1.1. Thermoset Polymer Dielectric Capacitors for Harsh Environment Applications

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Abstract
Capacitors for harsh environment applications must withstand extreme temperatures, high voltage stress, and ionizing radiation, while maintaining reliability and energy density. This paper introduces a new class of solid-state, thermoset polymer dielectric capacitors engineered for demanding conditions across a temperature range of -196°C to +160°C. Utilizing submicron highly cross-linked polymers that function effectively as thermally stable thermoset dielectrics and nanometer-thick aluminum electrodes, these capacitors demonstrate superior dielectric stability, self-healing behavior, and resistance to radiation-induced degradation. Experimental results confirm stable performance under cryogenic and high-temperature operation, including sustained capacitance, ESR, and leakage current profiles. The radiation-hardened dielectric network, combined with stable nano-interfaces, enables reliability in automotive, aerospace, defense, and space applications. The paper highlights parametric trends, self-healing thresholds, and encapsulation considerations critical to enabling the deployment of capacitors in extreme and mission-critical environments.

1. Introduction

There is a critical need for electronics that can endure harsh industrial, aerospace, and space environments, as components must withstand extreme temperatures and ionizing radiation (such as gamma rays, protons, and cosmic rays), which can lead to functional degradation. Capacitors designed for such demanding environments must operate effectively under extreme temperature conditions, mechanical stress, and radiation, often necessitating high energy density and enhanced reliability. Applications that require multiple extreme operating conditions are challenging to support a single capacitor technology.

High energy density is typically essential for applications involving capacitors with large capacitance, often coupled with higher voltage requirements, which restricts the use of ceramic multilayer capacitors. Similarly, for applications that involve cryogenic conditions and high voltages, electrolytic capacitors are unsuitable. High temperatures exclude polypropylene film capacitors, necessitating the use of capacitors with high-temperature films like PPS and PTFE. However, the higher-temperature polymer films may have poor energy density, and many polymer film capacitors can experience issues such as capacitance loss, increased leakage, reduced breakdown strength, and degraded equivalent series resistance (ESR) in the presence of radiation.

To address these limitations, the innovative NanoLam™ solid-state metallized polymer capacitor has been developed for demanding applications requiring high voltage, high capacitance, and high energy density [1-3]. This technology employs a nanolaminate composite structure comprising thousands of submicron, high-temperature polymer dielectric layers, paired with nanometer-thick aluminum electrodes in customizable prismatic form factors, ranging from thin sheets to compact blocks. NanoLam™ capacitors feature a high-temperature cross-linked dielectric that is produced through beta-radiation curing, specifically formulated to provide outstanding self-healing properties. Unlike thermoplastic polymer films, this thermoset design maintains parametric stability up to 200°C, with decomposition temperatures exceeding 350°C [4].

The manufacturing process revolutionizes production by integrating film fabrication, metallization, and capacitor winding into a single streamlined operation, utilizing formulated organic monomers and aluminum wire. This enables precise control over capacitor properties, such as submicron dielectric thicknesses, tailored electrode metallization, and optimized polymer chemistry. Notably, the ionizing radiation used to form the dielectric, in conjunction with a proprietary acrylate structure and high cross-linking density, results in capacitors that are resistant to degradation in the presence of ionizing radiation.

This work evaluates the performance of NanoLam™ capacitors across a temperature range of -196°C to +160°C, demonstrating their suitability for extreme temperature applications and the dielectric structural properties that enhance their resistance to degradation in the presence of radiation.

2. Harsh Environment Challenges for Capacitors

Capacitors functioning in harsh environments are subjected to various stressors that can greatly impact their performance and reliability. Recognizing these stressors is vital for the development of new capacitor manufacturing technologies and the advancement of dielectric materials. Critical factors that characterize a harsh environment include:

- Temperature Extremes: Both high and low temperature extremes challenge dielectric stability. High temperatures accelerate dielectric breakdown, while cryogenic conditions can induce brittleness and contraction mismatches.
- Mechanical Stress: Vibration and shock can damage internal structures and degrade interlayer adhesion.
- Electrical Stress: High voltages, surges, and ripple currents demand strong dielectric integrity and fast self-healing.
- Radiation: Exposure to ionizing radiation (gamma, neutron, cosmic) can degrade polymer dielectrics by inducing chain scission and oxidation.
- Environmental Exposure: Humidity and vacuum can alter insulation resistance, while condensation and outgassing affect longevity.

