KEMET film capacitors for high temperature, high voltage and high current

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ABSTRACT

Trends of several applications like down-hole drilling, commercial aviation (e.g. jet engines), heavy industrial and automotive are challenging the capabilities of capacitors and other electronic components. The growing harsh-environment conditions for these applications are high temperature, high voltage, and high current. At the capacitor component level, required features are very high reliability under mechanical shock and rapid changes in temperature, low leakage current (high insulation resistance), small dimensions, good stability with time and humidity, and high peak withstanding voltage. Capacitors for power-conversion circuitry must maintain a low AC loss and DC leakage at high temperatures.

KEMET has recently designed film capacitor series using PEN to address the needs of the above-mentioned circuits, in particular regarding the working temperature, voltage, and current.

This paper will cover technological advances in film capacitor technology to address harsh environment conditions needs, providing test results on temperature, voltage, and thermal shock acceleration factor.

1 – INTRODUCTION

Film capacitors are especially renowned for their reliability, their high current, and voltage withstanding capability and their resistance to intense mechanical shocks, due to their intrinsic physical elasticity. R&D activities focused on automotive and other markets' needs have made it possible to increase the working temperature for film capacitors up to 170 °C. Thanks to the last fifteen years reliability data, 170 °C is a temperature at which film capacitors can be considered to perform extremely well and be safe a component[1].

Temperature is clearly the most challenging parameter when looking at the design of film capacitors for drilling and aviation applications, where the maximum temperature exceeds 200 °C, and reaches up to 220 °C. Furthermore, in automotive and industrial applications the temperature is steadily growing and is forecasted to reach these maximum temperatures in the upcoming years. Even though the melting temperatures of many plastic film raw materials is well above 240 °C, it is clear that the film material must be properly treated (not only chemically during the extrusion of the raw material production process, but also physically and thermally during the production process of the film components) so that a long life can be expected and all the special electrical and mechanical properties of film capacitors are preserved when exposed to these working temperature ranges.

At a mounting technology level, in applications where capacitance needs to be very stable over a wide temperature range with good reliability and long life expectancy, through-hole (radial) film capacitors are an optimum choice with a very good performance/cost ratio. Anyway, the need of a new generation of equipment, very miniaturized and manufactured on fully-automated assembly lines, has requested several improvements in film capacitors technology to create SMD components able to withstand lead free (LF) reflow process, maintaining excellent electrical behavior, very high reliability and long life expectancy at higher and higher working temperatures.

The aim of this paper is to show designers that film capacitors can be a choice for extremely harsh environment applications like down-hole drilling, jet engines, industrial and automotive applications, even though their typical working temperature range reaches (or will soon reach) temperatures around 220 °C. At the same time, it is clear that future developments of these applications will represent a challenge for film components, should working temperatures increase even further, so a roadmap of R&D activities will be described, on which KEMET is focusing already so that film capacitors can keep being considered a choice for these high-temperature applications also in the future. A full characterization of film components as of today will therefore be the key information content of this work and will be summarized in the last section.

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2 – EXPERIMENTAL METHODS

Here is the description of the instruments, tools, and methods used during the performed measurements. For each of them, the specific measured parameters have been specified.

Agilent E4980, HP4284A Precision LCR meter and HP4192A Impedance Analyzer (1 kHz and 1 V_{rms}): Capacitance (C), dissipation factor (tg delta), Equivalent Series Resistance (ESR).

Radio Meter IM6 megaohmeter (1 – 999 V): Insulation Resistance.

Heraeus Mod. UT6060 Oven: Operational life DC and High Temperature Exposure.

Tenney JR Environmental Test Chamber: Shock test performed manually by using oven @ 220°C and Environmental Test Chamber @ -55°C.

Bertan 225 High Voltage Power Supply: Operational life DC.

Kikusui TOS9201: First Break Down Voltage - FBDV - test equipment. The test is carried out applying the following voltage ramp (Figure 1-1) on the capacitor.

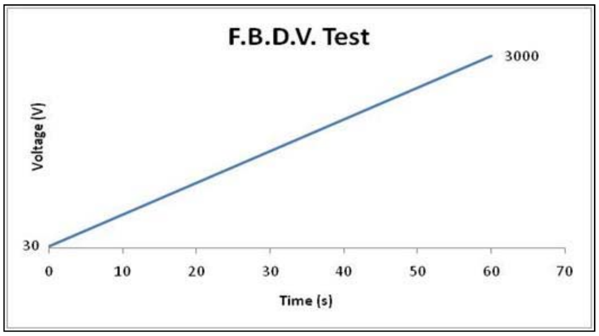


Figure 1-1: Voltage ramp-up used in the FBDV test

DSC (Differential Scanning Calorimeter) test equipment (Figure 1-2): This test allows the study of polymers' behavior when they are heated up at a specific heat rate (°C/s) and it is commonly used to observe and study polymers' thermal transitions (i.e. the melting point of an amorphous/semi-crystalline polymer or the glass transition).

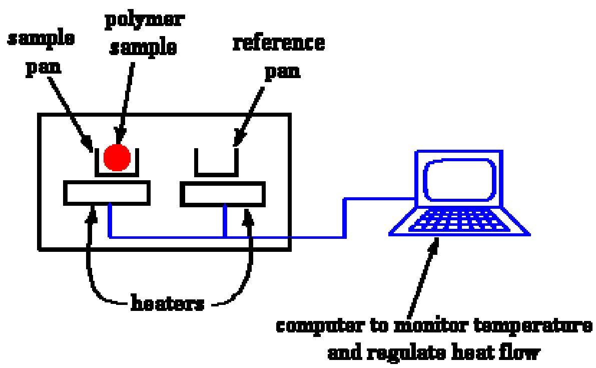


Figure 1-2: Differential Scanning Calorimeter test equipment.

Shock test system Lansmont Model 23: This system has a magnesium table that rides on a set of vertical linear guides. The sample is mounted to a fixture/table, which is lifted on the guides, and then released downward where it will be accelerated by gravity. It is programmed to control the acceleration and duration the impact of the table in order to generate the desired 500G, 2 msec shock pulse. An accelerometer is mounted on the fixture to record the observed acceleration level for each shock pulse. The accelerometer data is logged with a Lansmont TP-USB data logging system.

