

# High-Temperature, High-Power Capacitors: the Assessment of Capabilities

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## ABSTRACT

High-temperature, high-power capacitors are integral components being developed for high-temperature electronics to be used in aerospace, automotive, and other applications. Presently, a wide range of materials and capacitor technologies are being actively developed to address the needs of high temperature applications. Literature and experimental survey of existing materials and technologies focusing on commercially viable technologies has been made. Key parameters for characterizing and assessing capacitors have been compiled. Of the key competing capacitor technologies, including electrolytic, ceramic, polymer thin-film, and supercapacitors, none were found to be clearly superior to the others, thus requiring trade-offs between available choices. The review of these capacitors will be presented with respect to specific energy density, temperature capability, cost, ripple current capability, and failure tolerance. In addition to presenting a survey of existing capacitors, we have experimentally characterized RC constants as a function of temperature for a wide variety of materials including dielectric polymers, simple oxides, ferroelectrics, and glasses. While in general there is a trade-off between R and C parameters for different materials, outstanding RC's were observed in lanthanum doped BaZrO<sub>3</sub> ceramics and ferroelectric inorganics with high-temperature phase transitions.

## INTRODUCTION

High-temperature capacitors are being developed and used in a great variety of applications including automotive vehicles, aerospace, geothermal, and space exploration. An important subset of these capacitors are high-temperature, high-power capacitors. These capacitors are an integral part of the power electronic devices and circuits. One of the most important application areas for the use of high-temperature, high

power capacitors is in inverter circuits for use in hybrid vehicles. A wide variety of capacitors are required for the snubbers, filtering capacitors, and bus capacitors.

Capacitors are indispensable for carrying out functions such as energy storage, energy discharge, filtering, voltage smoothing, coupling, de-coupling, dc blocking, power conditioning, snubbing, electromagnetic interference (EMI) suppression, and commutation (typically used in resonant converters) in power electronic circuits.

In all major capacitor types, including multilayer ceramic capacitors (MLCCs), wound and stacked polymer capacitors, electrolytic capacitors, and supercapacitors, there is an ongoing effort to improve temperature range, performance characteristics, and long-term reliability.

Ceramic capacitors based on relaxor compositions containing bismuth titanates and lead titanate (BS-PT) [1] as well as MLC's containing lead lanthanum titanate zirconate PLZT [2] combine high dielectric constant with high-temperature operation. Because of the high-temperature morphotropic phase boundary (MPB) in these dielectrics, compositions are available which combine relatively flat and high dielectric constant which is more than 1000 times larger than the dielectric constant in conventional polymeric capacitors.

In comparison to MLCC's, the polymeric capacitors have a very desirable characteristic of graceful failure which in addition to permitting polymer capacitors to be operated closer to their breakdown strengths also improves the reliability of polymer capacitors. Furthermore, because the aluminum electrodes used in capacitors with graceful failure are only a couple of hundred angstrom thick, the current gates can be built within the electrode structure itself further improving the reliability [3]. While there are several polymer dielectrics that can be used in the temperature range of 200 °C and higher, the vast

majority of them have low dielectric constant in the range of two to three.

Some of the electrolytic capacitors also benefit from graceful failure. The challenges in extending temperature range of electrolytic capacitors and supercapacitors include high-temperature electrolyte stability, preventing loss of electrolyte over time leading to higher equivalent series resistance (ESR), and reduced reliance on potentially harmful electrolytes such as acetonitrile. The most important positive attribute of electrolytic capacitors and especially of supercapacitors, is their very high specific stored energy. For example, the capacitance adjacent to a single electrode in a supercapacitor can be in the range of 100 F/gm because of the commonly used high surface area carbon with surface area of 1000 m<sup>2</sup>/gm and a double layer capacitance of 10 mF/cm<sup>2</sup> [4]. While the specific energy of supercapacitors is outstanding, their specific power is inferior to ceramic or polymeric capacitors but is superior to conventional batteries and fuel cells (Fig.1). The supercapacitors find applications in regenerative braking and as a starter battery assist in automotive applications.