The above factors often combine to create even more demanding conditions. Advanced capacitor technologies like NanoLam™ address these challenges through innovative materials, manufacturing processes, and design approaches that enhance reliability across multiple stress dimensions simultaneously. The present work focuses on temperature extremes, electrical stresses and the nature of the dielectric that leads to degradation resistance in the presence of radiation.

3.0 Parametric Stability Under Extreme Conditions of Temperature and Voltage Stress

Effect of Voltage on Dielectric Breakdown

In contrast to traditional metallized capacitors, which consist of a single capacitor roll (e.g., a 30µF/900V unit), NanoLam™ capacitors are structured more like multilayer ceramics, comprising multiple stacked capacitor elements to form a single capacitor block. This design allows for testing of individual capacitor elements prior to their parallel connection, enabling short-term stress tests to be conducted on these elements before they are assembled into capacitor blocks.

Ambient Temperature	Cap 1kHz (uF)	Self-Healing Initiation (V)	Cap Change (%)
160C	5.289	1700	2.0
160C	5.266	1700	1.6
160C	5.098	1800	1.7
160C	5.092	1700	2.3
160C	5.06	1700	2.7
LN2	5.337	2400	2.5
LN2	5.275	2500	2.2
LN2	5.096	2600	2.6
LN2	5.103	2600	3.2
LN2	4.932	2400	3.7
RT	5.268	2300	0.4
RT	5.271	2400	0.4
RT	5.094	2500	1.6
RT	5.106	2400	1.6
RT	4.942	2450	0.2

Table 1. Self-healing initiation voltage of capacitor elements measured at extreme ambient temperature conditions.

Table 1 displays the voltage levels at which self-healing events occur in 850V capacitor elements at temperatures of -196°C, 25°C, and 160°C. During the tests, the applied DC voltage was gradually increased by 100V per second and held for two seconds at the point where self-healing was observed. The findings reveal that the breakdown voltage decreases at 160°C. Furthermore, the capacitor elements experienced a capacitance loss of 2-4%, indicating that prolonged exposure to this voltage may lead to further capacitance loss. To ensure the capacitors can withstand high overvoltage with no damage, the design criteria for most NanoLam™ capacitors specify that the rated voltage (Vr), which is 850V at 125°C, should be below 50% of the voltage at which self-healing events are detected. This suggests that, when operating at 160°C, the voltage applied to the capacitor may need to be derated to ensure a high level of reliability.

Since the rated voltage (Vr) for NanoLam™ capacitors is intentionally established well below the self-healing voltage threshold, the main factors influencing Vr are the application's requirements for ripple current, charge/discharge conditions, equivalent series resistance (ESR), ambient temperature and capacitance loss resulting from the corrosion of the aluminum electrodes throughout the capacitor's lifespan.

For instance, a 30µF/850V/125°C capacitor capable of handling up to 40Arms of ripple current at 85°C (as illustrated in Figure 1) achieves an energy density of 0.25 J/cc. However, capacitors engineered for pulse applications can tolerate higher ESR and operate at lower temperatures, often achieving energy densities that exceed this value by more than an order of magnitude.

Effect of Voltage and Temperature on Leakage Current

All NanoLam™ capacitors, irrespective of voltage, are manufactured using submicron dielectric layers that exhibit higher breakdown strength compared to the same polymer material with a thickness exceeding approximately 1µm [5,6]. The behavior of these thin polymer layers is similar to that of electrolytic capacitors, which also utilize submicron thick Al_2O_3 or Ta_2O_5 dielectrics. The leakage current is influenced by both voltage and temperature in a nonlinear fashion. Generally, the conduction mechanism occurs through charge carriers (typically electrons) that are thermally excited from traps within the dielectric material into the conduction band due to the application of an electric field.

