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Capacitors for the Pulsed Power Industry

INTRODUCTION

There are many different types of capacitors available today. Most capacitors produced are designed for mounting on circuit boards or other electronic equipment and are referred to as tantalum, electrolytic or DC film capacitors. Larger capacitors are used in applications such as AC drives and power conditioning equipment. The larger, higher voltage capacitors for 60 Hz circuits have traditionally been manufactured with paper, polypropylene or some combination thereof, with or without a liquid impregnant. Progress has been made in all these fields over the past decade. This paper is focused on defining the state-of-the-art for large (over 5 kg) capacitors for pulsed power applications.

Capacitors for use in pulsed discharge circuits can be divided into two broad categories. The first category is capacitors that use thin (5.5 µm) aluminum foil electrodes to conduct current through the capacitors, as shown in Figure 1. The second category is capacitors that have metallized electrodes in which the electrode is vapor deposited on a dielectric. The electrodes are typically aluminum or zinc with a thickness around 300 Å (.0003 µm). They are deposited on the capacitor dielectric prior to winding the capacitor as shown in Figure 5.

FOIL CAPACITOR CONSTRUCTION TECHNIQUES

There are numerous variations on the construction of wound capacitors. All have three basic common components: (1) a solid dielectric material, (2) a set of electrodes, and (3) a fluid between the wound layers.

SOLID DIELECTRICS

Over the past decade, there have been two major solid dielectric materials used for pulsed power capacitors. These have been kraft paper and polypropylene. In recent years, polypropylene has been used more than kraft paper for pulsed applications. Other polymers such as PET (Mylar®) and polyvinylidene fluoride (PVDF) have been used but to a lesser extent, and, with the exception of PVDF, will not be discussed here.

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ELECTRODE TYPE

The electrode for foil capacitors are usually aluminum foil that is 0.22 mils (5.5 µm) thick. Other thickness that have been used include 0.18 mil and 0.32 mil. The electrode is dead soft electrical grade aluminum.

FLUID DIELECTRICS

To achieve the best use of the dielectric material, it is necessary in a high voltage capacitor to replace the air spaces between layers of wound dielectric and electrode with a dielectric fluid. The addition of the fluid is done to decrease the stress across the space between the solids and increase the breakdown strength of this space. While there are many liquid and gaseous dielectric fluids to choose from, they all have two things in common. First, they all have a higher dielectric constant than the air that they replace. Secondly, they have a higher dielectric with-stand voltage than air. Common liquids used in pulse power applications include both naturally occurring substances such as mineral oil or vegetable oils like castor oil; as well as synthetics like DOP, polybutene, DINP, DINA, MIPB, and PXE. Some gasses such as SF6 and N2 are also used.

TYPICAL CAPACITOR WINDINGS

Figures 1 and 2 are typical capacitors and illustrate the way the solid dielectrics and electrodes are wound together to form a capacitor.

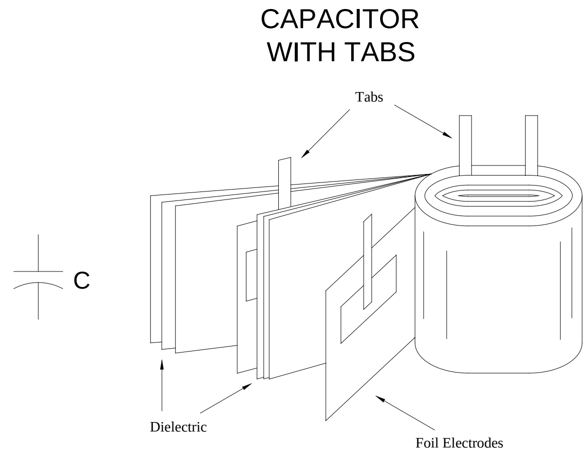

Figure 1

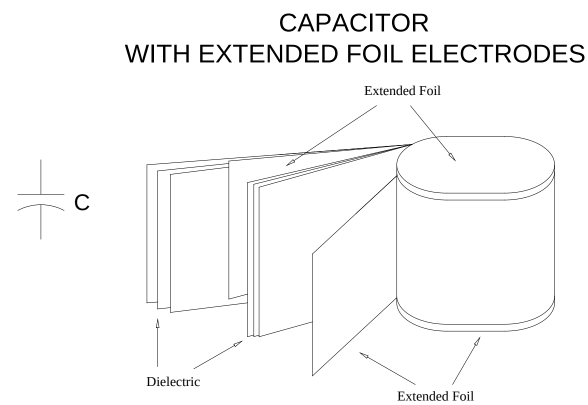

Figure 2

Both figures show the use of foil electrode. In both Figures 1 and 2, the two electrodes or plates of the capacitor can easily be identified. There are two layers of dielectric material. One is obviously between the two electrodes. If the electrode closest to the winding was extended for another turn, it becomes obvious that the second layer of the dielectric is also between the electrodes. This type of winding with two sets of electrodes and two sets of dielectric wound in a convoluted manner is common to all wound capacitors.