3 – FILM CAPACITORS OVERVIEW

Film capacitors are made of several plastic layers put on top one another, assuring by construction an excellent elasticity. The capacitance is created through the deposition of a thin aluminum layer on top of each plastic film layer. In the following figure, two among the most widespread film capacitors' technologies are shown: a standard one, in which the capacitor is made of single-sided metallized films, and one that withstands higher peak-currents named "double metallized", in which the capacitor is made of a sequence of plain films layers (with no metallization) and double metallized layers:

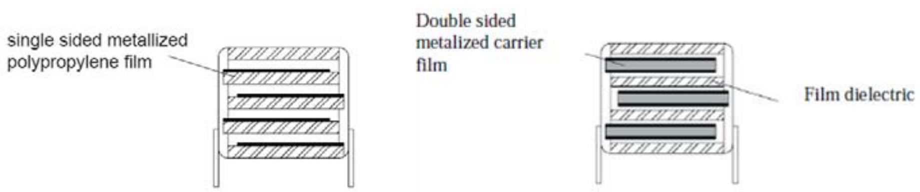


Figure 2: Single and double metalized technologies

Plastic film dielectrics used nowadays for capacitors are[2] [3]:

- PP: polypropylene;
- PET: polyethylene terephthalate;
- PEN: polyethylene naphthalate;
- PPS: polyphenylene sulphide.

Property	PP	PET	PEN	PPS
Dielectric Constant (@1 KHz)	2,2	3,3	3,0	3,0
Min Commercial Thickness (µm)	2,4	0,9	1,4	1,2
DF (% @ 1 KHz)	0,02	0,5	0,4	0,05
TCC (DC/C), -55 °C to +125 °C	± 2,5 %	± 5,0 %	± 5,0 %	± 1,5 %
Min Temperature (°C)	-55	-55	-55	-55
Max Temperature Typical (°C)	105	125	125	125
Max Temperature Extended (°C)	125	150	170	170
Dielectric Breakdown (V/µm)	400	280	300	220
Melting Temperature (°C)	178	254	266	283
Reflow & Multiple Reflows Tmax (°C) for SMD	NO	245	245 - 255	260
Self-healing	good	medium	medium-low	low

Table 1: Characteristics comparison between plastic film dielectrics

The self-healing property of film dielectrics (film's ability to self-regenerate an internal drop of insulation resistance) ensures a safe failure mode (open circuit).

Looking at table 1, PP film is the best in terms of self-healing while it is the worst in terms of melting temperature. This "rule" applies in general for all plastic films: PET has a higher melting temperature than PP, but has lower self-healing capabilities. PEN and PPS are the most suitable films for SMD applications (in particular to withstand the LF reflow process), but they have not the right properties for applications where voltage peaks, higher than the capacitor's rated voltage, are combined to the 50-60 Hz network frequency.

To compare the self-healing properties of different materials, their chemical composition must be considered. The lower the ratio between the number of Carbon (C) and Hydrogen + Oxygen (H+O) atoms, the lower the possibility to have conductive Carbon residues as an undesirable outcome of the self-healing process (see figure 3 here below):

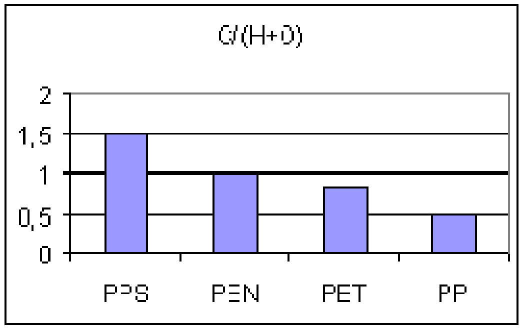


Figure 3: C/(H+O) # of atoms ratio in different plastic film dielectrics

There are also many other parameters to be considered in the study of self-healing phenomenon and, in particular, the higher the clearing energy content during the process, the higher the efficiency of the healing, taking place in the insulation between two adjacent metal layers [4], [5], [6].

At a mounting level, SMD capacitors must withstand higher temperatures during the soldering process (reflow) than radial capacitors. Naked SMD film capacitors are today capable of withstanding the high temperatures of the LF reflow process (up to 245 °C as per Jedec 020D1[7], capacitor volume > 350 mm^3, H_{max} > 2,5 mm).

Among the film dielectric listed, PET cannot be the right dielectric since, due to several laboratory tests, its physical characteristics deteriorate heavily on working temperatures over 150 °C, PP's melting temperature is 178 °C and PPS has an extremely high cost and low self-healing properties. On the contrary, PEN shows good characteristics under all these perspectives, therefore it will be the dielectric under analysis.

In the following figure, a DSC (Differential Scanning Calorimeter) graph is shown, in which it is evident that the PEN melting process starts at 257 °C.

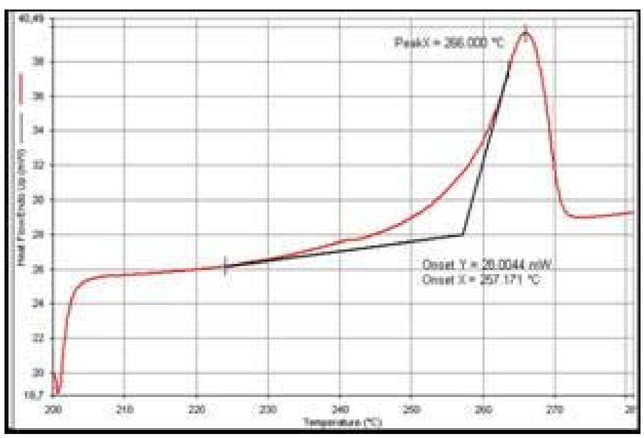


Figure 4: DSC thermograph of PEN

4 – HIGH CURRENT, VOLTAGE, AND TEMPERATURE APPLICATIONS: DESCRIPTION & CHALLENGES

4 – 1 Down-hole drilling

New oil reserves are being found further and further down in the ground, which is causing temperature requirements of drilling, exploration equipment, valve control and safety equipment to be extended. Typically, a 10 °C increase every 3 years is the norm. One of the most widespread applications in down-hole drilling is the Cockcroft Walton Generator, whose schematic (in full wave form) is hereafter shown:

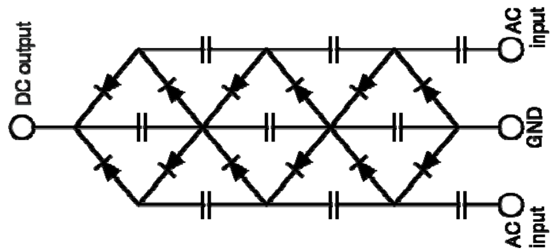


Figure 5: Cockcroft Walton Generator (full wave)

In this application, capacitors are combined with diodes to generate the very high voltages needed to create the pulse needed in the reverse Magnetic Resonance Imaging (MRI), used to explore into rock formations in looking for oil. The main requirement, from a mechanical point of view, is the dimension (a few inches is often the diameter they need to fit in).