- Thin Dielectric Layers:
  - In very thin dielectric films (typically on the order of 100s of nanometers), the properties can significantly differ from bulk materials. The thickness can influence the electric field distribution, charge carrier mobility, and trapping characteristics.
  - As films become thinner, effects such as increased surface-to-volume ratios and changes in molecular packing can affect the trapping states and the emergence leakage currents that may not be present in thicker dielectric layers [7,8]
- Field Enhancement:
  - In thin films, the electric field applied across the dielectric can be stronger due to the reduced thickness, which can increase the number of charges transitioning to the conduction band [9,10].
- Temperature Dependence:
  - The conduction mechanism also has significant temperature dependence, as higher temperatures increase the thermal energy available to the charge carriers, facilitating their excitation from traps into the conduction band.
  - In very thin polymer films, the temperature can also influence molecular dynamics, potentially affecting the density of trap states and the rate of charge transport [11,12].

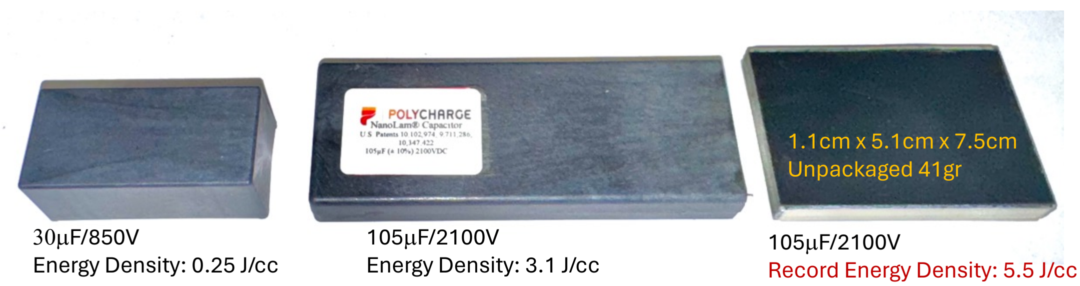

Figure 1. The above NanoLam™ capacitors have the same submicron dielectric thickness with different number of internal series sections, electrode designs and packaging to satisfy performance and life requirements for different application environments, leading to dramatically different energy densities.

The Poole-Frenkel mechanism is a relevant description for explaining conductivity in thin polymer dielectrics, particularly where trap states play a role in charge transport. However, it is critical to consider the specific properties of the thin films being studied, including how their physical and electrical properties may differ from bulk materials. Researchers often use the Poole-Frenkel model alongside other transport mechanisms to obtain a comprehensive understanding of charge conduction in these materials [13,14].

This type of conduction mechanism fits the Poole-Frenkel conduction model which describes conduction in dielectric materials, specifically through the thermal excitation of charge carriers from trapped states within the dielectric in combination with an applied field. The Poole-Frenkel conduction can be generally expressed with the following equation:

$$J = J_o \exp\left(\frac{qE}{kT}\right)$$

Where:

- J is the current density (A/m²).
- J_0 is a pre-exponential factor that can depend on material properties (A/m²).

- q is the charge of an electron ($1.6 * 10^{-19}$ C)
- E is the electric field (V/m), which can be expressed in terms of applied voltage V and dielectric thickness d as E=V/d
- k is the Boltzmann constant ($1.38*10^{-23}$ m^2 kg s^{-2} K^{-1})
- T is the absolute temperature (K)

Using the definition of the electric field, we can rewrite the formula to explicitly include voltage V and dielectric thickness d:

$$J = J_o \exp\left(\frac{qV}{kd} \cdot \frac{1}{T}\right)$$

Key Points

- Dielectric Thickness **(d)**: The thickness of the dielectric affects the electric field intensity. A thicker dielectric will lead to a lower electric field for a given voltage.
- Voltage **(V)**: Higher applied voltage increases the electric field, which can increase the current density due to enhanced carrier excitation.
- Temperature **(T)**: Temperature affects the thermal energy of the charge carriers; as temperature increases, more charge carriers can be thermally excited into the conduction band, often resulting in increased current density.

The experimental results presented in Figure 2 demonstrate that the variation of leakage current with voltage and temperature aligns with the exponential behavior described by the Poole-Frenkel equation. This data highlights the influence of applied voltage and temperature on the conduction mechanism for a specific submicron dielectric thickness. Consequently, it enables the prediction of the behavior of NanoLam™ polymer dielectrics under different conditions of electric field strength and temperature.

