MINIATURIZATION OF METALLIZED POLYESTER FILM CAPACITORS

Tchavdar Doytchinov[(1)], Raphaël Preseau[(2)]

[(1)] *Exxelia Technologies, Film Capacitors BU*
1, rue des Temps Modernes
77600 Chanteloup en Brie, France
Email: tchavdar.doytchinov@exxeliatechnologies.com

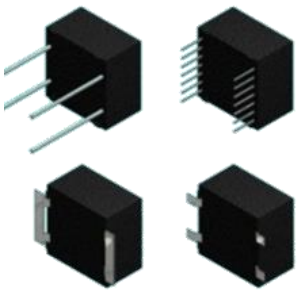
[(2)] *Exxelia Technologies, Film Capacitors BU*
1, rue des Temps Modernes
77600 Chanteloup en Brie, France
Email: raphael.preseau@exxeliatechnologies.com

1. INTRODUCTION

The evolution of electronic equipment towards ever increasing miniaturization requires smaller and smaller components. Thanks to their high quality and reliability, the metallized polyester film capacitors of Exxelia Technologies are widely used in different high performance demanding applications in Space, Defense and Aeronautic markets. The light weight and self-healing properties of this technology propose excellent technical solution for the filtering and energy storage.

PM 948 S

The well-known series PM90S and PM94S are used for many years in space projects in Europe and in the world by different space components customers, offering a reliable solution in different spacecraft subsystems and payloads. The knowledge acquired over the years in polyester film technology has permitted the miniaturization of the capacitors and their adaptation to various environmental constraints. In answer to the new requirements in high-professional electronics, Exxelia Technologies developed two new series of capacitors PM907(S) and PM948(S). To insure its long-term strategy in space market, our company initiated ESCC Evaluation and Qualification of new products. The objectives of this activity, supported by ESA and CNES, were evaluation the abilities and the reliability of proposed series in space applications and including the selected products into EPPL and EQPL.



PM 907 S

In the frame of both CNES and ESA projects and during 5 years testing Exxelia Technologies cumulated data allowing establishment of new temperature and voltage acceleration factors for polyester technology. This paper presents the main test results and reliability calculation.

The self-healing behaviour of PM907S and PM948S has been tested with the energy limit approach and this paper resumes the obtained results and conclusions.

To demonstrate the success factors of PM907S and PM948S some typical space applications using new series are shown in the last paragraph.

2. HIGH CAPACITANCE IN POWER ELECTRONICS FOR SPACE

The main capacitor families used in space applications are tantalum, ceramics and film technologies, each presenting some advantages and weaknesses obliging designers to take technical and economical compromises.

Thanks to porous structure of compressed powder, tantalum capacitors offer small sizes and better energy density for low voltages. Having a dielectric constituted by tantalum oxide, these capacitors are polarized and limited for quite low DC voltages, with very limited capabilities to withstand any reverse voltage. Because of high dielectric losses and ESR, this capacitor family has limited power capabilities. Tantalum capacitors are widely used for energy storage (backup, lasers, etc.) especially in low voltages, presenting a good compromise for integration.

Ceramic capacitors Type II cover low, but also high voltage applications, offering a good compromise between energy density and better power parameters. The low profile of chip capacitors is appreciated for integration in low power equipment for filtering, decoupling and energy storage. The energy density is obtained thanks to very high dielectric constant, but which relates to important drift of the capacitance and other characteristics versus temperature and electrical field variation. Adding Type I ceramic capacitors, this family is most popular in space electronics, covering very well the low voltage applications for control and measurement functions, but also for filtering in low power equipment.

In high capacitance space application different film capacitor technologies are proposed. Having low dielectric constant their sizes are usually bigger compare to other capacitor families. But thanks to low dielectric losses and stable characteristics, film capacitors offer an excellent solution in power electronics, showing much better capabilities for RMS and peak currents. Their flexible construction and very light masse relate to excellent thermomechanical withstanding. Different film capacitor technologies are present in ESA, NASA, JAXA and other space systems. Some PP (Polypropylene), PC (Polycarbonate), PPS (Polyphenylene sulfide) and PET (Polyethylene terephthalate) series are proposed in different systems, but mainly their sizes and shape variants present real difficulties for the integration. About 20-25 years ago Exxelia Technologies (former Eurofarad) developed the metallized PET series PM90S and PM94S which are widely used in space applications thanks to their energy density, electrical and thermomechanical behaviours. Indeed, thanks to their stable capacitance and much better power behaviour, polyester capacitors could cover power constraints with much lower capacitance value compare to other capacitor families, presenting similar dimensions and much lower masse. In the same time, the excellent self-healing properties of metallized film technologies offer high reliability level and possibility to avoid any additional protection (which is mandatory for all other capacitor families).