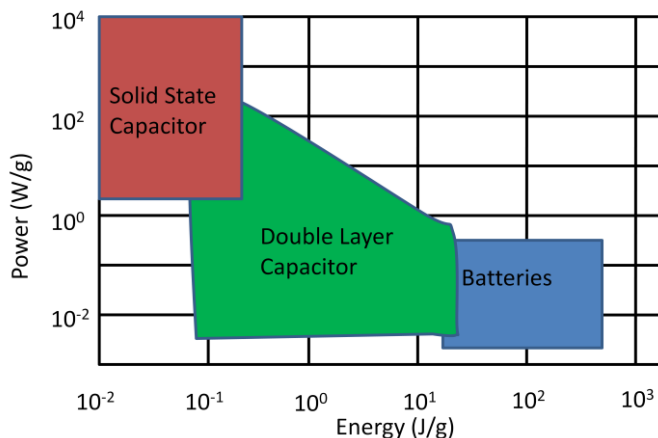


Figure 1. Sketch of Ragone plot for various energy storage and conversion devices. The indicated areas are rough guidelines.

The rest of the paper will compare previously mentioned capacitor types with respect to several important figures of merits for high-temperature, high-power applications. This paper also includes a summary of extensive experimental characterization of RC products for different capacitor types. In the area of bus capacitors for hybrid vehicles, this paper is guided by an unpublished report by one of the co-authors [5]. It should be mentioned that promising capacitors based on wide bandgap, thin-film dielectrics are not covered in this paper.

## EVALUATING CAPACITORS

**CAPACITOR REQUIREMENTS** - For high-temperature, high-power applications capacitors are judged with

respect to their specific energy and power densities, available voltage ranges, failure tolerance, cost, ripple current capability, dielectric losses, ESR, equivalent series inductance (ESL), and temperature stability of capacitance. Furthermore, for the high-temperature capacitors, the packaging of the capacitors and their electrode stability are of great importance because of the mechanical stresses developed during cycling and the acceleration of the kinetic processes at elevated temperatures.

**CAPACITOR PACKAGING** - Typical electrolytic, wound and multilayer polymers, as well as ceramic capacitors are shown in Figure 2.



Figure 2. Photograph showing the major capacitor types produced for medium power inverter applications. The aluminum electrolytic capacitors are in the 5,000 to 10,000  $\mu$ F 450 V range, The wound polymer capacitors are in the 250  $\mu$ F 600 V range, the multilayer polymer capacitor compounds are in the 3  $\mu$ F 600 V range. The largest multilayer ceramic capacitor shown is a 1  $\mu$ F 500 V rated capacitor, and the ant ferroelectric/ferroelectric capacitors are 5  $\mu$ F 250 V range.

Multilayer ceramics and multilayer polymer capacitors have the best form factors for efficient packing in the inverter. Wound polymer and electrolytic capacitors are commercially available in large capacitor values. The capacitor form factor influences its electrical and thermomechanical properties. For example, multilayer structures have superior ESRs compared to the wound polymer capacitors, while the wound capacitors may have better reliability due to the reduced probability of dielectric breakdown to be initiated at the electrode edges.

The approximate ranges of voltage and capacitor sizes are shown in Figure 3 along with the area of interest for DC bus capacitors for hybrid electric vehicles.

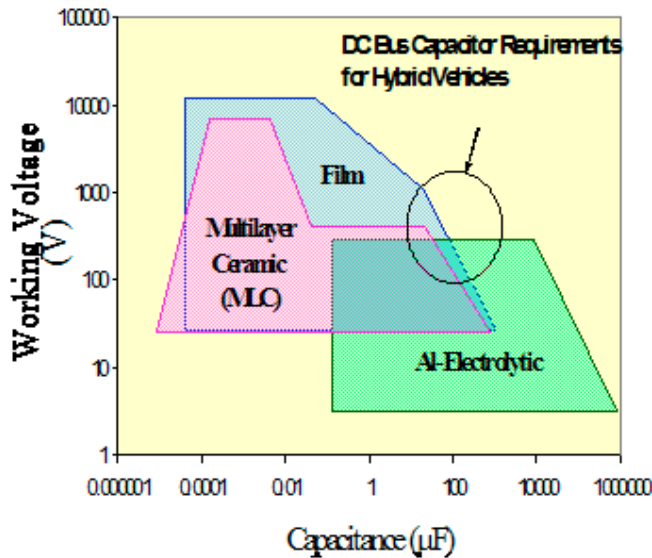


Figure 3. Typical capacitance and working voltage ranges for the main capacitor classes used in power electronics application [6]. DL represents double layer capacitor.

