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HIGH ENERGY DENSITY CAPACITORS

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Abstract-Metallized film capacitors with energy densities as high as 3 J/cc and stored energy as high as 260 kJ per unit are now commercially available. These capacitors can be custom-designed for specific applications so as to minimize the size and weight of the capacitance for the lifetime and duty required. Applications requiring pulsed energy discharge times of 10 microseconds to 10 milliseconds are typical, but DC filtering and other types of duty can also be addressed. Packaging options include industry-standard drawn steel cans, proprietary molded plastic cases, and large welded steel cases. The performance of these capacitors as a function of voltage and size will be described.

I. Introduction

Pulse power capacitors are high voltage, fast discharge devices designed for energy storage and delivery in applications such as railguns, ETC guns, x-ray equipment, and defibrillators. Large science experiments such as the Sandia National Laboratory Z machine and the US Department of Energy National Ignition Facility use pulsed power capacitors to supply high current and power density. Pulsed power capacitors have been used to drive pulsed plasma thrusters for attitude control on spacecraft. Depending on the application, large capacitors can be hardened to acceleration (as high as 80 G's) and radiation. Pulsed power capacitors can be provided in a variety of package options, including industry-standard drawn steel cans, proprietary molded plastic cases, and large welded steel cases. Performance metrics that drive pulsed power capacitor development and applications include stored energy density, pulse life, and DC life. This work describes the performance characteristics of the type CMX capacitors recently introduced by General Atomics Electronic Systems (GA-ESI).

II. Performance Metrics For Pulsed Power Capacitors

A. *Stored Energy Density*

The stored energy density of a capacitor is an important parameter for applications which are space limited, including warship-mounted railguns, ETC tank guns, and electric reactive armor. The stored energy density (D, in J/cc, J/cm^3 or MJ/m^3) of a capacitor can be calculated using

$$D = 4.43 * 10^{-6} * K * PF * E^2 \tag{1}$$

Where K is the relative permittivity of the dielectric, PF is the packing factor (the volume fraction of the capacitor that is actually storing energy), and E is the electric field applied to the dielectric in V/um. The relative permittivity of GA-ESI's capacitor films ranges from 2 to 14. The packing factor is highly dependent on peak voltage and discharge time and can range from 0.7-0.8 in millisecond discharge devices to 0.5 in microsecond discharge capacitors. Typical values for electric field in pulsed power capacitors range from 500 V/um – 800 V/um. The electric field is limited by the breakdown strength of the polymer dielectric, which is the maximum field which can be applied before a breakdown event short-circuits the electrode.

B. *Pulse Life*

Pulse life is the number of charge/discharge cycles a capacitor can undergo before experiencing failure due to capacitance loss. Capacitor lifetimes are usually defined as a 5% decrease in capacitance, depending on the application. This end of life capacitance loss is much lower than that which would cause a system failure. Pulse life testing is achieved by charging up a capacitor over a set amount of time, holding the charge voltage constant, and discharging though a defined resistive load. The charge and discharge times are controlled by limiting the current from the power supply and by varying load resistance, respectively.

C. *DC Life*

Some applications require the capacitor to remain charged for long periods of time until an event triggers operation at an unpredictable time. DC life testing is achieved by charging the capacitor to the test voltage and periodically measuring capacitance. Gradual capacitance loss results over time; again, the capacitor is considered failed after a 5% loss in capacitance.

III. Recent Advances In Pulsed Power Capacitor Technology

Advancement of capacitor manufacturing techniques and film quality at GA-ESI has resulted in improved stored energy density, pulse life, and DC life. The type CMX capacitor is one manifestation of this development effort. Pulse and DC life test results are presented for capacitors using the CMX technology; a 2 J/cc single winding model capacitor, a 2 J/cc single stack capacitor, a 3 J/cc 100 kJ Type CMX capacitor, a 3 J/cc 50 kJ Type CMX capacitor, and a 2 J/cc 260 kJ Type CMX capacitor.

The last 25 years of capacitor development have led to tremendous gains in energy density and total delivered lifetime energy. Increased energy density has primarily been achieved by increasing the breakdown strength of the polymer dielectric. This has been accomplished by enhancing resin purity and improving manufacturing techniques which reduce the number of electrical defects in the film which lead to breakdown events. Self-healing electrodes also enable the capacitors to operate at higher energy densities. Capacitor manufacturing processes have been enhanced to ensure complete impregnation of dielectric fluid between the film layers, and to eliminate impurities in the fluid itself. Figure 2 demonstrates the progress in energy density, and Figure 3 shows the lifetime total delivered energy of millisecond discharge capacitors to date.