The difference between Figure 1 and Figure 2 is the way that the foil is connected to the outside world. In the case of Figure 1, tabs are used to make a connection to the electrode. The tabs connected to one electrode will be grouped together and connected to the terminal of the capacitor. This is commonly called "tab construction" and has the advantage of being inexpensive to assemble and the electrodes can be divided up so that several capacitors can be manufactured in one winding.

Figure 2 is a capacitor winding with one foil extended out the top of the winding and the other foil extended out the bottom.

This is commonly referred to as "extended foil construction". The connection to the outside world is often made by soldering tabs to the electrode. A second method of making a connection to this type of capacitor is to spray the extended foil with a molten metal. This operation is commonly referred to as "endspray".

Once this is completed, a tab is soldered to the endspray. The advantage of the extended foil construction is that it has a higher current carrying capability and is normally used in high current pulsed power applications.

In the capacitors of Figure 1 and 2, the operating voltage can be increased by increasing the thickness of the dielectric used. There is a practical limit to how high in voltage a single section can go. As the voltage increases, the field between the electrodes increases causing high areas of stress concentration particularly at the edges of the electrode. Adding thickness to the dielectric pass this particular point will not result in an increase in voltage breakdown that is adequate to justify the additional dielectric. While this practical limit varies with capacitor design and application, it is usually below 12,000 volts for pulsed power applications.

HIGH VOLTAGE CAPACITOR
WITH FOIL ELECTRODES

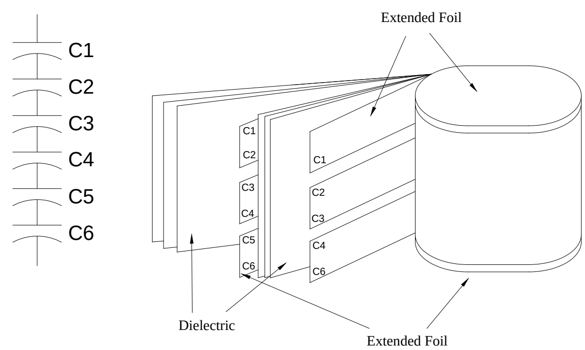

Figure 3

High voltage capacitors can be constructed with the type of windings shown in Figure 1 or 2 connected in series. A more common construction for high voltage capacitors used in pulsed discharge circuits is shown in Figure 3. Here six series capacitor elements are manufactured in each winding. The winding can operate comfortably at 60 kV. On a typical 120 kV capacitor, there would be two sets of such windings in series as shown in Figure 4.

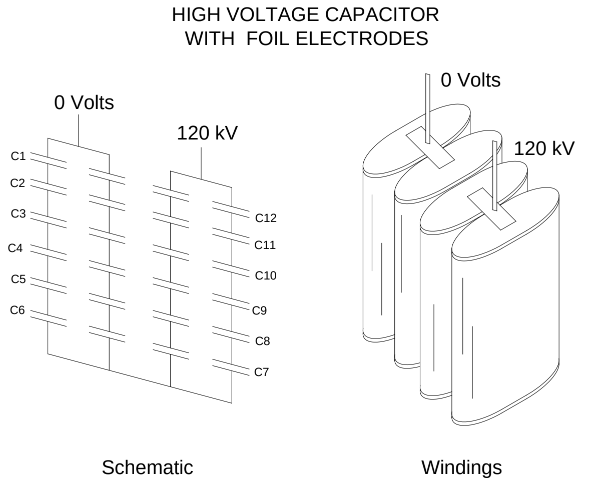

Figure 4

PAPER & FOIL CAPACITORS

Paper/foil capacitors have been manufactured for pulsed discharge applications for most of this century. The construction is simple with aluminum foil electrodes separating the kraft tissue. During the manufacturing process, the capacitors are heated under vacuum to remove the water in the paper, about 5% by weight. Then, while still under vacuum, a liquid dielectric is introduced. The kraft tissue easily absorbs the dielectric.