**CAPACITOR FIGURES OF MERIT** - There are three useful figures of merits (FOM) to characterize high-temperature, high-power capacitors: volumetric capacitance, energy density, and RC constant. These figures of merit emphasize the importance of developing capacitors with high volumetric capacitance, high energy density, and low energy losses.

The experimental volumetric capacitance (typically given in units of  $\mu\text{F}/\text{cm}^3$ ) for a multilayer capacitor is defined as:

$$C_{vol} = \frac{\epsilon_0 \epsilon_r}{d^2} f \quad (1)$$

where  $d$  is the thickness of the individual layer,  $\epsilon_r$  is the effective relative dielectric constant,  $\epsilon_0$  is the permittivity of free space, and  $f$  is a geometric factor smaller than one used to account for the finite electrode thickness, electrode margins, and extra packaging volume;  $f$  can be made equal to unity if only active dielectric volumetric capacitance is emphasized. The primary material parameter that leads to high volumetric efficiency is the relative dielectric constant. The volumetric capacitance is an important quantity for applications where space is at premium, and the high dielectric constant materials with thin layers will maximize the volumetric efficiency. Capacitor miniaturization also reduces thermally induced stresses and is especially valuable for high-temperature applications requiring large capacitance value. The dielectric thickness specification is dependent upon several important factors, including breakdown field strengths and long-term reliability. The volumetric capacitance,  $C_{vol}$ , does not include voltage, and generally lower voltage rated capacitors have higher volumetric capacitance. Doubling of the voltage from

100 to 200 V resulted in  $C_{vol}$  derating of 33% for the ceramic X7R MLC and of 45% for the polyester film foil capacitor [7].

The total capacitance and its voltage are related to the energy stored in the capacitor as:

$$\text{Energy} = \frac{1}{2} CV^2 \quad (2)$$

Where  $C$  is the capacitance in Farads,  $V$  is the capacitor's voltage in Volts and stored energy is in Joules. In order to limit ripple current in power electronic inverters, it is desirable to have the capacitor energy as high as possible. However, capacitor volume and weight specifications are often stringent for high-temperature applications. Therefore, a useful figure-of-merit to compare capacitors is the energy density. The energy density accounts for both the volumetric capacitance and voltage requirements and is given by:

$$E_{vol} = \frac{1}{2} k \epsilon_0 (gE)^2 \quad (3)$$

where  $k$  is the dielectric constant,  $\epsilon_0$  is free space permittivity,  $E$  is the dielectric breakdown strengths, and  $g$  is the field derating factor. The field derating factor is closer to one for the capacitors with graceful failure, good long-term reliability, and high Weibull modulus of breakdown strengths. The long-term reliability of capacitors is commonly studied with highly accelerated life testing (HALT). Interestingly, different expressions for voltage acceleration factor are used for the ceramic and polymer capacitors, and more work is needed in this area.

From Equation 3, the two dielectric material contributions to the energy density are the dielectric constant and the dielectric breakdown strength. Oxide dielectric materials such as  $(\text{Ba}, \text{Sr})\text{TiO}_3$  and  $\text{Pb}(\text{Zr}, \text{Ti})\text{O}_3$  have dielectric constants in the 500 to 2000 range. Polymer materials typically have dielectric constants between 2 and 5. Polymer materials generally have much higher breakdown fields which contribute to the capacitor energy density. In addition, polymers film capacitors have an inherent graceful failure mechanism which allows for higher operating fields. Graceful failure has been primarily demonstrated for polypropylene based capacitors and similar graceful failure needs to be demonstrated for high temperature dielectric materials and capacitors.

The final figure of merit especially important for high-temperature capacitors is RC product. Physically it represents the time constant for internal discharge of unbalanced charges either on electrodes or in the bulk of the dielectric. Similar to leakage current, it is a measure of insulation resistance for a capacitor. However, RC product FOM advantage over leakage current is its independence of the capacitor geometry. In fact, RC product is equivalent to the  $\rho\epsilon$  product with the latter representing purely material parameters. Geometry independence makes it possible to use  $\rho\epsilon$  product to compare different families of dielectrics with respect to