3. DEVELOPMENT OF PM 907 (S) AND PM 948 (S) SERIES

Based on well-known series PM90S and PM94S and using same packaging materials and leads, Exxelia Technologies developed in 2007 and 2008 new metallized PET series PM907S and PM948S with the main goal to propose higher energy density keeping reliability level. Fig.1 shows the strong heritage of Exxelia Technologies in this technology.

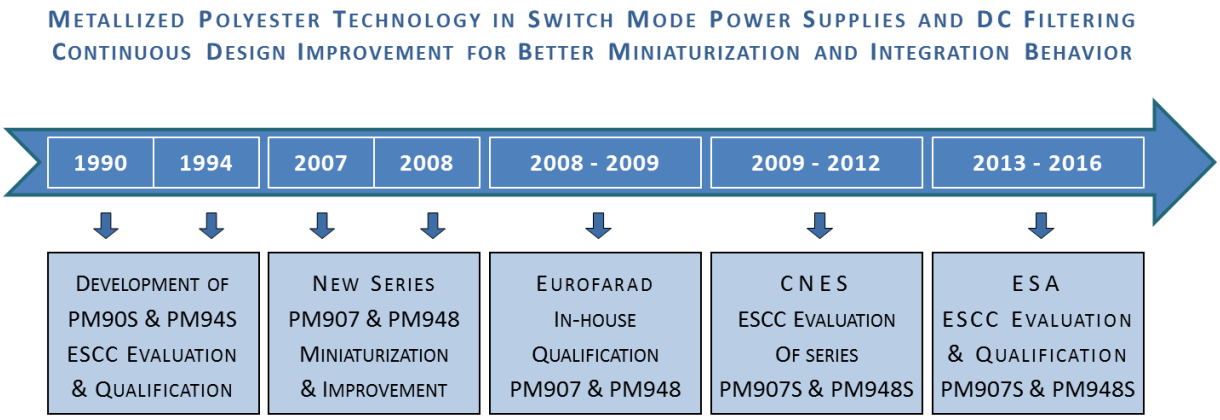


Fig. 1. Polyester Technology Background of Exxelia Technologies (former Eurofarad)

The technological progress and higher level of energy density are based on several improvements of the dielectric treatments during the manufacturing process and last technics of electrodes metallization. The new series PM907(S) and PM948(S) present extended voltage ranges covering the need of new space and aeronautic power electronic topologies.

These series are considered as alternative solution to ceramic and even tantalum capacitors, proposing high level of reliability and open circuit failure mode.

The Fig.2 presents main goal in the PM907(S) and PM948(S) development and their voltage, capacitance and temperature areas:

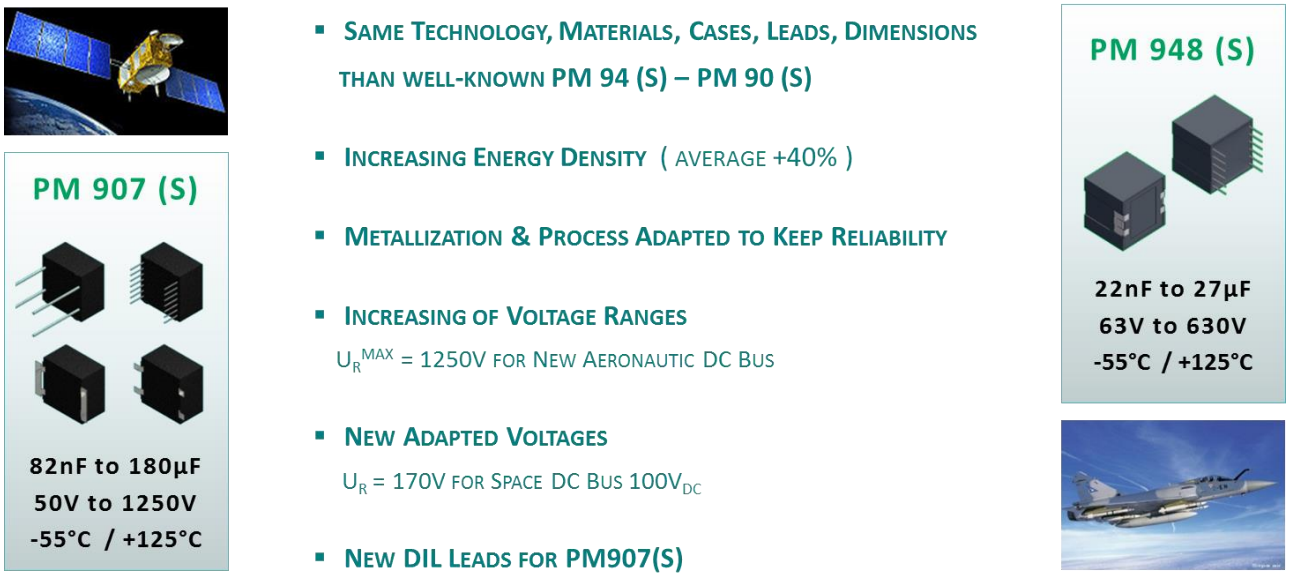


Fig. 2. Voltage, capacitance and temperature areas covered by PM907(S) and PM948(S)

After more than 5 years testing in the frame of In-house Qualification and two projects with ESA and CNES for ESCC Evaluation and Qualification, Exxelia Technologies demonstrated the advantages and reliability of PM907S and PM948S capacitors.

4. ESCC EVALUATION AND QUALIFICATION

The ESCC Evaluation of PM907S and PM948S has been done in the frame of two contracts with CNES and ESA and presents the main interest of activities. Several parameters have been explored with the main goal to demonstrate the technological limits. The results obtained during these evaluation programs provide various data about the behaviour of the new series.

The test vehicles have been defined in different voltage ranges, using for each of them the minimum and maximum of capacitance values. The most representative voltages have been tested: 50V – 63V – 170V – 200V – 250V – 630V … 1250V and the choice of capacitance values allowed covering the evaluation of different case sizes and dielectric thicknesses. The thermomechanical behaviour of all leads versions has been investigated.

The ESCC Evaluation Program and the large sampling of voltage and capacitance values, but also the testing of different cases and leads variants allowed demonstrating of homogeneous designing of both series.

Fig. 3 resumes some of main tests and investigations performed during several years activities in the frame of the ESCC Evaluation projects.

