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# Energy Storage in Polymer Laminate Structures: Aging and Diagnostic Approaches for Life Validation

### INTRODUCTION

This is the first time that energy discharge capacitor technology capable of graceful aging has been demonstrated at these energy levels. When a capacitor is selected to perform properly in an electronic circuit, its characteristics are optimized to provide the designer with a well-defined level of reliability for the component throughout the design lifetime of the circuit [l-5]. Fig. 1 shows a number of the more important technical factors that influence the capacitor designer's choice of geometry, connections, and materials [3, 5, 6]. The selection of a capacitor design requires matching available capacitor characteristics and parameters to the application needs. In addition to the basic capacitance value and voltage rating, specifying all the characteristics allows the supplier to provide the most cost-effective capacitor for the given application.

The fundamental design parameters are controlled to a large degree by environmental factors, such as temperature range, voltage, wave-shape, pulse repetition rate (rep-rate) and duty cycle. Essentially all these environmental factors affect the life expectancy of the capacitor, as shown schematically in Fig. 1 [2-14].

### RECENT ADVANCES IN POLYMER LAMINATE ENERGY STORAGE CAPACITOR TECHNOLOGY

This preliminary study of polymer laminate structures reports on the ageing issues related to the performance of large, cost-effective, high energy density, multi-kilojoule energy storage capacitors that have recently been developed for high-energy pulsed power conditioning applications. In this work, a new class of graceful-aging capacitors has been developed primarily for energy discharge applications, such as electrically energized lasers, electromagnetic guns and launchers, and dc power distribution bus filtering. In such systems the energy is either released from the capacitor in times ranging from tens of microseconds to milliseconds, or the AC ripple components in filtering operations are at frequencies up to a few tens of kilohertz.


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The performance, reliability, and operational constraints of the capacitors are discussed and information is presented concerning the effects of various parameters on the life of the capacitor.

## BACKGROUND

The need for graceful-aging, polymer-laminate pulsed capacitors that deliver energy over time periods of sub-milliseconds through near DC, as opposed to microseconds or less, for numerous power electronics applications has spurred the development of large metallized electrode-pulsed capacitors. These capacitors differ radically in several significant ways from capacitors that use discrete aluminum foil electrodes. The information offered here is drawn from applied research that has been successfully undertaken by the authors over the past decade, primarily at Aerovox., on polymer laminates that comprise new types of large metallized pulsed energy discharge capacitors in the voltage range of 2 kV to 22 kV up to 100 kJ, with volumetric energy densities increasing up to nominally 20 Joules per cubic inch or 2.5 $MJ/m^3$.

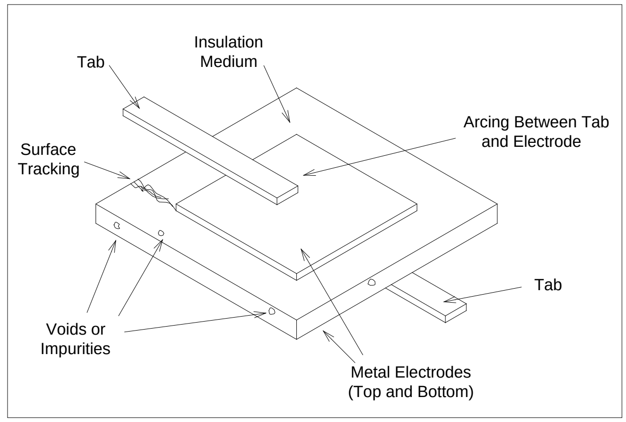


**Fig.1. Illustrates schematically a number of the more important technical design factors influencing the capacitor designer's choice of geometry, connections, and materials.**

## DESIGN LIFE CHARACTERISTICS

This new class of graceful-aging energy discharge capacitors is technologically founded on the factors summarized below:

The fractional area less per unit DC on-time (often referred to as the time held at full charge voltage, before energy discharge takes place) for small area laminates is nearly constant [15-20]. In addition, this has been shown to scale to very large areas, as found in multikilojoule energy storage capacitors; furthermore, the fractional capacitance loss per DCC on-time or number of charge-discharge cycles is constant to within very small bounds [21, 22].