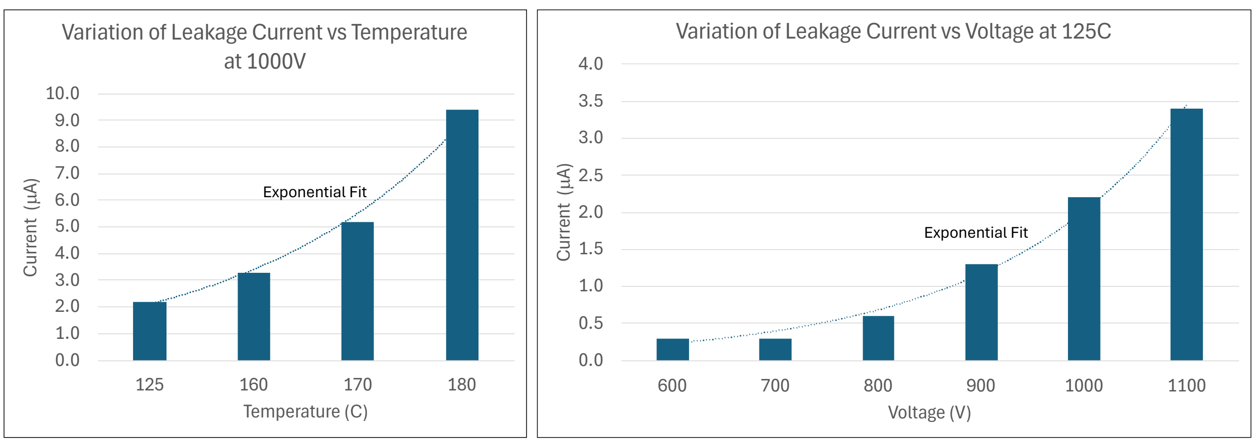

Figure 2. Leakage current measurements of a 30μF/1000V NanoLam^{TM} capacitor, comprising 10 individual capacitor elements, as a function of temperature, greater than the rated temperature Tr =125^{o}C, and voltage, starting at 600V to 1.1xVr (Vr=1000V).

4.0 Performance at Cryogenic Temperature

NanoLam^{TM} capacitors, like conventional metallized film capacitors in general, are critical for cryogenic applications such as:

- Spacecraft electronics (lunar/Mars missions, satellites).
- Quantum computing (superconducting circuits).
- Cryogenic sensors (astrophysics, medical imaging).

There are however a number of challenges when designing capacitors for operation at liquid nitrogen (LN2) temperature (-196^{o}C) and below, which include:

- Thermal contraction mismatches (cracking, delamination).

- Dielectric brittleness at ultra-low temperatures.
- Hermeticity loss (condensation, ice formation).

Capacitor Brittleness at Cryogenic Temperature

- Above the glass transition temperature (Tg), polymer chains are able to move and absorb stress.
- Below Tg, the chains are "frozen," that can lead to brittleness and fracture.
- Most polymer film dielectrics, including polypropylene, polyester, and polyphenylene sulfide, function above their Tg. Consequently, they exhibit relatively high coefficients of thermal expansion (TCE). Below approximately -10°C, nearly all capacitor film dielectrics experience glass transition and become brittle at temperatures below -100°C.
- In contrast, the NanoLam™ dielectric has a glass transition temperature (Tg) of 200°C, ensuring that the capacitors operate well below this Tg. As illustrated in Figure 3, this characteristic, combined with its highly cross-linked structure, results in low coefficients of thermal expansion (CTEs) in the x, y, and z directions.
- The highly cross-linked (thermoset) polymer dielectric, layered with thousands of aluminum electrodes within a single capacitor element, results in a structure with relatively low CTEs. Furthermore, the nanolaminate capacitor structure has the following effects:
  - *Arresting cracks*: Thin, ductile metal layers can slow or deflect crack propagation across the polymer layers.
  - *Reducing catastrophic failure*: When a crack travels through the acrylate, it meets an aluminum barrier every 200-800 nm, potentially absorbing energy and blunting the crack tip.
  - *Impact*: Aluminum absorbs some impact energy and can deflect cracks. Toughness is enhanced over pure polymer, but the whole structure is still relatively brittle at this scale and temperature.
  - *Creep:* At -196°C, both layers essentially have zero creep; crosslinked acrylate freezes molecular motion, and aluminum at this temperature which is extremely resistant to plastic flow

