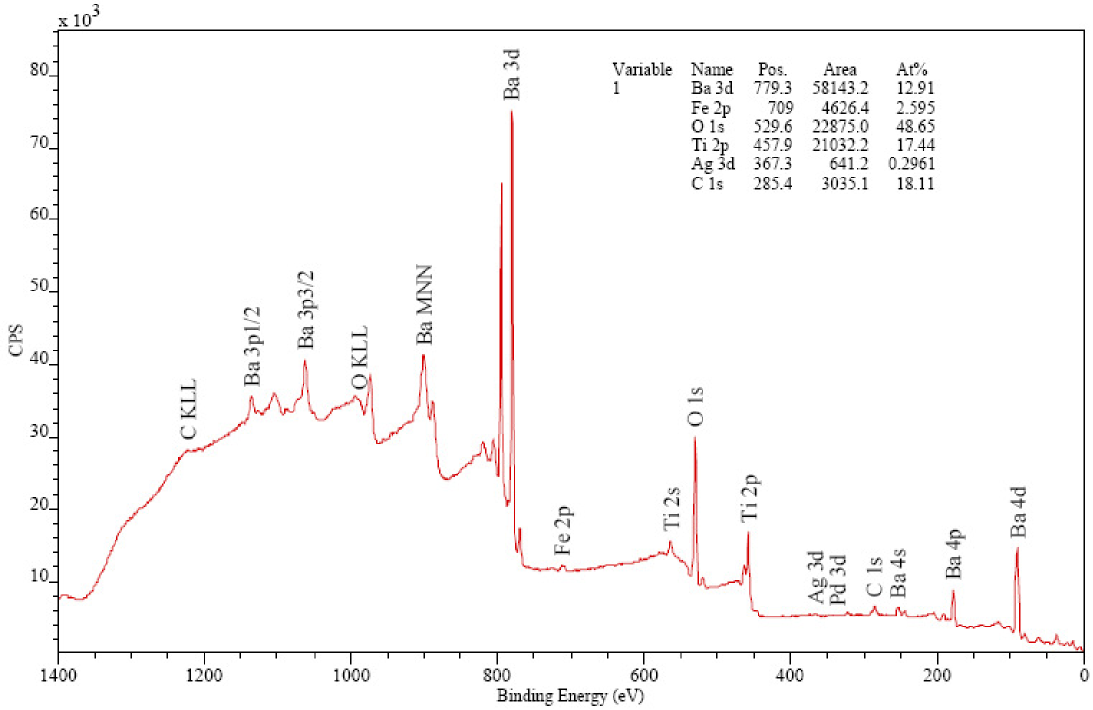
Termination Type		Total showing failure at time of removal from chamber (1978 Hrs.)	Total showing failure at some point during test	Total showing failure after baking
Standard	Capacitance	0	0	0
	Dissipation Factor	2	3	0
	Insulation Resistance	14	18	13
Flexible	Capacitance	0	0	0
	Dissipation Factor	0	1	0
	Insulation Resistance	0	0	0

Table 7: Total failures throughout all portions of testing

3.3 Failure Analysis

The failure analysis for the capacitors from the storage test involved two portions. The first step was cross-sectioning to determine if a short was present. Cross sectioning with resistance monitoring was used on a failed standard termination capacitor. The resistance slowly rose as material was removed until the capacitor was completely cross-sectioned away. A short would have shown a spike in resistance at the point in which it was reached; however this gradual rise indicates a bulk degradation of the ceramic. A second failed standard termination capacitor was sanded with 30 microns being removed from the top, bottom and sides of the capacitor. Therefore the only sides which did not experience sanding were the termination sides. No rise in resistance was found indicating that the leakage path must be inside the capacitor.

X-ray Photoelectron Spectroscopy (XPS) was employed to determine the failures from the storage tested capacitors. It was believed that there may be a material difference between the ceramic used in the standard termination MLCCs and the flexible termination MLCCs due to differences in the color of the ceramic, as well as the differing failure rates. XPS demonstrated that there was no difference in the material composition of the two dielectrics. Both sets of capacitors had barium titanate dielectric with iron as a dopant. Measurements were taken of regions on the surface of the capacitors and also in a region inside the capacitors. An example of the spectrum for the standard termination dielectric is shown in Figure 20.