The question of the aging rate is a matter of discussion, and work by MacDonald et al. clearly shows the importance of conductivity in impregnants as a control of clearing rates [23].

The model developed shows that the breakdown voltage and time-to-breakdown is a function of:

- Temperature
- Solution pH
- Anion activity
- Applied voltage

The following observations can be made [23]:

1. For cases of interest to designers of high power electronics systems, all the voltage is likely applied across the film because of the rapid charge injection into the impregnant, whose conductivity is always significantly higher than that of the insulating polymeric film [24].
2. For high voltage situations, as the voltage is applied to the laminate structure, several breakdown sites can arise initially in a few seconds; however, continued growth in sites depends upon the total time of the application of voltage and voltage fraction division across the insulating film and the semi-conductive fluid [23]. Now if most of the voltage is not dropped across the film/solution interface as is generally the case, a unity growth rate of breakdown sites per second is assured.
3. The distribution of the times-to breakdown is very sensitive to the conductivity of the fluid. The positive results obtained through the introduction of low concentrations of conductive dopants into impregnants, well-known to the power transformer industry for many years as stabilizers, are consistent with the fundamental observations made in the MacDonald study [23].

## OBSERVATION ON NEW TECHNOLOGIES FOR GRACEFUL-AGING ENERGY STORAGE CAPACITORS

Capacitor dielectrics for wound capacitors are thin, ranging from a few microns to a few hundred microns. In a large capacitor, this translates to a very large surface area. One major drawback of foil electrode capacitors is that the capacitor will have failed if any part of the dielectric breaks down. When a foil capacitor suffers a dielectric breakdown, the electrodes become connected through a low impedance connection at the point where the fault occurred. At this point, the part of the capacitor where the fault occurred is normally a short circuit and is unable to accept a charge. In a multi-series section capacitor, the shorting of one of the series sections will result in the remaining sections operating at a higher stress.

This problem does not exist for self-healing, metallized electrode capacitors. With a self-clearing electrode, a fault in the dielectric will result in the thin metallized electrode in the immediate area of the fault being vaporized or turned from a metal conductor into a metal oxide insulator [24-33]. Because of this, these capacitors can be designed to operate at the average breakdown strength of the insulating dielectric, rather than at the minimum breakdown strength, as is required with foil capacitors [23].

Large capacitors with self clearing electrodes survive dielectric faults that number in the hundreds of thousands with the only visible evidence being a small loss of capacitance [30].

## METALLIZED POLYMER FILM CAPACITORS

Fig. 2 is a typical metallized polypropylene capacitor winding cross-section after a "clearing" event has taken place. The capacitor's electrode is deposited on the dielectric prior to winding the capacitor. The electrode is extremely thin.  In order to get any significant current out of a capacitor, an electrical connection must be made to the entire edge of the electrode. This area is identified as the end connection in the figures.  Here, the edge of the electrode is connected to the "end spray." In order to make sure that there is a significant amount of electrode is exposed to the "endspray," the end of the electrode is offset. This offset is referred to as the "stagger" in the winding.

When the electrode is deposited on the dielectric, there is one area that is left unmetallized. This insulating area is identified in Fig. 2 as the "margin." This is done so that neither electrode will touch both end-sprayed areas of the capacitor, shorting out the windings. One electrode is connected to one side and the other electrode will connect to the opposite "end spray."

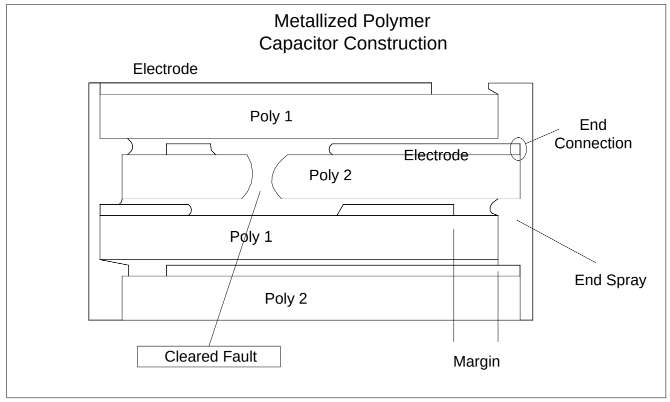


**Fig. 2. Typical metallized polypropylene capacitor winding cross-section after a “clearing” event has taken place.  The capacitor's electrode is deposited on the dielectric prior to winding the capacitor and the current-carrying electrodes are explicitly made extremely thin in order to enhance the clearing process both locally and throughout the capacitor.**