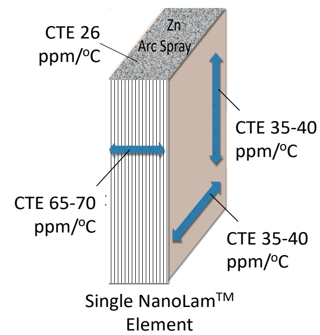

Figure 3 CTE of NanoLam™ capacitor element in xyz directions.

Self-Healing Properties

Conventional metallized film capacitors depend on the presence of an air gap to enhance the effectiveness of the self-healing process. The oxygen in the air aids in converting aluminum (Al) into aluminum oxide (Al_2O_3) while facilitating the removal of carbon as carbon monoxide (CO) and carbon dioxide (CO_2). At liquid nitrogen (LN_2) temperatures, the air liquefies, creating a partial vacuum that can limit the availability of oxygen in the interlayer spaces, potentially reducing the effectiveness of self-healing.

In contrast, NanoLam™ capacitors feature a dielectric designed specifically to optimize self-healing properties. This dielectric has a molecular structure characterized by high oxygen-to-carbon (O:C) and hydrogen-to-carbon (H:C) ratios, which enhances the removal of carbon in various forms, including CO, CO_2, methane (CH_4), ethane (C_2H_6), and other low molecular weight hydrocarbons. As a result, solid-state NanoLam™ capacitors can effectively self-heal without requiring an air gap, whether in air or vacuum, thus eliminating concerns about the loss of hermeticity in the package.

Impact on Dielectric Properties

The effects of LN_2 temperatures on the dielectric properties of NanoLam™ capacitors are illustrated in Table 2. The phenomenon of dipole "freezing" is evidenced by a 10% reduction in capacitance and a 54% decrease in the dissipation factor. As expected, the conductivity of the electrodes and terminations increases, resulting in lower equivalent series resistance (ESR).

30µF/850V Capacitor Tested at 25°C and -196°C					
Ambient Temperature (C)	Capacitance 1 kHz (µF)	Dissipation Factor (1 kHz)	ESR 10kHz (mΩ)	20 kHz (mΩ)	100kHz (mΩ)
25	29.95	0.0044	6.48	5.1	3.8
-196	26.93	0.0020	3.22	2.85	2.43
% Change	10%	54%	50%	44%	36%

Table 2. Key dielectric properties of NanoLam™ capacitors at LN2 temperature

Multiple capacitor elements rated at 5µF/850V were subjected to a 100-hour immersion test in a LN_2 bath. Previous studies have shown that these capacitor elements can endure multiple thermal shock cycles, transitioning from a temperature of +140°C directly into an LN_2 bath [4]. In this experiment, the capacitor elements were immersed in LN_2 under voltage bias and were periodically removed to measure key dielectric parameters. As illustrated in Figure 4, there was no significant change in capacitance, equivalent series resistance (ESR) at 10 kHz, or dissipation factor over the 100-hour testing period. This outcome was anticipated, assuming that the components were not mechanically damaged, since, as indicated in Table 1, the self-healing initiation voltage at -196°C is more than double the rated voltage of 850V.

Capacitor Encapsulation Package

The capacitor packaging presents ongoing challenges. The current epoxy material, designed for higher temperature applications with a Tg of 150°C, tends to crack at LN_2 temperatures. Epoxies such as Master Bond Henkel STYCAST, which are recommended for cryogenic applications, also develop microcracks and induce stress on the capacitor block. A promising packaging solution involves a low CTE liquid crystal box, potted with a silicone resin. Further development is necessary in this area to enable the use of NanoLam™ capacitors in cryogenic temperature applications.