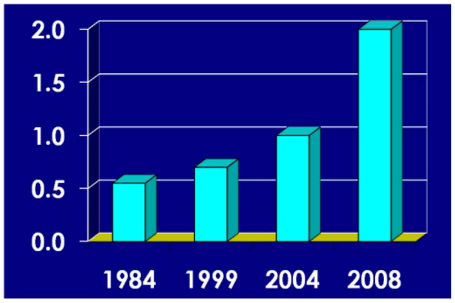

Figure 1. Progress in stored energy density (vertical scale in J/cc) for millisecond discharge capacitors manufactured at GA-ESI.

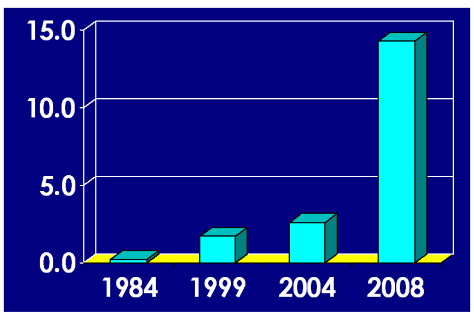

Figure 2. Progress in total delivered lifetime times energy (vertical scale in GJ/discharge * pulse life) for millisecond discharge capacitors manufactured at GA-ESI.

A. 2 J/cc Single Winding Model Capacitors

Single winding model capacitors are useful for rapidly evaluating a particular technology with minimal manufacturing lead time. Six 2 J/cc model capacitors using the CMX technology were produced and tested with the previously mentioned pulse life and DC life test procedures at 2380 V. Results of the pulse life test are shown in Figure 3.

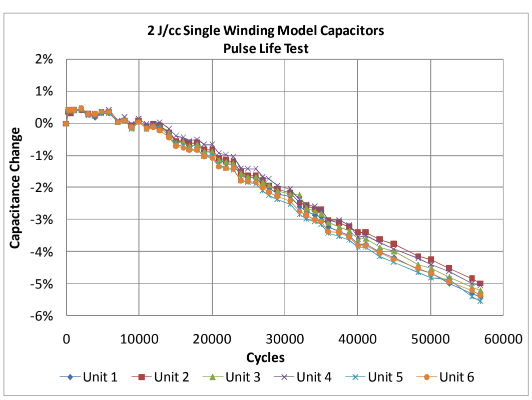

Figure 3. Pulse life test results for 2 J/cc Single Winding Model capacitors.

The model capacitors experienced no capacitance loss for the first 10,000 cycles. At 55,000 cycles the units had a 5% decrease in capacitance. DC life tests were performed on three model capacitors at 2380 V. The results, shown in Figure 4, indicate 5% capacitance loss occurring at 460-470 hours of continuous DC operation.

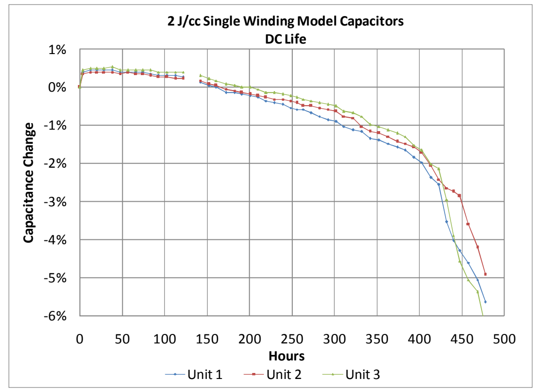

Figure 4. DC life test results for 2 J/cc Single Winding Model capacitors.

B. 2 J/cc Single Stack Capacitor

Single stack capacitors consist of several windings in a parallel configuration. This allows for evaluation of capacitor technologies on a scale closer to that of large steel-case capacitors without the high production overhead that is characteristic of these units. Pulse life testing was performed on two 2 J/cc single stack capacitors. The results are shown in Figure 5. No capacitance loss was observed during the first 10,000 cycles. 5% capacitance loss was accumulated after 60,000 cycles.