## THE "SELF-CLEARING" PROCESS - GRACEFUL AGING

If a fault should occur in the dielectric, current will flow from one end-sprayed connection, through one electrode, through the fault, out the opposite electrode and to the opposite end-sprayed termination. The current in the area of the fault will attempt to go through a metal conductor so thin that it is optically translucent. The amount of current that can go through this thin electrode is very limited. The electrode in the immediate area of the fault will be blown away, acting much like a fuse, and the current will be safely interrupted. Once the fault has been cleared, as shown in Fig. 2, the capacitor will continue to function, with the only measurable damage being a small loss of capacitance.

Metallized electrode capacitors have proved to be extremely consistent capacitors that can be designed at high energy densities, for cyclelives up to 50,000 shots, without running into the infantile failure mode problem that has plagued solid aluminum foil capacitors. These new capacitors are designed to age gracefully, having no observed single point of failure, coupled with a known, predictable aging rate.

When a fault occurs in such a capacitor, the electrode is cleared away through vaporization or oxidation before any significant current can flow into the fault site. This characteristic allows the capacitors to go through tens of thousands of cycles before the capacitor capacitance is substantially reduced (say, by 5% or so). Capacitor performance assessments for two commercially available classes of high energy density metallized film capacitors show that the maximum volumetric energy densities currently practical are close to 2.5 megajoules per cubic meter [21].

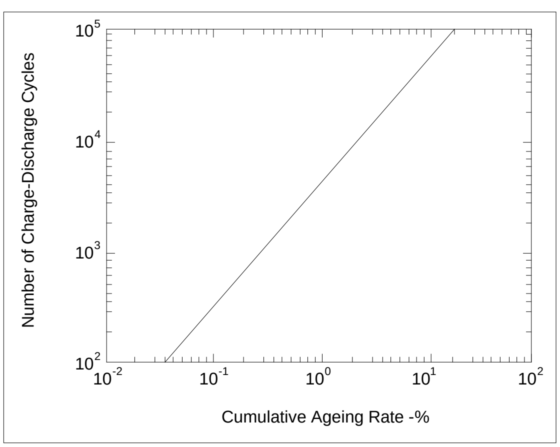


**Fig. 3. Cumulative ageing rate of capacitance reduction for multi-kilojoule class metallized capacitors as a function of the number of charge-discharge cycles.**

This is the first time that energy discharge capacitor technology capable of graceful aging has been demonstrated at these energy levels. The aging mode of these new capacitors is one of a slow decrease in capacitance due to the clearings that are occurring within the capacitor, resulting in a decreased metallic electrode area and hence a decline in capacitance. After the capacitor loses about 5% of its capacitance, the loss of capacitance-per-shot accelerates. Also, at between 5 to 10% loss in capacitance, sufficient gas (generated by the clearings) normally will have accumulated inside the case so as to make case swelling noticeable. For this reason, a 5% capacitance loss has been chosen as the normal end of design life for this class of capacitor.

A Weibull hazard analysis was undertaken in this work on test data from 162 high energy density metallized electrode capacitors after an accumulation of 1,133,421 shots. The ageing rate to this 5% total capacitance loss point averaged a <2.5 x $10^{7}$ fractional change in capacitance, $\Delta C/C$, per charge-discharge cycle, with a coefficient of fit of 0.9666. The data support the observation of very few infantile failures, along with an extremely predictable graceful ageing rate for this technology.

Fig. 3 illustrates the cumulative ageing rate of capacitance reduction for multikilojoule class metallized capacitors as a function of the number of charge-discharge cycles. The rate is quite small up through 1,000 cycles, with a


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rapid reduction in capacitance by about 10% per shot at 100,000 shots; more recent designs show a 0.16% loss per 1,000 shots.