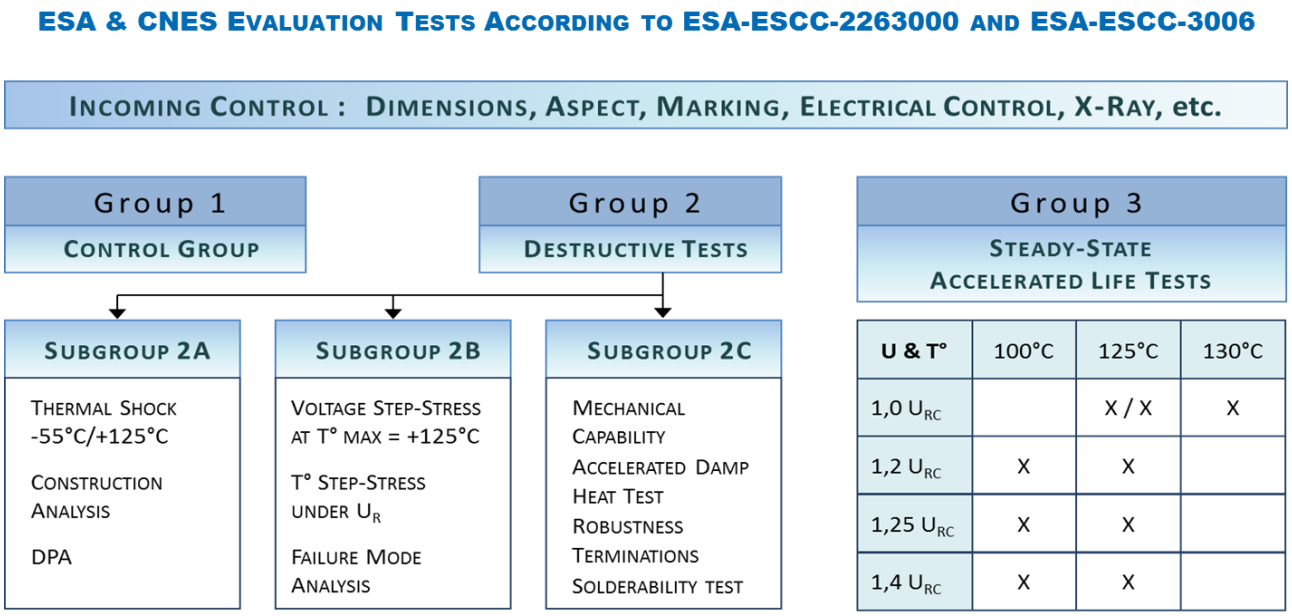


Fig. 3. Main tests performed in the frame of ESCC Evaluation activities

The Step-stress tests of Subgroup 2B aimed the first investigation of technological margins in voltage and temperature and allowed defining of Steady-state accelerated life tests of Group 3. The well-adapted screening process for polyester film technology has been confirmed.

Fig. 4 shows the evaluation voltage and temperature step-stress tests with first step corresponding to Chart III conditions. All failures have been observed on the last steps, demonstrating aging phenomenon.

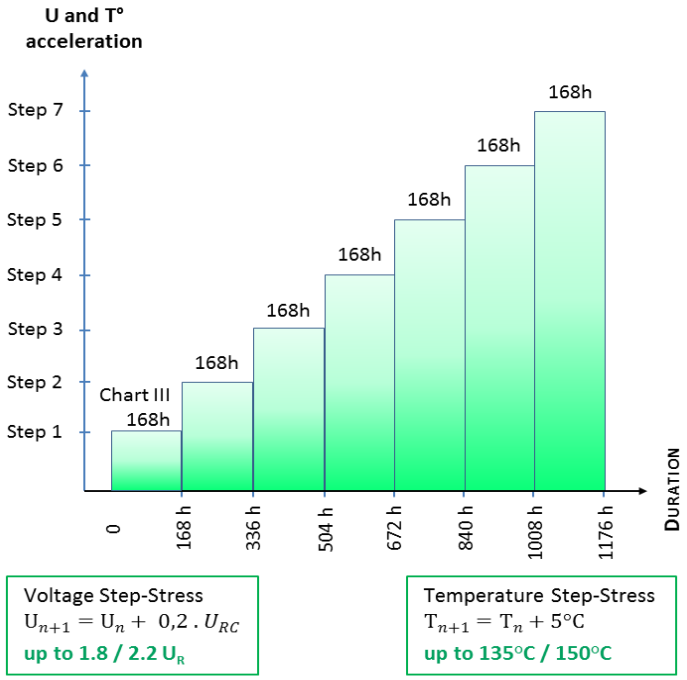


Fig. 4. Voltage and Temperature Step-Stress of PM907S and PM948S

Based on step-stress tests analysis, the conditions for steady-state accelerated life tests have been defined. Fig. 5 shows different accelerated conditions explored during activities for different voltage and capacitance ranges.