Over the years, the processing of the kraft tissue was improved to decrease defects and increase the density of the tissue. The high point for this construction was in the mid 1980's when the first 50 kilo Joule (kJ) capacitors were built. These capacitors were fairly large (12" x 16" x 27") and had an energy density of about 0.4 Joules/gram (J/g). The achievement was impressive at the time.

The paper/foil capacitors have some drawbacks. The kraft tissue, as good as it was, always had defects. If a capacitor is built with one or two layers of kraft and run at high energy densities, the reliability of the capacitor is relatively poor. If one of two layers has a conductive path through the paper at high stress, the remaining layer would have to withstand twice normal voltage. As a result, reliable, low voltage (<2,000 Volts), high energy density, capacitors did not exist using this technology. The reliability was much better at higher voltages when 5 or 7 layers of tissue could be used.

PAPER, POLYPROPYLENE & FOIL CAPACITORS

The use of Polypropylene as part of the dielectric system is widely used in the industry. This dielectric system gained popularity for several reasons. It could be made in thinner thicknesses than kraft, it had fewer defects, the dielectric losses are better and the polypropylene has the inherent ability to store more energy than kraft.

For very high repetition rates, capacitors with only polypropylene are used with no paper as the solid dielectric. These "all film" capacitors are commonly found where the pulse rate is in the kHz range. Typically rep-rate applications require that the capacitors operate for life times

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in the millions of charge/discharge cycles. To accomplish this, the capacitors are run at relatively low energy densities.

METALLIZED ELECTRODE 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 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 to a metal oxide insulator. Because of this, the capacitors can be designed to operate at the average break-down strength rather than the minimum breakdown strength as required with foil capacitors. Large capacitors with self clearing electrodes survive dielectric faults that number in the hundreds of thousands with the only visible evidence of this being a small loss of capacitance.

METALLIZED POLYMER CAPACITORS

Figure 5 is a typical metallized polypropylene capacitor winding. The capacitor's electrode is deposited on the dielectric prior to winding the capacitor. Inside the capacitor, the various components are arranged as shown in Figure 6. The metal electrode is deposited on the dielectric as shown. 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 endspray. In order to make sure that there is a significant amount of electrode exposed to the endspray, the end of the electrode is offset so that the electrode is exposed to the endspray. 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 is identified in the figures as the margin. This is done so that neither electrode will touch both endsprayed areas of the capacitor. One electrode is connected to one side and the other electrode is connected to the opposite endspray.

METALLIZED POLYMER
CAPACITOR CONSTRUCTION

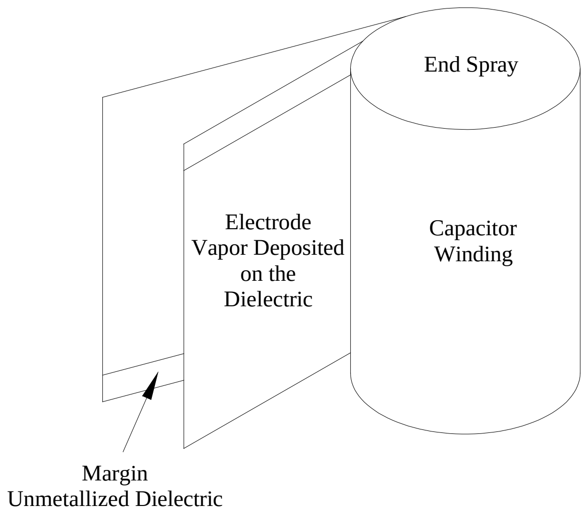

Figure 5

Metallized Polymer
Capacitor Construction

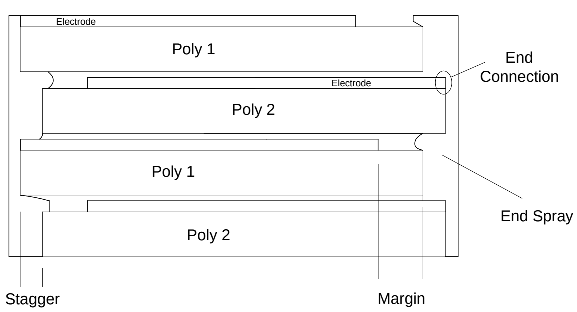

Figure 6

SELF CLEARING PROCESS

If a fault should occur in the dielectric as shown in Figure 7, 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 be attempting to go through a metal conductor that is so thin it is 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 interrupted. Once the fault has been cleared, as shown in Figure 8, the capacitor will continue to function with the only measurable damage being a small loss of capacitance.