## THE EFFECT OF STRESS VARIATIONS ON PERFORMANCE

The relationship between life/aging rate and the dielectric in a capacitor is usually expressed in terms of a power law where the change in life will be equal to the inverse of the change in stress raised to some power. In the case of these new types of capacitors, test data show a 15th power ageing rate dependence upon the ratio of charging voltage to the single shot voltage (i.e., the single shot voltage is the charging voltage at which only one useful energy discharge pulse is obtained from the capacitor).

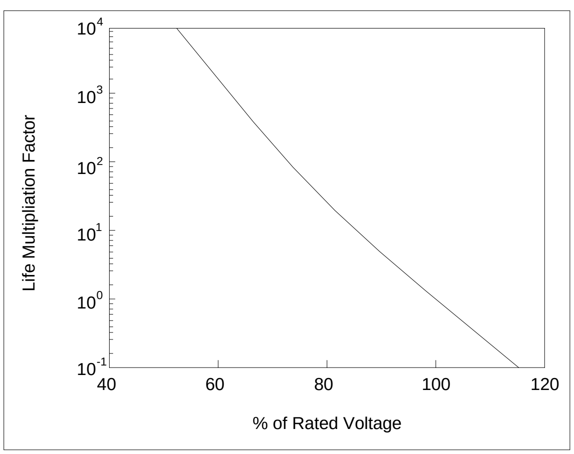


Fig. 4 Life multiplication factor as a percent of rated dc voltage

This is a very steep dependence compared with prior energy discharge capacitor technologies, resulting in negligible infant mortality, as well as allowing operation very close to the single cycle-life voltage, while preserving reasonable ageing rates at high reliabilities. Fig. 4 illustrates the life multiplication factor as a percent of rated dc voltage, clearly showing the drastic reductions to be anticipated in operating this class of capacitor even slightly over the design rating. The "rated dc voltage" is the dc sustaining voltage that yields the manufacturer's design life for the capacitors, generally at a nominal temperature of 20°C. This happens because with metallization, defects are being continuously cleared during actual operation. This all takes place during operation at nearly the intrinsic withstand voltage of the thin insulating films that are actually storing the desired electrostatic energy [19-21].

Operating the capacitors below 80% of rated voltage results in very long cycle-life, dominated by thermal ageing – a predictable effect. Low level testing of equipment can be done for extended periods of time with minimal, if any; consumption of life of the capacitors [21, 22].

## PEAK CURRENT ISSUES

The peak current capability of a typical 1995 design, 16 kV; 50 kJ, 0.7 J/g, 10,000 shot life energy discharge capacitor is:

- Design peak current: 40,000 amps
- Design limit for full life operation: 100,000 amps
- Fault capacity with minor degradation : 200,000 amps

Crowbarring this capacitor with a peak current in excess of 400,000 amps will cause the type of damage described in the above paragraph. A 200,000 amp discharge will normally result in a measurable, but slight, degradation. The capacitor will perform to specifications if the peak current is kept below 40,000 amps.

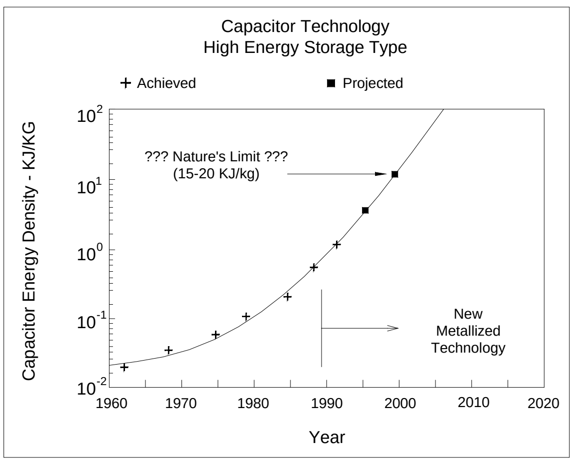


**Fig. 5 shows the timeline of increasing energy density in energy discharge capacitors starting from the early 1960s.**

## THE FUTURE

Fig. 5 shows the timeline of increasing energy density in energy discharge capacitors, starting from the early 1960s [23-25]. Metallized technology capacitors from U.S. industry have been in the field for several years, at energy densities of 0.5 - 1.5 KJ/Kg [21, 25].

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