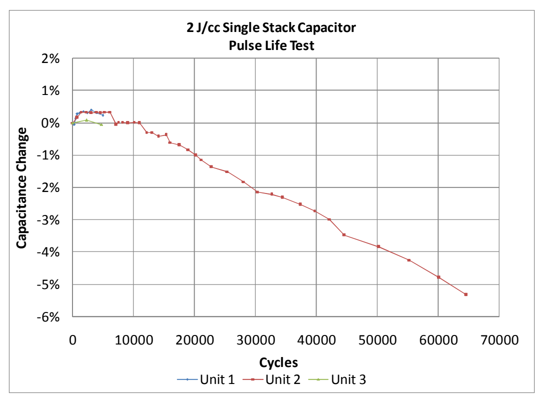

Figure 5. Pulse life test results for the 2 J/cc Single Stack capacitor.

C. 3 J/cc, 50 kJ Type CMX Capacitor

The 3 J/cc, 50 kJ Type CMX prototype is a 6.6 kV, 2310 uF unit measuring 4.4” x 14.25” x 16.4” and having 3.0 J/cc or 2.4 J/g. It weighs only 46 lbs and is easily carried, as shown in Figure 6.

Figure 6. 3 J/cc, 50 kJ Type CMX capacitor.

Pulse life testing was performed at 6.6 kV with a 3 second charge time and a 1 second hold time; results are shown in Figure 7. Peak current was 15 kA. At 1400 cycles the unit experienced a 5% loss in capacitance.

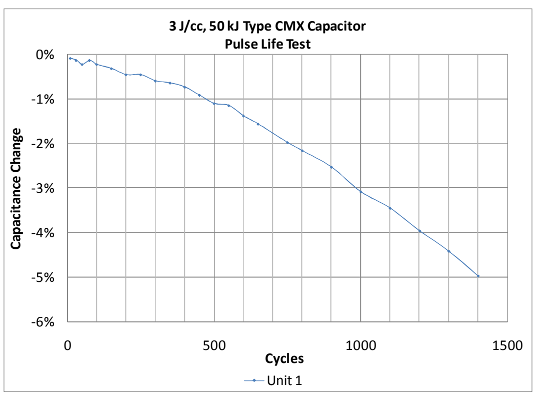

Figure 7. Pulse life test results for the 3 J/cc, 50 kJ Type CMX capacitor.

D. 3 J/cc, 100 kJ Type CMX Capacitor

The 3 J/cc, 100 kJ Type CMX prototype is a 4600 uF unit rated for operation at 6.6 kV. It measures 6.5" x 18.25" x 17" and weighs 95 lbs. It has a stored energy density of 3.0 J/cc or 2.3 J/g. The pulse life test was performed at 6.6 kV using the procedure mentioned previously. Charge time was 7 seconds and hold time was 0.5 seconds. Peak discharge current was 6 kA. The test results are shown in Figure 8. The capacitor showed less than 1% capacitance loss over 1000 cycles. Measured energy density remains slightly above 3 J/cc for the entire test duration.

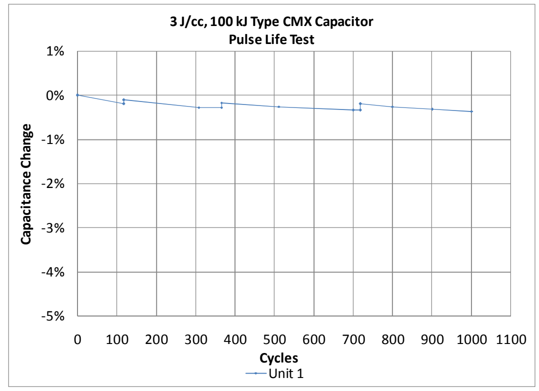

Figure 8. Pulse life test results for the 3 J/cc, 100 kJ Type CMX capacitor.

E. 2 J/cc, 260 kJ Type CMX Capacitor

The 2 J/cc, 260 kJ Type CMX capacitor is a 4000 uF unit rated for operation at 11.3 kV. It measures 13.5" x 16" x 36" and weighs 309 lbs. It has a stored energy density of 3.0 J/cc or 2.7 J/g in a welded metal type case. A pulse life test was performed on two capacitors with a 180 second charge time, 10 second hold time, and a 5 minute repetition rate. The results in Figure 9 demonstrate no capacitance loss for the first 4000 cycles of operation. After 10,000 cycles the units had between 0.5% and 1% capacitance loss, and the test was suspended.