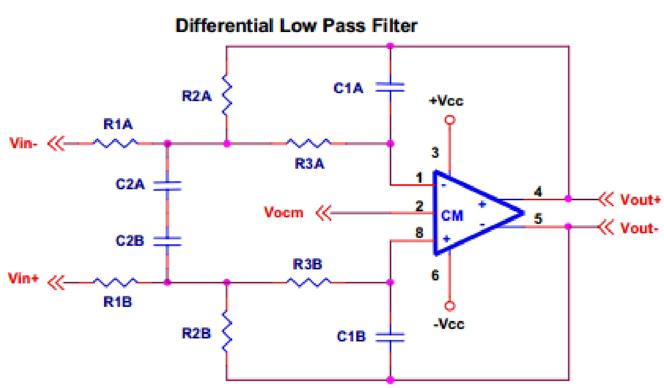
Other down-hole drilling circuit applications include decoupling, energy storage, filtering of inductive spikes (originated because of the very long power cables used in the drilling equipment), signal measurement, and feedback circuits. Typical voltages, capacitance, and sizes used in all these applications are 560 pF to 1,000 pF 1,500 VDC rated (real maximum voltage applied reaches 1,300 VDC).

Due to the extreme mechanical shocks equipment are subject to in down-hole drilling applications, most manufacturers elect to use through-hole (radial) parts, due to the fear that surface-mount products might "fall-off" during operation. Other manufacturers who use surface-mount tend to use products with gold extended terminations, to assure a greater resistance to mechanical shocks.

High temperature, reaching a peak of 220 °C peak in these applications, is not the only issue for plastic film, though: humidity is also to be considered, as when equipment are removed from high-temperature environments and are withdrawn through a cooler, condensation forms on the circuits (designers need, therefore, to consider this issue). Furthermore, equipment left "top-side" may be exposed to salty and humid conditions (depending on application). The resistance and reliability combination of these three factors (temperature, humidity and salty environment), should then drive the design choice at a component level in terms of box or naked components mainly.

4 – 2 Aviation

In the proximity of jet engines, many electronic applications at extremely high temperatures take place: pressure and temperature sensors and thrust regulators just to name a few. These applications are typically low voltage, and include coupling/decoupling, filtering, operational amplifiers and instrumentation-amplifier feedback circuits, line filters, and wave forms shaping. Hereafter, some general schematic showing their principles of functioning:



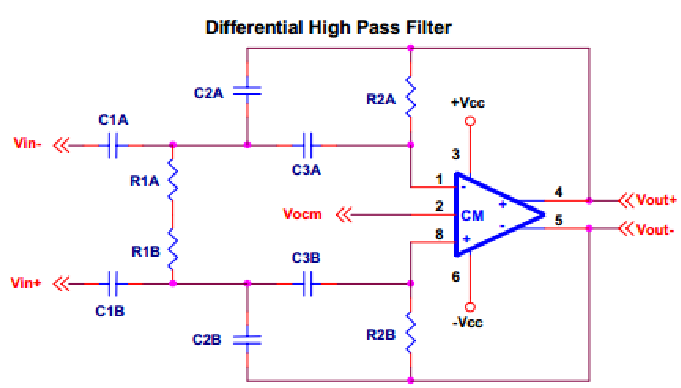


Figure 6: Filters schematics

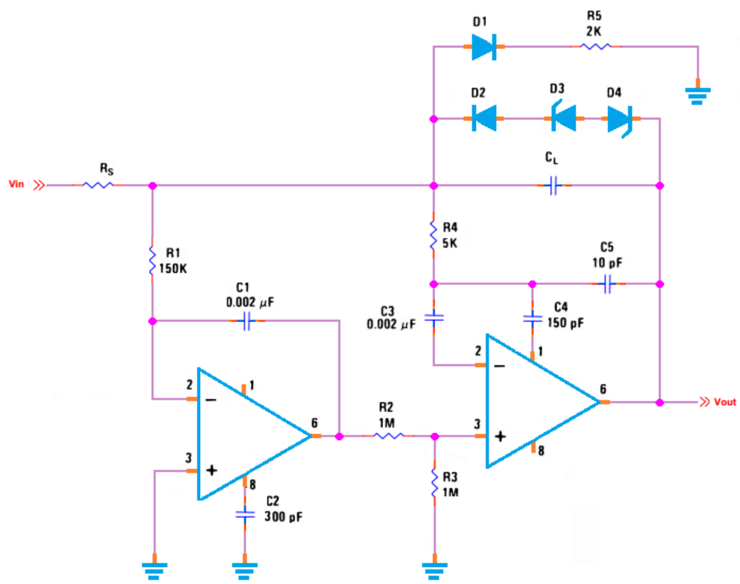


Figure 7: Filters schematics

5 – TESTS AND PERFORMANCES

A photograph showing naked SMD film capacitors in different sizes is shown here below:

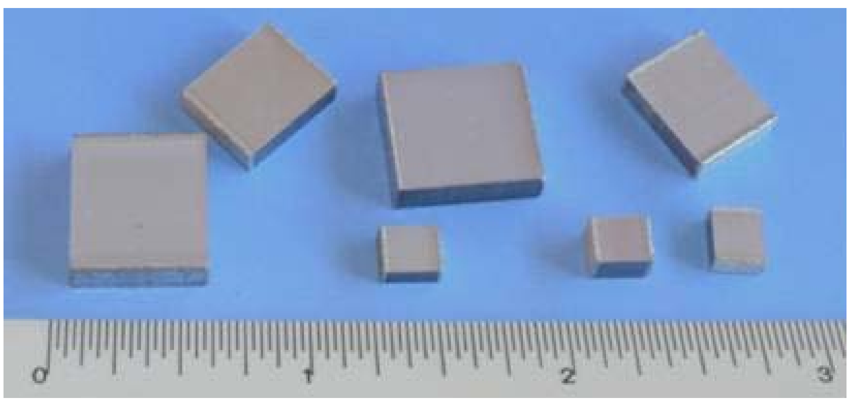


Figure 8: Naked SMD PEN capacitors

In order to evaluate the usage of PEN film at high temperatures, PEN film has been characterized up to 240 °C regarding the shrinkage level and up to 220 °C regarding capacitance, tg delta (dissipation factor) at different frequencies and insulation resistance (IR).