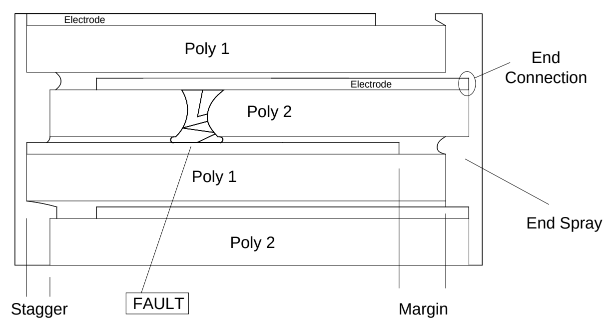

Figure 7

Metallized Polymer
Capacitor Construction

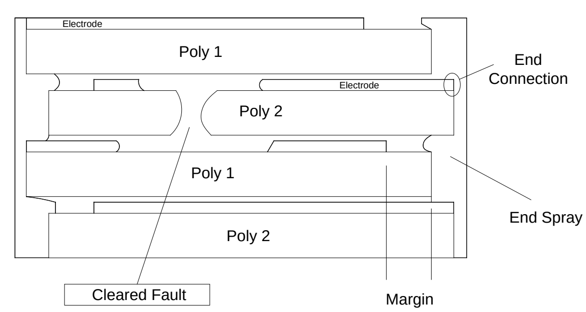

Figure 8

OTHER METALLIZED ELECTRODE CONSTRUCTIONS

The construction shown in Figures 5 through 8 is common for most self clearing metallized polymer capacitors. There are a number of variations on the theme that allow the use of metallized electrode capacitors at higher currents and higher voltages. Figure 9 is a metallized electrode capacitor where the electrode is deposited on a separate insulating medium that is not part of the dielectric. If the electrode substrate is paper, the dielectric Polypropylene and the capacitor is impregnated with a liquid, this would be called a "soggy foil” capacitor.

This capacitor has the advantage of being able to operate at higher currents than the capacitor described above. Notice that there are two separate metallized electrodes for each layer of dielectric as opposed to one in the capacitor as shown in Figure 6. This results in twice as much electrode involved in the end connection and twice the current carrying capability. Also, since the electrode is not deposited on the dielectric, the energy associated with the clearing generally does less damage to the dielectric.

DOUBLE METALLIZED KRAFT
(SOGGY FOIL)
CAPACITOR CONSTRUCTION

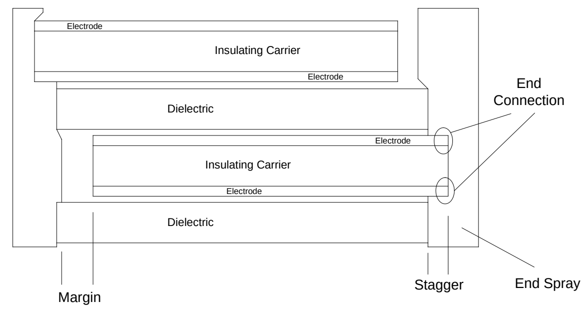

Figure 9

Another variation on the theme is shown in Figure10. Here one of the double metallized electrodes of Figure 9 has been replaced with a layer of aluminum foil. This hybrid design was developed after the soggy foil capacitors were introduced by Aerovox® as the Aerofoil® capacitor product line in 1979. This capacitor has a number of advantages over the capacitor of Figure 9 in that the aluminum foil is capable of removing heat from the center of the section. This feature allows the capacitor to operate at high RMS current levels.