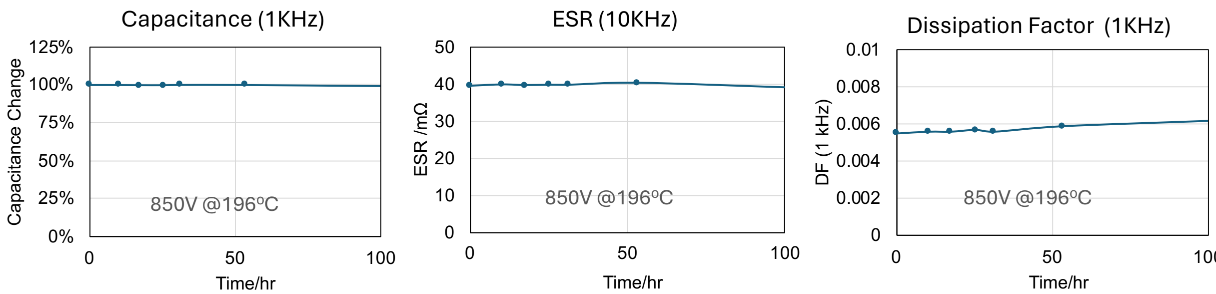

Figure 4. Typical performance of 5.0µF/850V capacitor elements in LN2 temperature

4.0 Performance at High Temperature

High-temperature capacitors are essential components in systems that require dependable operation in extreme thermal environments. Their ability to maintain performance and safety standards under such conditions makes them crucial in aerospace, automotive, oil and gas, industrial, military, and power electronics applications. While commercially available capacitors can generally meet most high-temperature demands in aerospace and industrial settings, challenges arise in applications that require a combination of specific parameters that no single capacitor technology can provide.

For example, certain applications may necessitate high capacitance values, operation at elevated temperatures and voltages, stable capacitance across temperature and bias, high energy density, and exceptional reliability. In these scenarios, the requirement for high capacitance and high voltage eliminates tantalum capacitors, while the need for capacitance stability across temperature and bias makes ceramic capacitors impractical. Furthermore, high-temperature specifications exclude polypropylene film capacitors which have the highest energy density among polymer film capacitors. Consequently, the requirement for high-temperature operation necessitates the use of high-temperature film capacitors, such as PEN, PPS, and PTFE, which exhibit lower energy density because of their reduced breakdown strength.

NanoLam™ capacitors have been specifically designed to meet the distinct requirements of high temperature, high capacitance, high voltage, and high energy density—needs that other capacitor technologies cannot adequately fulfill. High-temperature applications typically range from approximately 125°C to over 200°C. However, it is essential to find a balance between the thickness of the aluminum electrodes to ensure self-healing properties and the potential for capacitance loss and increased ESR resulting from the corrosion of the aluminum electrodes. Otherwise, as in the case of high temperature capacitors like PTFE, thicker aluminum electrodes are used to minimize electrode corrosion effects , in conjunction with a thick PTFE dielectric to accommodate high-temperature applications where energy density is not a critical factor and when competing capacitor technologies exhibit inferior properties such as energy density and lifespan.

Given the wide range of applications, high-temperature capacitors may also be needed for use in lower ambient temperatures (85°C to 125°C) to manage high ripple currents, which can elevate the capacitor's temperature due to I^2R losses. For instance, Figure 5 illustrates the capacitance loss and changes in ESR over 3,000 hours for a 30µF/850V NanoLam™ capacitor, designed primarily for automotive DC-link applications and tested at 140°C. Modeling, along with temperature measurements taken at various points on the capacitor, indicates that operating at 140°C is comparable to functioning at an ambient temperature of 85°C, with a hot-spot temperature of 149°C and a surface temperature of 116°C. This condition was achieved by subjecting the capacitor to a ripple current of 40Arms at 20 kHz.

To illustrate how a high-temperature capacitor can be effectively used in a lower temperature environment while managing high RMS current, the 850V NanoLam™ capacitor was tested alongside a state-of-the-art 30µF/1100V metallized polypropylene capacitor rated for 20Arms from a leading OEM. Notably, the 1100V capacitor was 2.4 times larger than the 30µF/850V NanoLam™ capacitor. The current was first applied until both capacitors achieved thermal equilibrium. After applying a voltage of 850V, the polypropylene capacitor started to degrade within 15 minutes due to thermal runaway and was removed from the test. This indicates that a harsh operating environment is not solely defined by extreme temperature conditions. High ripple currents, along with high repetition rate di/dt pulses, can produce sufficient I^2R heating to damage a capacitor.