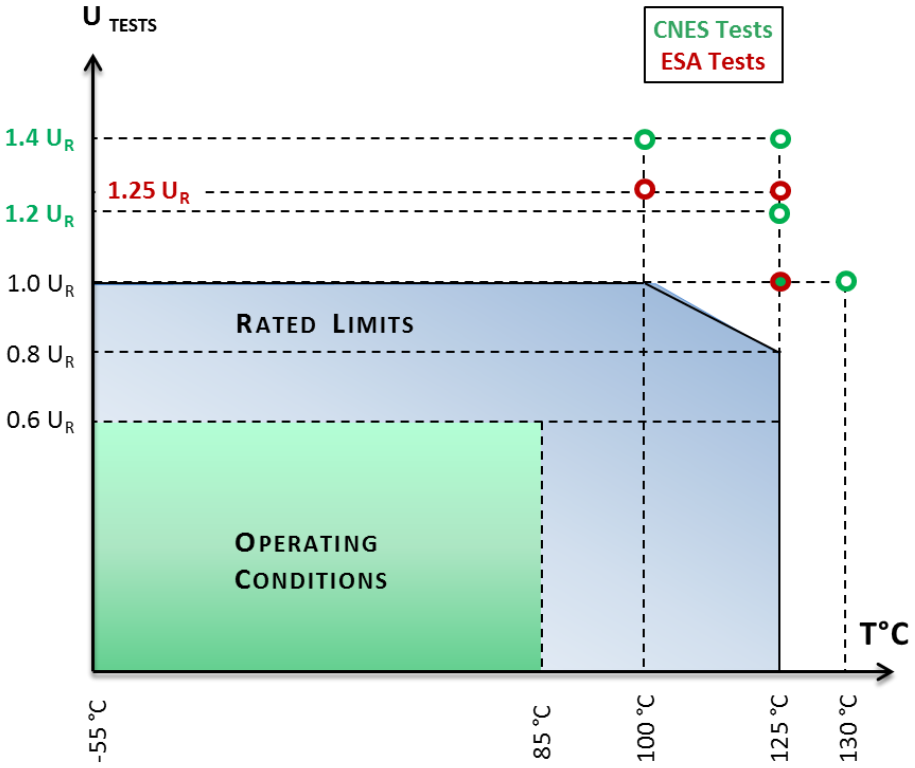


Fig. 5. Steady-State Accelerated Tests performed on PM907S and PM948S series

The life tests results have been analysed in order to define the failure mode in different conditions. All tests performed with low accelerated conditions demonstrated progressive losing of the capacitance, corresponding to the self-healing phenomenon. Some of tests have been conducted to the total losing of the capacitance in order to prove the open circuit failure mode.

For high accelerated voltage and temperature tests it was observed some insulation resistance decreasing or even short-circuits. This unusual failure mode can be explained by the level of accelerated parameters, situated out of manufacturing process and controlled limits. Indeed, during capacitors production several specific treatments are applied in order to stabilize and select the components in the butch. This selection area guaranties the self-healing properties which imply an open-circuit failure mode in the limit of rated conditions.

In case of high voltage or temperature solicitations, the electrostatic pressure between the winded layers of the capacitor, becomes too high and leads to a loss of the self-healing property, so a short-circuit failure mode could be observed. Moreover, the high temperature solicitation dilates the polymer and furthers the weakness.

The physical phenomenon can be described with the Schottky injection model. Indeed, under high electrical field and high working temperature, the hopping conduction appears as the dominant mechanism of breakdown. This is assumed in different polymers as PET (Polyethylene terephthalate), PP (Polypropylene), PC (Polycarbonate), PPS (Polyphenylene sulfide) etc.

In the Schottky model, the conduction current and his density, as shown in Eq. 1, are function of temperature and electrical field. So, when high voltage or temperature stress are applied on the polymer dielectric, the conductivity becomes too high and leads to an insulation loss and unattempt short-circuit failure mode.

$$J(E,T) = \alpha . T^2 . e^{(-\frac{\Phi}{k_B . T})} . e^{(\frac{\beta . \sqrt{E}}{k_B . T})} \quad (1)$$

with,

j: current density
α,β: constants
Φ : Energy barrier height
T: temperature
E: voltage gradient
k_B : Boltzmann's constant 8,62.10^{-5} eV/K

5. AGING LOW AND ACCELERATION FACTORS

In the frame of both CNES and ESA projects and during 5 years testing Exxelia Technologies cumulated data allowing establishment of new temperature and voltage acceleration factors for polyester technology.

The evaluation of temperature and voltage acceleration factors has been based on the Prokopowicz and Vaskas law shown by Eq.2.

$$\frac{t1}{t2} = \left(\frac{V_2}{V_1}\right)^n \exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (2)$$

Where:

t_i : time to failure under conditions "i"
V_i : Voltage under conditions "i"
n: voltage stress exponential
E_a : activation energy for the dielectric
k: Boltzmann's constant = 8,62 . 10^{-5} eV/K
T_i : absolute temperature for conditions "i"

The voltage stress exponential "n" depends mainly of the dielectric nature. Its value is between 5 and 10 for film capacitor technologies and presents bigger voltage acceleration compare to ceramic dielectrics.