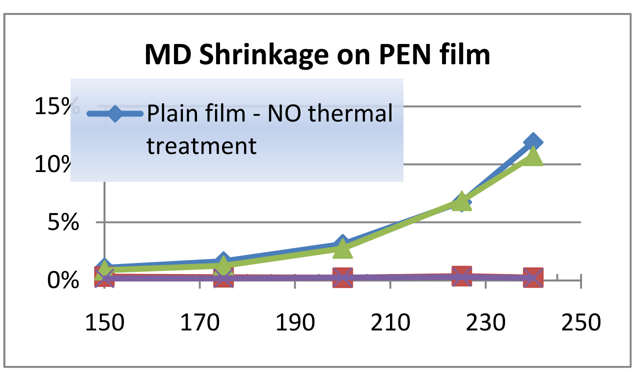


Figure 9: PEN MD (machinery direction) shrinkage

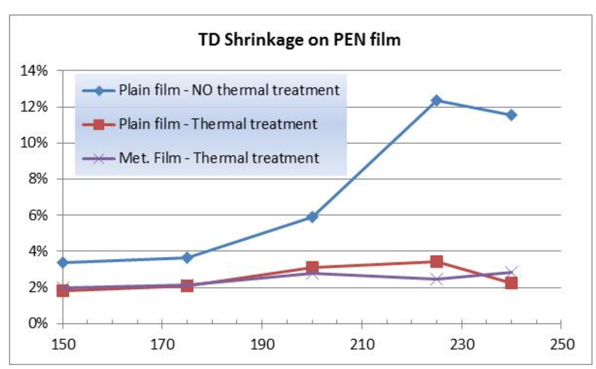


Figure 10: PEN TD (transversal direction) shrinkage

In figure 9, an exponential increase with temperature of the machinery direction (MD) shrinkage is shown, for film that has not been subject to a thermal treatment (the “core” phase of the film components manufacturing). With “machinery direction” it is intended that the shrinkage is tested into the same direction of the film extrusion. The thin metallization layer onto the film does not change significantly the shrinkage level (see “plain film” vs. “metallized film”). These shrinkages have to be considered during the process design of the film capacitors. On the contrary, it’s possible to see in figure 9 that the specific thermal treatment, performed on the SMD capacitors during their manufacturing, strongly reduces the shrinkage (that is however not zero).

Similar considerations can be made regarding the transversal direction (TD) shrinkage. With “transversal direction”, it is intended that the shrinkage tested is in a perpendicular direction with respect to the extrusion.

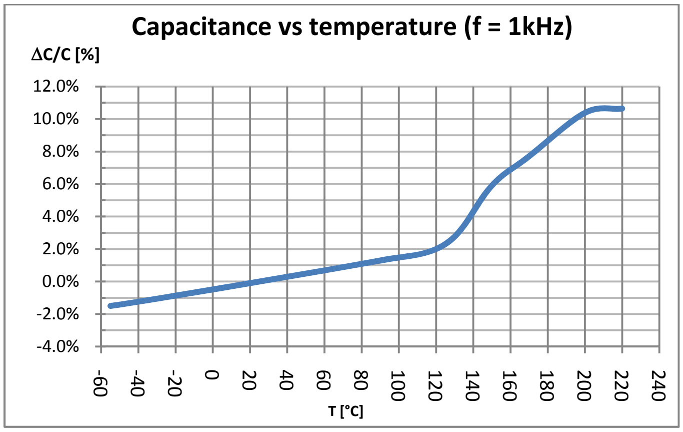


Figure 11: PEN %Cap Change vs. temperature

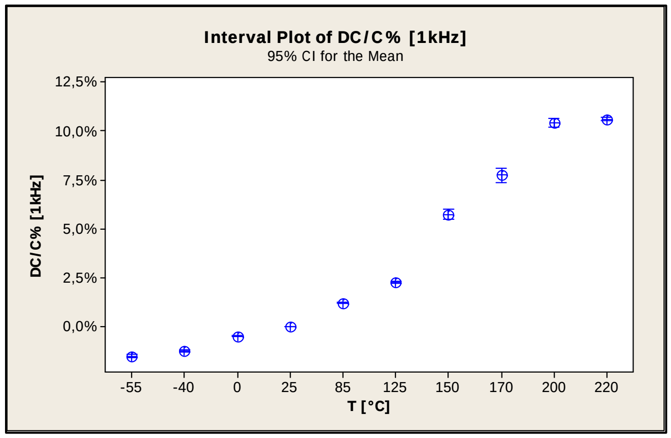


Figure 12: PEN %Cap Change interval plot

In the above figures (11 and 12) it is possible to see the average PEN increase of the capacitance value and it interval plot up to 220 °C . The increase is contained within +12% with a negligible change between 200 °C and 220 °C.

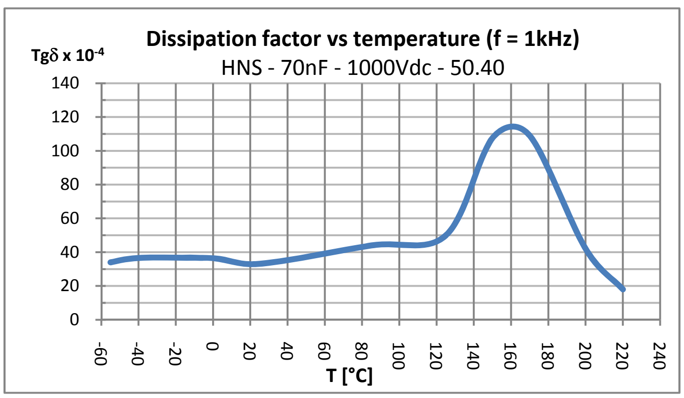


Figure 13: PEN Tg delta (dissipation factor) vs. temp.

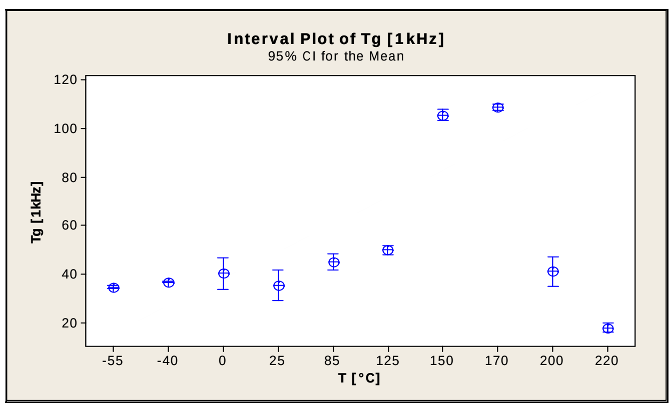


Figure 14: PEN Tg delta (dissipation factor) change interval plot

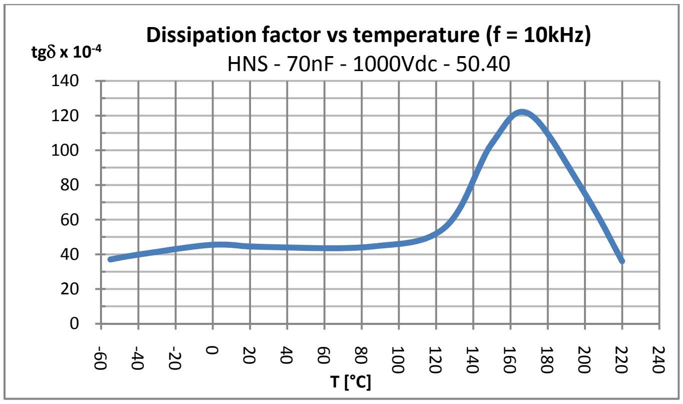


Figure 15: PEN tg delta (dissipation factor) vs. temp.