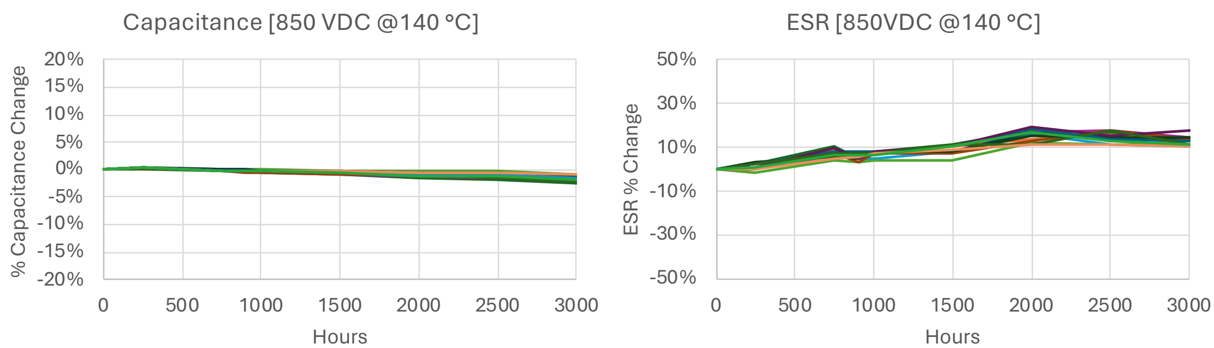

Figure 5. Capacitance and ESR stability of multiple 30µF/850V NanoLam™ capacitors at 140°C ambient temperature.

When using high energy density NanoLam™ capacitors in high temperature applications, a major challenge is how to protect the capacitor from ambient moisture. For example, at 160ºC the dielectric maintains high enough dielectric strength (1700V for an 850V capacitor – Table 1), but the epoxy used to encapsulate the capacitor has a Tg of 150ºC. Operating above the Tg increases the CTE (almost double for many epoxies) and the molecular relaxation allows moisture to enter the package. Therefore, one solution other than developing a higher Tg epoxy which is not a trivial effort, is to lower the operating voltage, which reduces the rate of electrode corrosion. As shown in Figure 5, the 850V capacitor rating when reduced to 670V, it can be used in a 160°C application with stable parametric performance over 1000hrs. For use at higher temperatures the mismatch in CTEs between box-epoxy-capacitor is too high, requiring either a hermetically sealed metal package or a simple wrap & fill design which is used by most higher temperature capacitors.

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When utilizing high-energy density NanoLam™ capacitors in high-temperature applications, a significant challenge is protecting the capacitor from ambient moisture. For instance, at 160°C, the dielectric maintains sufficient dielectric strength (1,700V for an 850V capacitor, as mentioned above), but the epoxy used to encapsulate the capacitor has a

Tg of 150°C. Operating above this Tg increases the coefficient of thermal expansion, often nearly doubling for many epoxy materials, and allows molecular relaxation that can permit moisture to enter the package.
One potential solution, aside from the complex task of developing a higher Tg epoxy, is to reduce the energy density of the capacitor by lowering the operating voltage, which in turn decreases the rate of electrode corrosion. As illustrated in Figure 6, NanoLam™ capacitors with an 850V rating can be effectively used at 670V for a 160°C application, providing stable parametric performance over 1000 hours.

5. Resistance to Degradation in the Presence of Radiation
The highly cross-linked NanoLam™ acrylate and methacrylate polymers used as dielectric materials in radiation-rich environments (cosmic, nuclear, or high-energy), exhibit some unique advantages of conventional thermoplastic capacitor dielectrics.