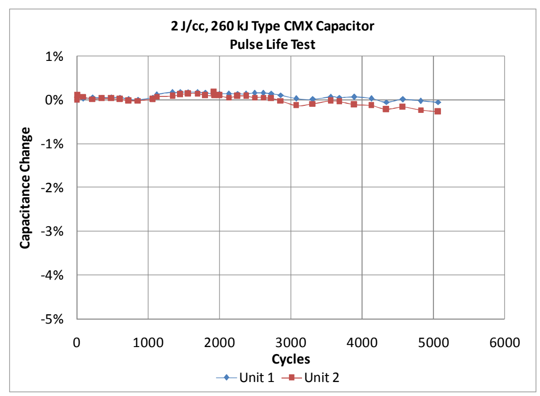

Figure 9. Pulse life test results for the 2 J/cc, 260 kJ Type CMX capacitor.

F. Energy Density vs. Pulse Life for Type CMX Capacitors

A capacitor can be made to operate at a specific energy density by changing the charge voltage and thus the electric field. Higher electric fields on the dielectric film cause more rapid dielectric aging; as a result the pulse lifetime of the capacitor will be affected negatively. Generally, lifetime is increased logarithmically by a decrease in the operating voltage of a film capacitor. Figure 10 shows the measured and projected pulse lifetime for type CMX capacitors as a function of operated energy density.

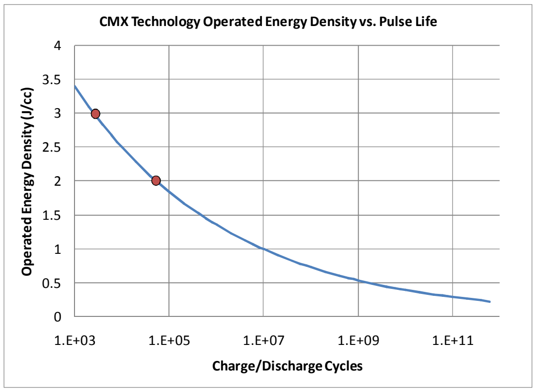

Figure 10. Operated energy density vs. pulse life for type CMX capacitors.

Capacitors using the CMX technology have achieved greater than 1000 charge/discharge cycles at 3 J/cc, greater than 50,000 cycles at 2 J/cc. The projected lifetime for operation at 1 J/cc is 10 million cycles.

Figure 11 shows pulse life test results for three scales of the CMX capacitor technology; the 2 J/cc model capacitor, the 2 J/cc single stack capacitor, and the 260 kJ CMX capacitor. The graph shows that the three scales have very similar trends of capacitance change with pulse life, although the CMX capacitor exhibits less of an initial capacitance increase. This similarity can be attributed to the self-healing behaviour of the electrode; electrode area scaling is eliminated which allows for operation near the breakdown field of the dielectric regardless of capacitor size.

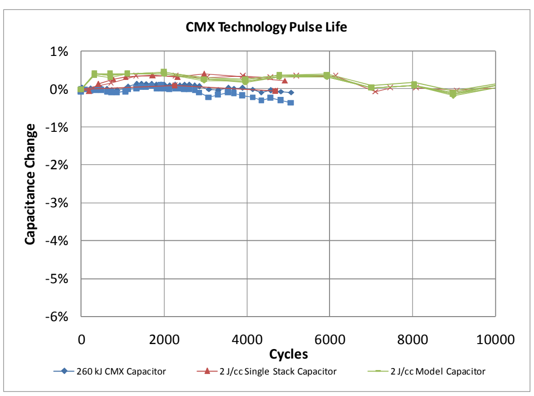

Figure 11. Pulse life test results for three scales of production of the CMX capacitor technology.

IV. Conclusions

GA-ESI has made significant advancements in capacitor film quality and manufacturing techniques. Evaluation of these advances by way of small scale model and single stack capacitors has lead to the development of the CMX technology. Single winding model capacitors, single stack capacitors, 50kJ, 100kJ, and 260kJ capacitors were tested for pulse life and DC life. Results show pulse lifetimes >50,000 cycles and DC lifetimes of up to 470 hours in the CMX capacitors at 2 J/cc. The largest type CMX capacitors can deliver 260 kJ of stored energy with a peak current of 150 kA and a lifetime of >55,000 charge/discharge cycles. The advancements that GA-ESI has made in film quality and manufacturing techniques have contributed to the exponential growth in energy density and pulse lifetime of capacitors over the past 25 years. These advancements are expected to continue; opening up new possibilities for scientific, military, and industrial applications.

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