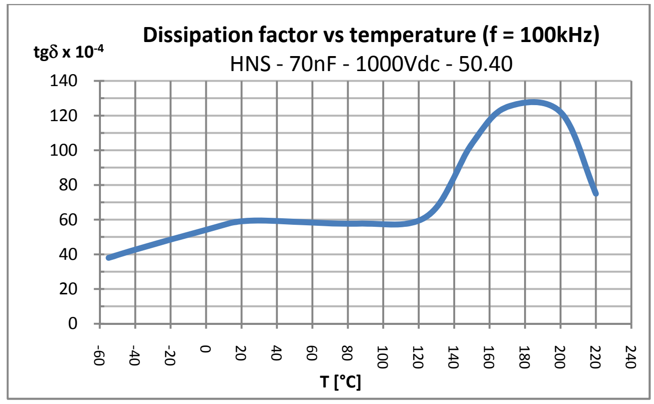


Figure 16: PEN tg delta (dissipation factor) vs. temp.

In the above figures (13, 14, 15 and 16) PEN tg delta (dissipation factor) behavior vs. temperature at 1, 10 and 100 kHz is shown. These graphs show an extremely positive result: the dissipation factor starts decreasing above 160 °C, reaching extremely low levels at 220 °C, strongly reducing, therefore, a potential further temperature increase due to the self-heating of the capacitors in application. This is also considered important since, in each application, equilibrium is to be reached between the thermal power generated inside the component and the dissipated one. Equilibriums reached at temperature above 160°C are considered stable: higher temperatures show a lower dissipation factor, therefore lower internal power generated.

In order to consider the usage of PEN film capacitors at such high temperatures as technically safe, an evaluation of the physical-chemical structure of the film with timing has been carried on and, to do this, it was decided to monitor the weight change with time of capacitors exposed continuously to 220 °C. At the end of the test, a comparison using a DSC (Differential Scanning Calorimeter) test has been made on a film sample.

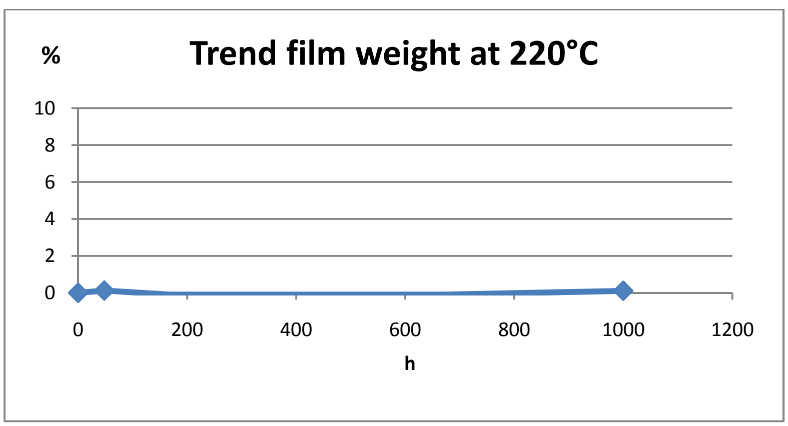


Figure 17: PEN film %weight change vs. time (@ 220 °C)

The above trend provides very important information: the weight change is negligible. This result shows the absence of chemical reactions that could deteriorate the film, generating gas and, therefore, reducing the film weight.

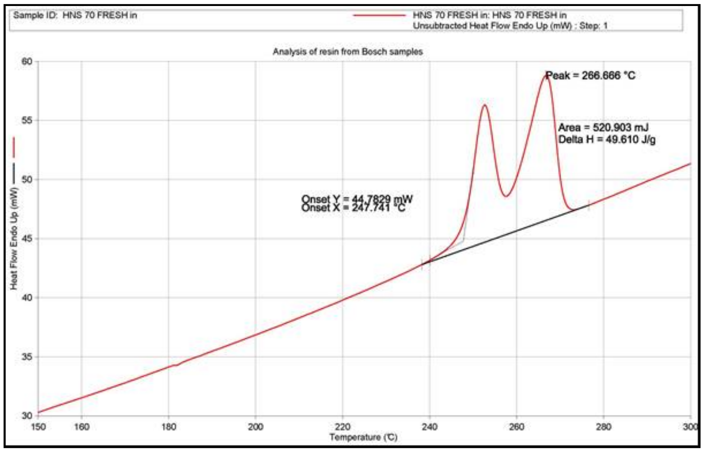


Fig 18-1: DSC analysis on Film sample without treatment at 220°C

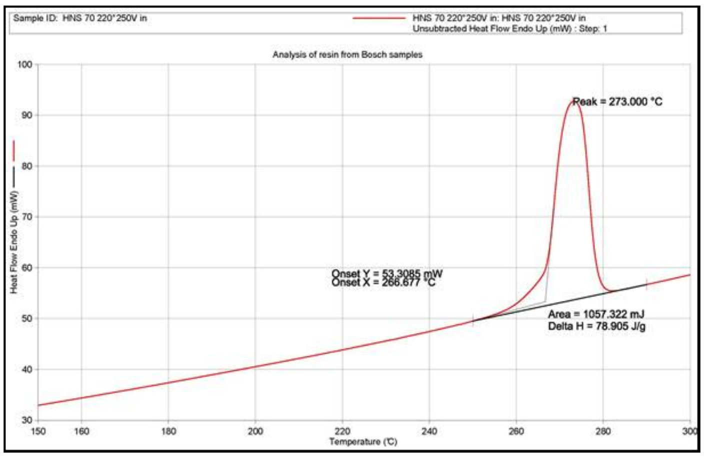


Fig 18-2: DSC analysis on Film sample treated at 220°C

The two DSC tests above (figure 18-1 and 18-2), show that after 1,000 hours at 220 °C, the film cristallinity grade has increased (Delta H goes from 49.6 J/g to 78.9 J/g, with Delta H intended as the enthalpy needed to melt the crystalline portion of material subject to test) but without showing anomalies: this result conjugated with the weight test result bring to the conclusion that, from a theoretical point of view, PEN film capacitors can work up to 220 °C. However, the increase in cristallinity grade indicates that a voltage de-rating will probably be needed when working at these temperatures.

In order to evaluate the aging of the film with temperature and time, several first breakdown voltage (FBDV) tests have been carried out at different time frames, in order to monitor the break down voltage decrease with time at 220 °C. These tests have been performed on 1,000 VDC and 400 VDC rated PEN SMD film capacitors.