Variable	Name	Pos.	Area	At%
1	Ba 3d	779.3	58143.2	12.91
	Fe 2p	709	4626.4	2.595
	O 1s	529.6	22875.0	48.65
	Ti 2p	457.9	21032.2	17.44
	Ag 3d	367.3	641.2	0.2961
	C 1s	285.4	3035.1	18.11

Figure 20: XPS Results for standard termination dielectric

To measure the inner dielectric of the capacitors it was necessary to break the capacitors. In breaking the capacitors it was found that the flexible termination capacitors experienced a clean break with a flat shear plane. The standard termination capacitors were much more brittle and would disintegrate rather than having a clean shear plane. It is hypothesized that the difference in the dielectric is not a material difference, but rather a grain size difference. Due to the high sintering temperature used in the manufacturing process it is not possible to determine the grain size used in each of the capacitor types.

In testing it was noticed that the standard termination capacitors were experiencing a discoloration which was occurring in the dielectric around the end terminations. This discoloration can be seen in Figure 21.

Figure 21: Image of standard termination MLCC with staining present in the dielectric

A cross section showed that the discoloration was also permeating into the dielectric in the area of the electrodes. An image of this cross section is shown in Figure 22.

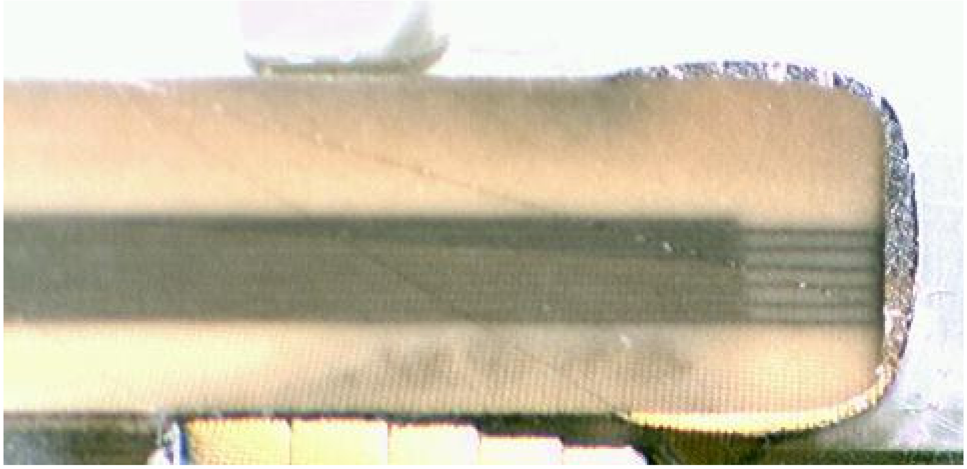
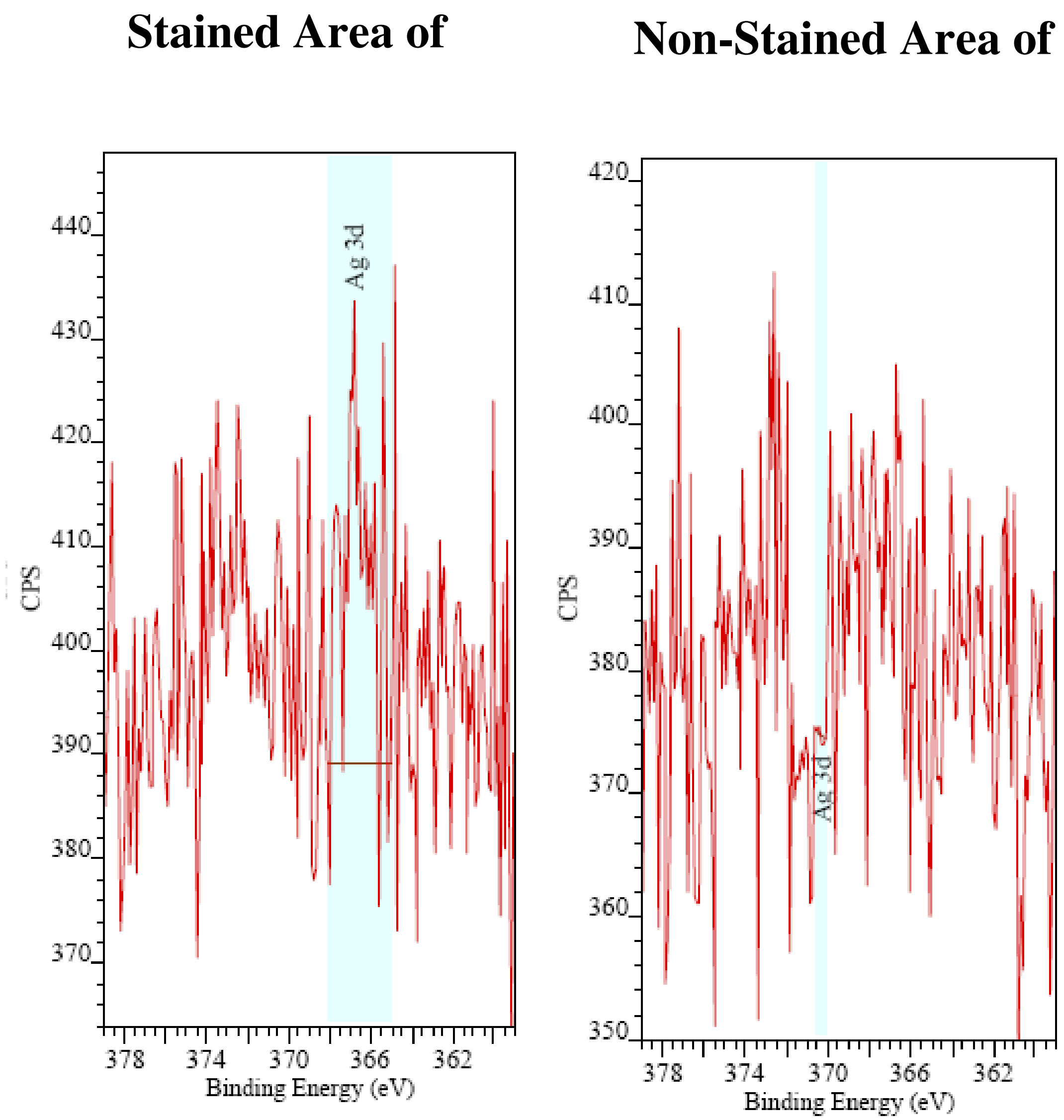