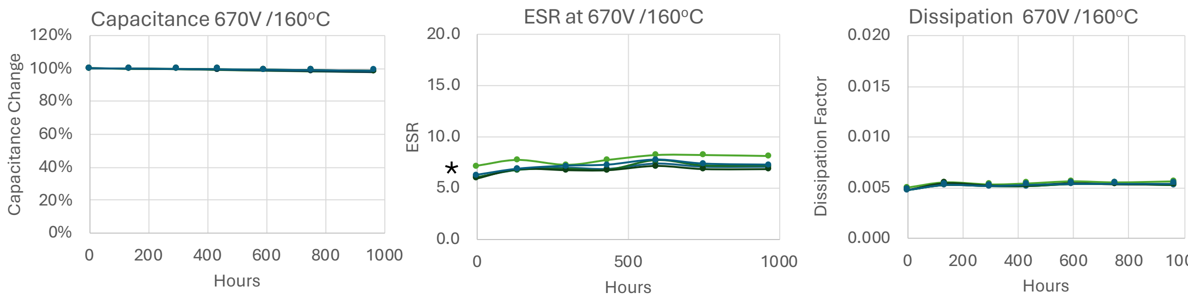

Figure 6. Parametric performance of 30μF/850V capacitor at 160°C when derated to 670V. The star (*) in the ESR graph denotes a 10KHz ESR limit that should not be exceeded in order to minimize electrode corrosion over the life of the capacitors.

High Cross-Link Density = Dimensional and Chemical Stability [15]

- Radiation generates free radicals, which can cause chain scission or cross-linking.
- A pre-cross-linked network resists additional cross-linking or chain breakage, maintaining mechanical integrity.
- Less prone to shrinkage, swelling, or distortion under ionizing radiation (gamma, electron, or proton beams)

Superior Dielectric Stability Under Radiation Stress [16]

- Acrylate and methacrylate backbones, especially when rigidized with aromatic or cycloaliphatic groups—exhibit low dielectric loss and stable permittivity even after exposure to radiation.
- Highly cross-linked networks can suppress dipolar reorientation, which might otherwise degrade dielectric behavior.

Resistance to Radiation-Induced Charge Trapping [17]

- In polymers with low cross-link density, ionizing radiation can create deep traps, leading to space charge accumulation.
- High Cross-linked networks reduce trap depth and density, improving dielectric breakdown strength and reliability.

Tailorable Glass Transition Temperature (Tg) for Thermal-Radiation Co-Resistance [18]

- Methacrylate polymers can be designed with high Tg (>150 °C) using bulky side groups (e.g., tert-butyl, cycloaliphatic, aromatic).
- This enhances thermo-mechanical stability, crucial in space applications or near high-energy electronics.
- High Tg also reduces segmental motion, which is often a trigger for radiation-induced degradation.

Superior Resistance to Oxidative and Hydrolytic Breakdown [19]

- Acrylate/methacrylate systems can be formulated with radical scavengers (e.g., hindered amine light stabilizers, phosphates, benzotriazoles) to further protect against radiation-induced oxidation.
- Their low moisture uptake compared to linear polyesters or polyimides helps avoid hydrolysis under radiation.

Cross-linked acrylates and methacrylates exhibit excellent adhesion to metal oxide or aluminum nanolayers, which supports the multilayer design of NanoLam™ capacitors. Additionally, radiation resistance is maintained at the nano-interfaces. This means that adhesion, chemical stability, and mechanical strength at these extremely thin (nanoscale) interfaces do not significantly degrade under radiation exposure. As a result, the material continues to operate reliably without losing dielectric strength or experiencing interfacial failure. An evaluation of NanoLam™ capacitors conducted by Sandia for shock and radiation exposure led to their approval by the DOE Nuclear Deterrence Division for use in critical applications, allowing them to replace polymer film capacitors that are over five times larger.

6. Summary

In summary, the development of NanoLam™ capacitors represents a significant advancement in capacitor technology, particularly for applications in harsh environments characterized by extreme temperatures, electrical stress, and radiation exposure. Traditional capacitor technologies often fall short in meeting the stringent requirements for high energy density, reliability, and performance under such challenging conditions. The unique properties of NanoLam™ capacitors, including high glass transition temperature, superior breakdown strength, self-healing capabilities, and resistance to radiation degradation, position them as a viable solution for demanding applications in defense, automotive, aerospace, and space industries. The ability to function within an extensive temperature range of -196°C to +160°C highlights their adaptability and effectiveness under extreme environmental conditions. Packaging remains the primary thermal constraint at cryogenic temperatures and those exceeding 160°C. Further advancements are necessary to address the shortcomings of the current encapsulation design, which involves epoxy potting the NanoLam™ capacitor blocks within a polymer casing.

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