To calculate the acceleration factor between both temperatures T_1 and T_2, the Prokopowicz and Vaskas model assumes that the pre-exponential term and activation energy in Arrhenius law are temperature-independent.

The activation energy indicates the sensitivity of the reaction rate (degradation of the dielectric) to temperature. It is the necessary molecular energy over the stable state of the dielectric composite that must be acquired in order that process occurs. The activation energy E_a depends mainly on the dielectric nature, which for PM907S and PM948S is the PET polymer.

The MIL-HDBK-217 assumes coefficients:

$$n = 5 \quad \text{and} \quad E_a = 0{,}15 \text{ eV}$$

The cumulated data during Evaluation activities of PM907S and PM948S allowed the calculation of the voltage acceleration factor and activation energy for the actual PET technology:

$$n = 7 \quad \text{and} \quad E_a = 0{,}8 \text{ eV}$$

The difference observed for the acceleration factors could be explained by the characteristics of the raw materials and manufacturing process used by Exxelia Technologies today and those tested many years ago when MIL-HDBK-217 has been established. Indeed, a notable progress in PET dielectric characteristics and electrode metallization has been observed during the years. Combining with the continuous process improvement acquired over the years by Exxelia in polyester film technology, it has permitted the miniaturization of the capacitors, which present today different acceleration factors compare to the technology available half century ago.

Using acceleration factors established for PM907S and PM948S a theoretic life time calculation could be done for any conditions based on the ESCC Qualification life test, which is performed with 2000 hours duration under 1.25Uc at 125°C. For example, a theoretic life time of about 110 years could be calculated for the maximum operating rates in space applications, which are usually limited by the voltage derating $0.6U_R$ and 85°C.

6. SELF-HEALING PROPERTIES AND ENERGY LIMITATION

In the frame of ESA project, the self-healing behaviour of PM907S and PM948S series has been tested with the energy limit approach.

This test was aimed at demonstrating the no-limit of self-healing phenomenon with 15 Joules energy capacitors assembly. This limit of the maximum energy level was mentioned in the previous revisions of ECSS-Q-ST-30-11C which describes the derating roles for metallized PET capacitors.

A capacitor bank with approximately 30 Joules energy (two times higher compare to the ECSS limit) has been assembled using capacitors PM907S R2 100µF 10% 170V. This capacitor value presents big interest in some space applications using $100V_{DC}$ bus (for capacitor bank filter in PCU and PCDU allowing low impedance DC bus, in some power propulsion units, for energy storage in laser applications, etc.). All capacitors have been parallel connected directly to a DC-regulated power supply, without any serial components (resistors, fuses, etc.).

The endurance test has been conducted at 125°C under $1.25U_R$ till the end of components life in order to determine the EOL (end of life) failure mode. After several thousand hours test, self-healings appeared and it was noted a capacitance drift, which proved the no-risk of using higher energy level for bank assemblies. The test demonstrated the self-healing behaviour of PM907S and PM948S and their open circuit failure mode.

7. SUCCESS STORIES

During the years of the Evaluation test activities the new series have been widely embedded in spacecraft subsystems and payloads by different actors in the space domain. Some examples of projects in Europe, but also in Japan, China, Russia, India, Korea and other countries could be mentioned: Ariane 5 but also the future Ariane 6, IRIDIUM, METOP, COSMO (2nd generation), EUCLID, SARah, GOSAT-2, GLONAS, LUCH, ALCOMSAT, BEIDOU navigation system and many others.

Thanks to their high energy density, light weight and self-healing properties the new series PM907S and PM948S found rapidly a particular interest for their integration in the power, telemetry and altitude and orbit control subsystems of several space platforms. The last generation of different space equipment like PSR, PCU, PCDU, power regulators for the battery management, antennas position and electro-mechanical drive systems, LIDARs, etc. already use the new capacitors. Several PPU developments in Europe, Russia, Japan, Israel and other countries have been initiated using PM907S and PM948S advantages. The new capacitor series are also widely used in the launchers and different payloads developed last years in different countries.