Figure 22: Propagation of stain into the ceramic dielectric of a standard termination MLCC

XPS was completed on the surface of the capacitor, and also in a region after extensive sputtering was completed on the surface of the MLCC. The discolored area was found to have silver which was not present in non-discolored areas. The differences between the amounts of silver were determined using a high resolution scan. These results are shown in Figure 23. Please note that the axes are not on the same scale (CPS = Counts per Second).



Stained Area of

Non-Stained Area of

Figure 23: Silver amounts in stained and non-stained area of MLCC

In the standard termination capacitors the end termination is comprised of silver which is against the dielectric without a barrier layer. Unlike the flexible termination capacitors, the termination contains pure silver without any polymer. It is believed that the discoloration is due to a bulk diffusion of this silver from the end termination into the dielectric of the capacitor. This silver is also believed to be the cause of the low insulation resistance in the standard termination capacitors.

There was a growth appearing on the end terminations of the flexible termination capacitors which was not present on the standard termination capacitors. This growth was impeding measurement of the capacitor on the equipment and was not electrically conductive. An optical image of this growth can be seen in Figure 24, and a SEM image can be seen in Figure 25.

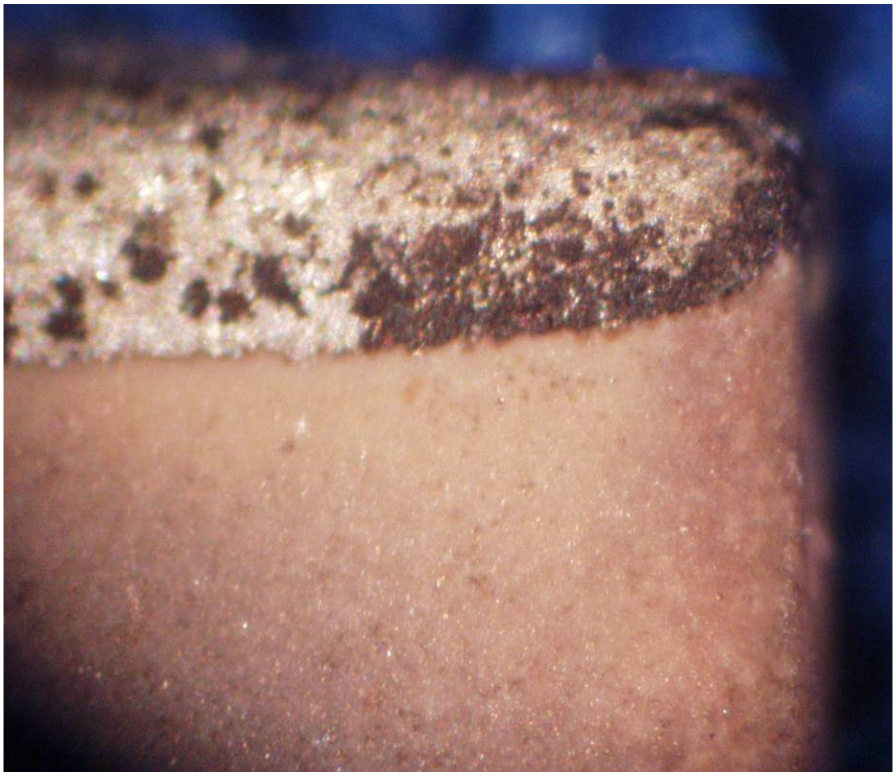


Figure 24: Optical image of growth on flexible terminations

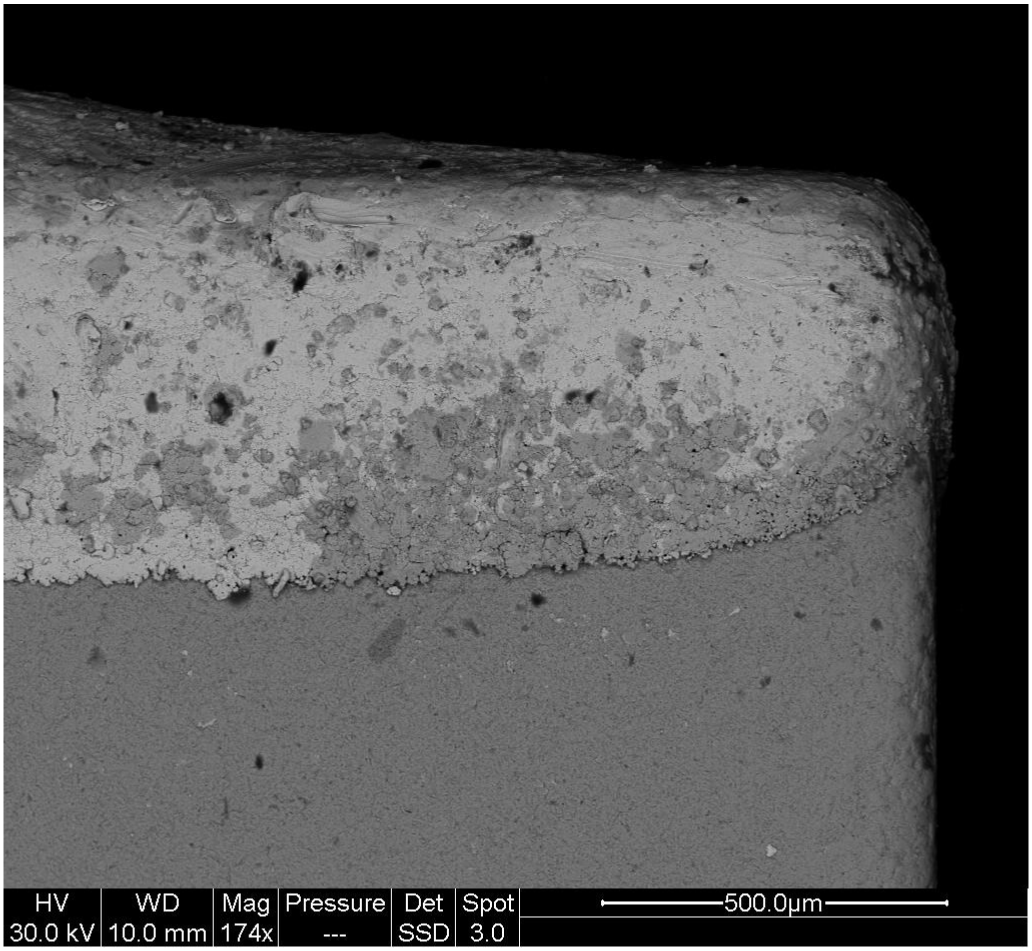


Figure 25: SEM image of growth on flexible terminations

XPS was used to analyze the material and it was found to be caused by tin oxide. The metallization coating the standard and flexible terminations is the same, both nickel coated with tin, however this problem is solely on the flexible termination capacitors, which indicates that the silver filled polymer is having some effect on the tin coating of the end termination. The XPS results for an area without the oxidation (pure tin) are shown in Figure 26, while the results for the oxidized tin are shown in Figure 27.

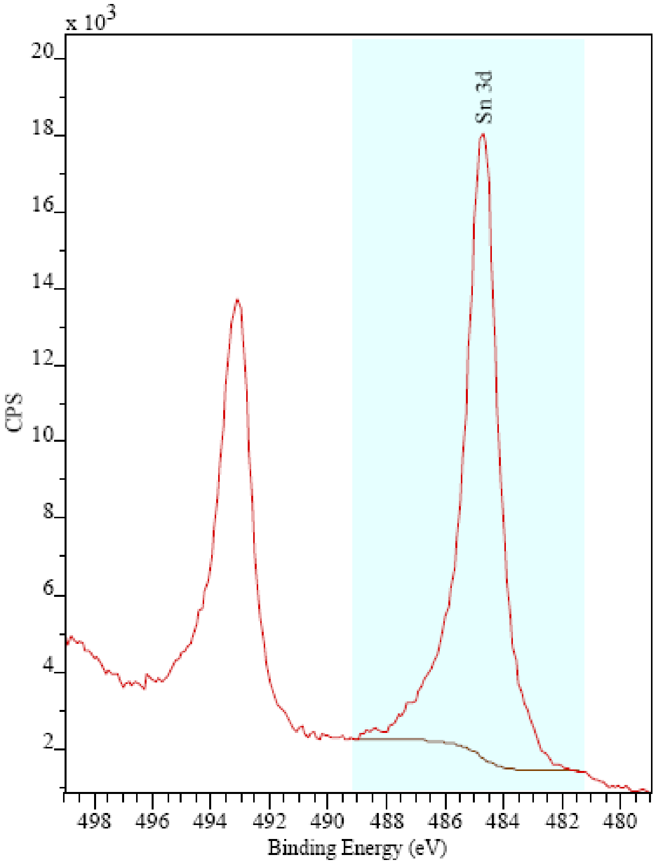


Figure 26: XPS results for pure tin (termination area without oxidation)