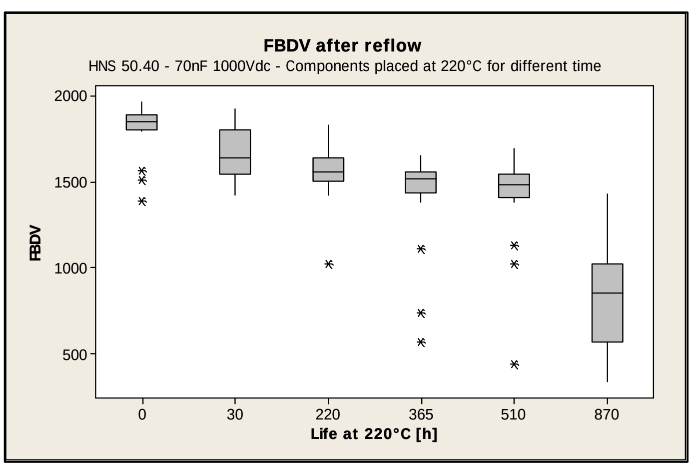


Figure 19: PEN first breakdown voltage level vs. time (@ 220 °C)

In figure 19 it is clear that the original high voltage break down level decreases (as it was expected) reaching, after 1,000 h, a value 75 to 80% lower than the starting value. This result indicated that a PEN capacitor should be 75-80% de-rated to work at 220 °C. A confirmation of this result was found on PEN 400 VDC rated capacitors (400 VDC capacitors can work up to 100 VDC at 220 °C). Here below a simple table summarizing the findings on PEN de-rating (reference is the 25 °C voltage level):

	DC Voltage level (V)		
25°C	**1,000**	**400**	**250**
105°C	1,000	400	250
220°C	200	100	50

Table 2: PEN de-rating vs. temperature

In down-hole drilling, in several circuits 50 VDC and 100 VDC capacitors are typically used. As per the above table, for a usage at 50 VDC at 220 °C a 250 VDC rated product should be chosen, and for a usage at 100 VDC / 220 °C a 400 VDC rated product should be selected. In order to confirm again the above data, several life tests have been carried on at 170 °C and at 220 °C on 1,000 VDC PEN SMD film capacitors:

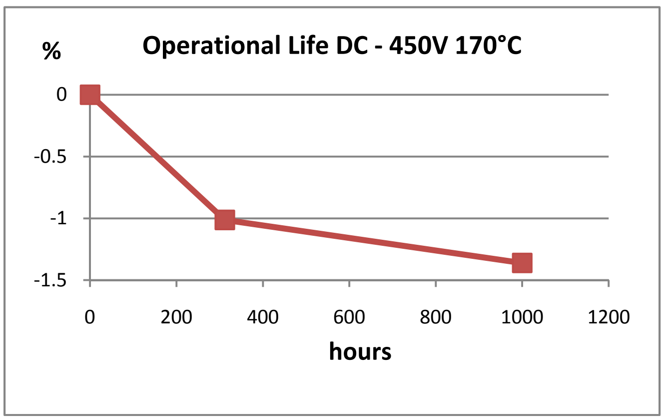


Figure 20: PEN %Cap Change vs. time (@ 450 VDC/170°C)

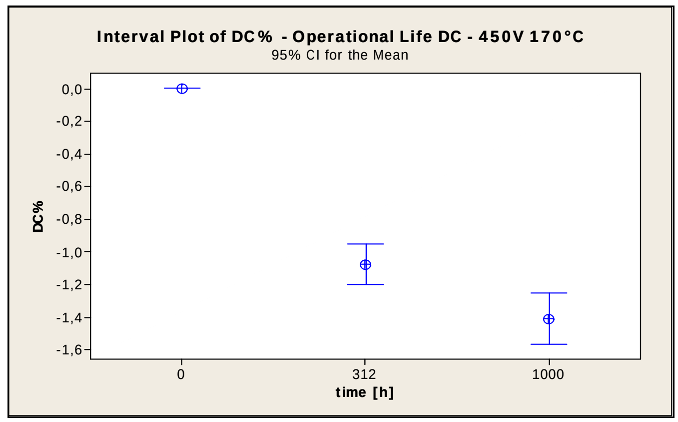


Figure 21: PEN (@ 450 VDC/170°C) interval plot

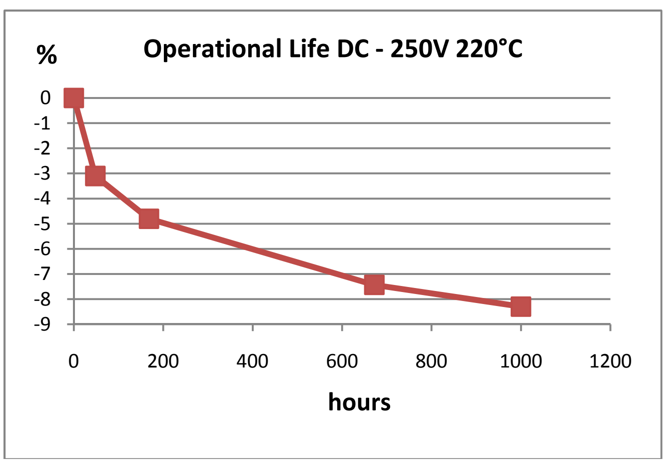


Figure 22: PEN %Cap Change vs. time (@ 250 VDC/220°C)

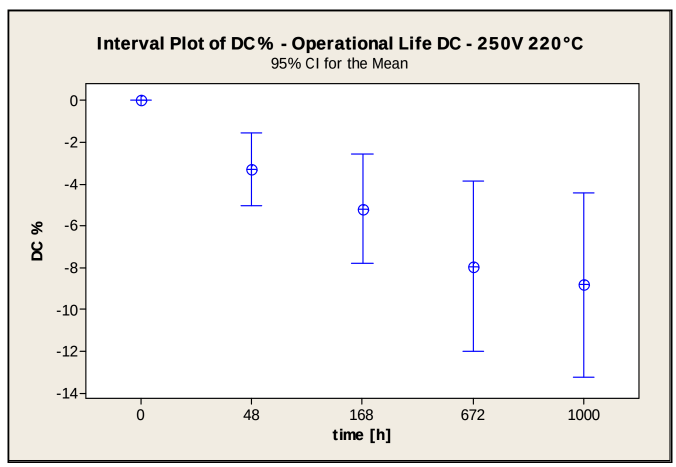


Figure 23: PEN %Cap Change (@ 250 VDC/220°C) interval plot

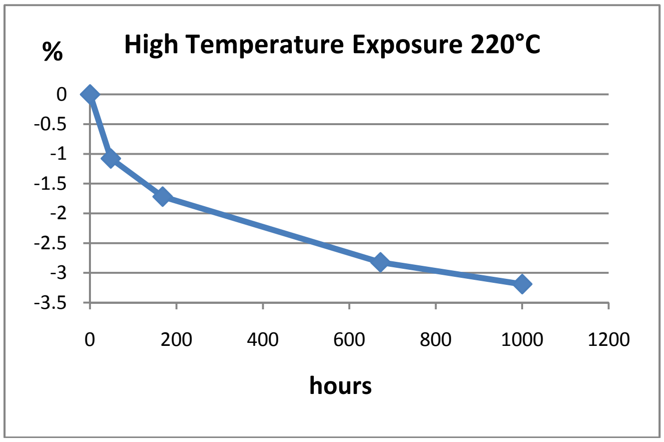


Figure 24: PEN %Cap Change vs. time (@ 220°C)

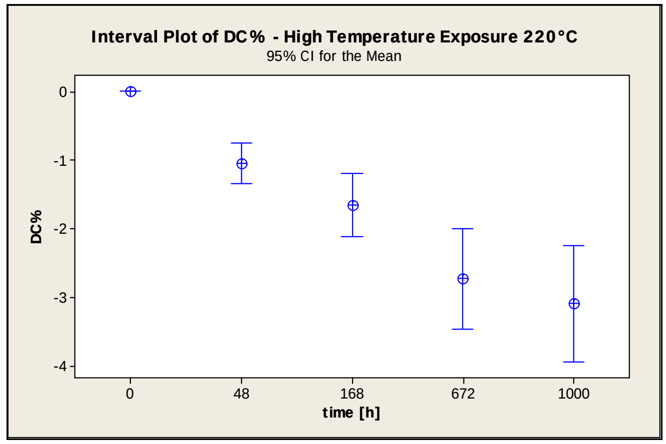


Figure 25: PEN %Cap Change (@ 220°C) interval plot

The above graphs show the capacitance deviation with time, up to 1,000 h, in different environmental/electrical conditions.