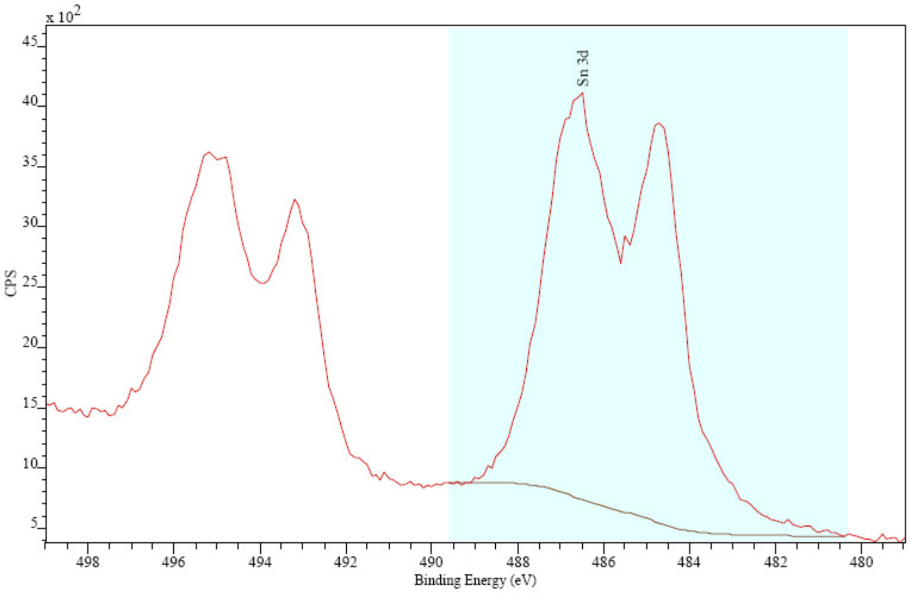


Figure 27: XPS results for oxidized tin on the flexible terminations

3.4 Discussion

This experiment examined the reliability of flexible and standard termination MLCCs when stored in elevated temperature and humidity conditions. Given the lack of a voltage bias it is hypothesized that there is a degradation that is occurring in the ceramic dielectric of the capacitors which is causing the loss of insulation resistance in the capacitors. It has been shown that vacancies in the dielectric of the capacitors can cause a loss of IR and a general degradation of the capacitors.

Failure analysis indicated that the failure location was internal to the MLCC and that at least one of the causes was a bulk diffusion of silver from the end termination. This failure mechanism is something which has not been shown in currently published data. This is also something which did not occur in the THB test, which could be due to soldering of the capacitor to a board, or the application of a voltage bias.

The difference in the ceramic dielectric between the standard and flexible termination MLCCs is still something of debate. XPS demonstrated that the material compositions are indistinguishable. There is a color difference between the two capacitors and there are differing numbers of electrodes between the two MLCCs (this can be seen in the introduction where the terminations are described). It is believed that there is likely a grain size difference, and possibly a different sintering temperature which is causing these differences.

3.5 Conclusions

Standard and flexible termination capacitors were exposed to an 85°C/ 85% RH storage condition for 1978 hours. Degradation and failures were found to occur upon the first measurement for the standard termination capacitors, which was not found to occur in the flexible termination capacitors. At the conclusion of testing there were 18 capacitors which had failed at some point during the test of the standard termination capacitors, compared with one flexible termination capacitor. Many of the capacitors were found to experience intermittent failures. The capacitors would fail at once measurement, yet would recover upon a later measurement.

This test demonstrated the effect of the termination type on the reliability of MLCCs exposed to elevated temperature and humidity conditions. The standard termination MLCCs experienced greater degradation and failures than the flexible termination MLCCs. The sole flexible termination failure occurred only at one instance for dissipation factor. Over half of the standard termination MLCCs failed at some point during the test and nearly half were failures after the bake-out.

Standard termination MLCC failures were always for insulation resistance first, and may later fail for dissipation factor. In contrast to this the sole flexible termination failure occurred only for dissipation factor and recovered soon after. This indicates that there may be different failure mechanisms occurring within these capacitors.

XPS was used to determine if a chemical change was present in the dielectric of the capacitors. A material which was forming on the terminations of the flexible termination MLCCs, and not the standard termination MLCCs, was determined to be tin oxide using XPS. XPS was also able to determine that one of the failure mechanisms in the standard termination capacitors was a bulk diffusion of silver from the end termination into the dielectric of the capacitor.

4 Contributions

The two studies described in this thesis were completed to examine and compare the reliability of the standard termination and flexible termination MLCCs. Since flexible termination capacitors are relatively new there is little published data currently available on their reliability. These contributions are explained below.

- This study made a comparison of the reliability of flexible and standard termination capacitors from the same manufacturer when exposed to THB conditions. This analysis provides knowledge of the reliability differences which can serve as a guideline for capacitor termination selection.
- This study determined the failure mechanisms in biased flexible termination capacitors.
- This study is examined the effect of a conformal coating in mitigating the degradation occurring in MLCCs exposed to non condensing THB conditions.
- This study introduced a new failure mechanism, bulk diffusion of silver from the end termination for precious metal electrode standard termination MLCCs.
- This study created a comparison of the times of failure for standard and flexible termination MLCCs in a elevated temperature and humidity storage environment.

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