The graphs confirm that no critical effects are underlined up to 220 °C (the capacitance drop clearly shows a decreasing % reduction as time passes by, bringing to an equilibrium).

A summary of the results is shown in the below figure:

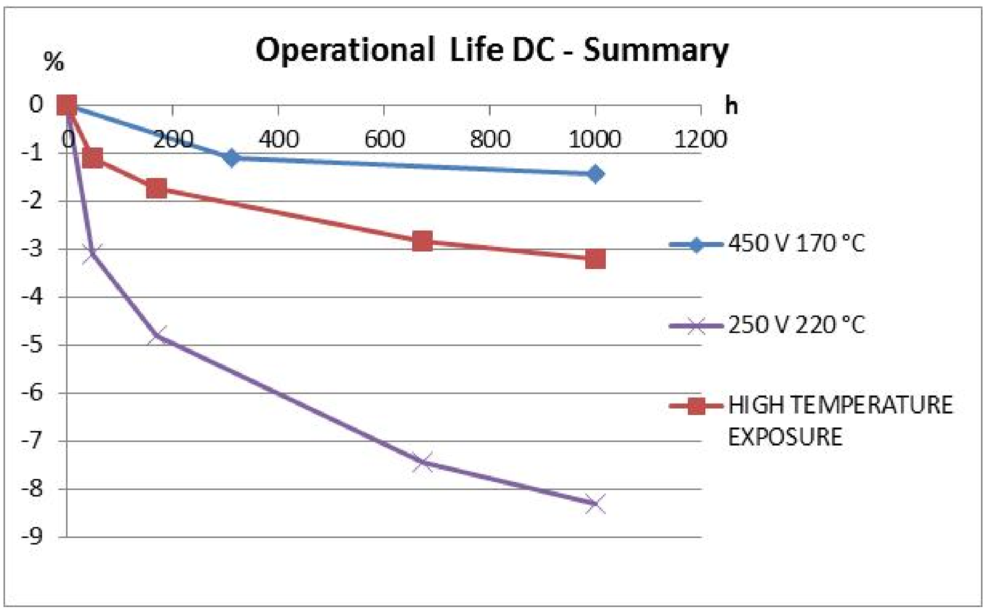


Figure 26: PEN %Cap Change at different life test conditions

The above graph leads to several conclusions about the effects on the capacitors caused by two stresses applied separately or simultaneously: voltage and temperature. At 450 VDC/170 °C an average capacitance deviation of -1,4% is recorded after 1,000 h. With only temperature applied (220 °C), an average capacitance drop of -3,2% after 1,000 h is shown.

Applying both voltage and temperature determines a positive synergism of the two stresses, bringing the average capacitance drop to -8,3% with a minimum value recorded of -12,2%. However, the capacitance drop is limited within -15% and, therefore, these tests are considered as a very positive result: the usage of PEN film at such temperature levels is safe.

Another stress cause to be considered in these applications is represented by intense mechanical shocks. A specific test at 500 g has been carried on, as per figure 27-2. Shock testing was performed on PCB board units installed onto special fixtures designed especially for shock test equipment.

The boards were subject to 500 g / 2 msec half-sine shock testing, in 6 directions (Z+, Z-, X+, X-, Y+, and Y-), see figure 27-1. Test samples were visually inspected after each test orientation without observing any physical changes on any of the test samples.

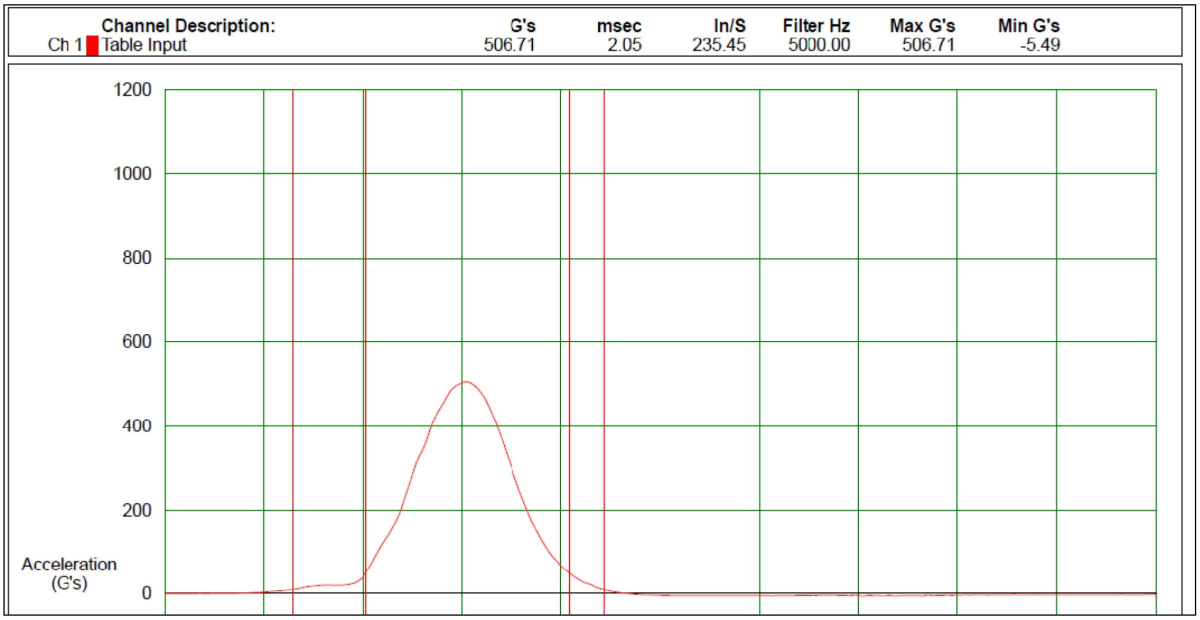


Figure 27-1: 500 g shock test waveform

Figure 27-2: Boards used for the 500 g shock test

On the here below figures it is possible to see the change of capacitance and tgδ value after the shock test:

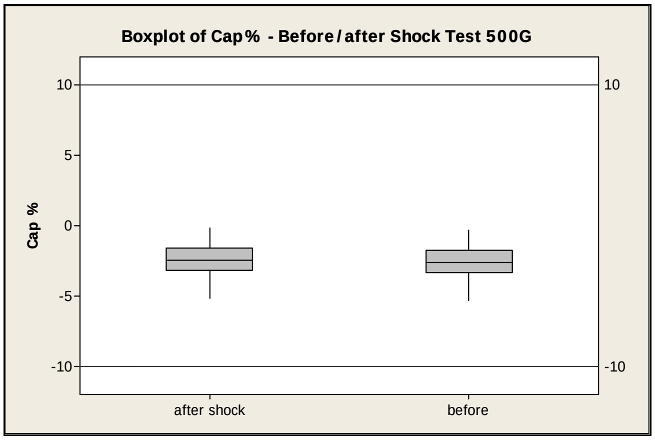


Figure 28-1: PEN %Cap Change vs. 500g shocks interval plot

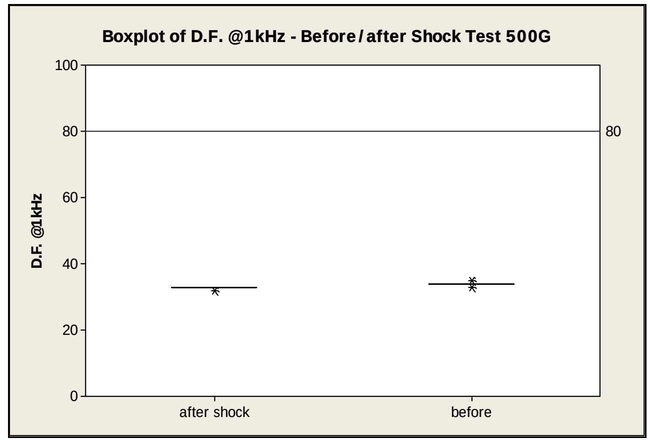


Figure 28-2: PEN DF change vs. 500g shocks interval plot

The two above graphs show a negligible capacitance and tg delta (dissipation factor) deviation. This confirms the great performances of film capacitors vs. mechanical shocks. Capacitors have been measured also in terms of insulation resistance (IR) and for dielectric strength (DS) voltage withstanding. Any anomaly has not been seen nor recorded on insulation resistance and dielectric strength performances and from a microscopic analysis point of view either.

Applications that foresee high temperature levels, usually stress the electronic board and its components due to rapid changes of temperature. In order to verify the robustness of film capacitors vs. this important aspect, 1,000 cycles from -55 to +220 °C have been carried on (on parts soldered on a PCB). SMD components have been selected because their thermal stress during the mounting on the PCB (reflow) is considered a worst-case scenario. In fact, if components with leads and resin are used (box radial components), the stress is absorbed not only from the plastic film of the component but from the leads, too.

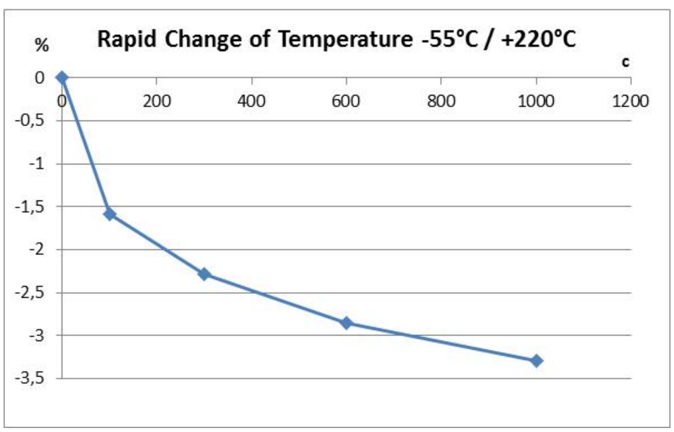


Figure 29-1: PEN %Cap Change vs. thermal shocks

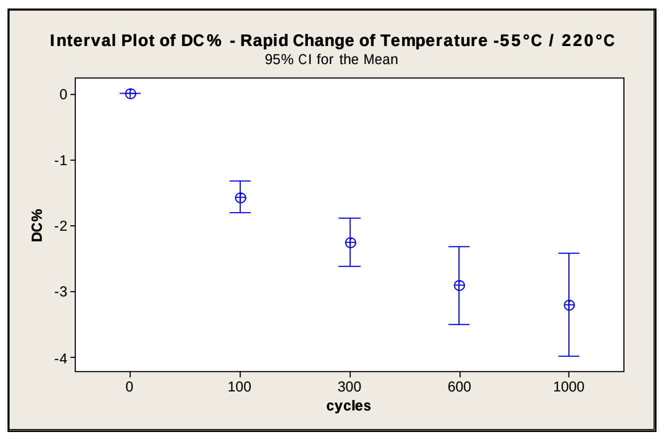


Figure 29-2: PEN %Cap Change vs. thermal shocks interval plot

Any anomaly either from aesthetical point of view or from electrical point of view has not been observed Comparing figure 29-1 with figure 24, it is clear that what influences the capacitance change is not the thermal cycle itself but the exposure to the high temperature level involved.

6 – SUMMARY, FUTURE TRENDS AND CHALLENGES

Film capacitors are historically used for their excellent reliability characteristics, but they have never been used with working temperatures above 170 °C, as there are no data about their suitability for these high temperatures, either from the film supplier nor from the film capacitors producers.

In this paper, PEN film capacitors have been tested from physical, chemical, electrical, and environmental point of view, in order to highlight any anomaly to working temperatures up to 220 °C. Each data and test has not confirmed any critical aspect on working at such temperatures, for a period up to 1,000 h. The film is physically stable; the capacitance deviations reach equilibrium levels, the tg delta (dissipation factor) decreases after 160 °C, reducing further temperature increase (self-heating), which might determine avalanche phenomena.

The only aspect that has to be considered is the right voltage de-rating to apply, which depends on the final temperature reached by the capacitors, considering also the potential self-heating effect.

PEN film capacitors, either in SMD or radial technology, can therefore be a choice for working temperatures up to 220 °C.

For future developments on film capacitors on these applications, based on the good results found, a general guide is:

1) Up to 200 °C, standard tin capacitor terminations can be used, while above this temperature modifications of the terminations design (e.g. gold material) should be evaluated. Moreover, for SMD components, standard SAC solder paste can be used up to 200 °C.
2) HMP (High Melting Point) solder cannot be used due to their very high melting temperature (301 °C) and a standard reflow peak of 380 °C. At such reflow temperatures, common plastic film raw materials are not suitable: other mounting technologies have to be evaluated.
3) The good result on tg delta values over 160 °C might strongly influence the ripple current withstanding capabilities from that temperature and above.

7 – REFERENCES

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