DOUBLE METALLIZED KRAFT
(AeroFoil°)
CAPACITOR CONSTRUCTION

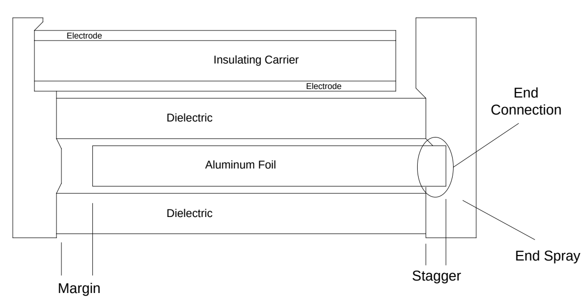

Figure 10

Since the capacitor of Figure 10 has a foil electrode like the capacitor of Figure 1, it is possible to divide the foil up and use tabs to make connections to the outside world. This allows for the construction of several capacitors in one winding with one electrically common point. The common point is the endspray that is connected to the double metallized electrode.

THE IMPORTANCE OF THE SOFT FAILURE MODE

The “soft failure mode” is defined as a capacitor that reaches end of life with only the controlled loss of capacitance. There are several mechanisms in a metallized capacitor that can result in capacitance loss but the typical dielectric puncture and resultant clearing as shown in Figures 6, 7, and 8 is the most common. The tracking of the loss of capacitance is one method of evaluating the health of the capacitor. As a self clearing metallized electrode capacitor approaches end of life, gas will start to accumulate in the capacitor and the rate at which the capacitor is losing capacitance will increase. Failure due to this mechanism is usually defined as the loss of a certain percentage of the initial capacitance. Typically, this has been set at 5% of initial capacitance. At the point picked, there should be no free gas in the capacitor that would cause a secondary fault that would result in an endspray to endspray type flash over.

The soft failure that self clearing capacitors see at end of life is the slow loss of capacitance. The capacitance loss slowly approaches the number that has been defined as a failure. If the capacitor happens to go a little over the capacitance loss number, nothing drastic will happen as is demonstrated by Figure 12. As long as the capacitor is operating in the self clearing range it is much safer to operate than their predecessors. A number of large banks of capacitors with self clearing capacitors [8], [9], [10], [11] are operating in the field. These banks have demonstrated that the probability of having a violent failure is significantly less for this type of capacitor than for banks with an equivalent foil electrode capacitor.

The fact that the loss of capacitance can be monitored as a means of evaluating the condition of the capacitor and the maintenance of the equipment can be scheduled, rather than driven as unscheduled events due to capacitor failures. Self clearing capacitors reaching end of life can be identified and properly addressed before the failure reaches the catastrophic stage. The cost of a capacitor failure in a small system is significant. The cost of a failure in a large system is massive. In 1991, B. T. Merritt and K. Whitham [1] estimated the cost of a failure on the 25 MJ Nova-1 system to be $10,000 per capacitor failure. This estimate included not just the capacitor replacement but the cost of down time and equipment repair due to collateral damage. While the cost of repair has probably doubled since then, the fact remains that violent capacitor failures are costly. With the soft failure mode of the self clearing capacitors, the unscheduled down time and collateral damage is avoided.

WHEN METALLIZED CAPACITORS ARE NOT SELF CLEARING

Not all metallized electrode capacitors are self clearing. Some metallized electrode capacitor designs have proven to be unacceptable in some applications. Failure modes occur due to design deficiencies that result in a capacitor that will not perform properly in a particular application. No metallized electrode capacitors will maintain the ability to remain self clearing under all situations. At some combination of temperature, voltage, shot history and duty, the capacitor fails to clear properly. For the capacitor to maintain the soft failure mode throughout its life, it must be properly designed for the application. A poor design or the misapplication of the capacitor can result in the same type of failures seen in foil capacitors.

It is important to avoid secondary faults within the capacitor that would circumvent the self clearing mechanism. A secondary fault is one that occurs inside the capacitor but does not include self clearing mechanism. A flash over of the terminals inside the capacitor case would constitute such a fault. This is a design, application, and operating procedural issue. A poor design, a misapplication or operating the capacitor beyond the design limits could cause this problem to occur. It there is any question about the suitability of the design for a particular application, testing of the capacitor under the specific conditions of interest is recommended.

THE ABILITY TO SCALE RESULTS

The collection of performance data on self clearing capacitors is significantly easier than for foil capacitors. With foil capacitors the test is normally terminated when a dielectric break takes place and the capacitor is no longer functional. One sample yields one data point. If a minimum of 5 data points are needed before the results are considered significant, and there are 4 test conditions to be checked, it will take 20 foil capacitors to yield the data needed for a low confidence level evaluation.

An example of small scale results defining the performance of full sized capacitors is shown in Figures 11 and 12. The conditions under which data were taken are described in detail in Reference [8].

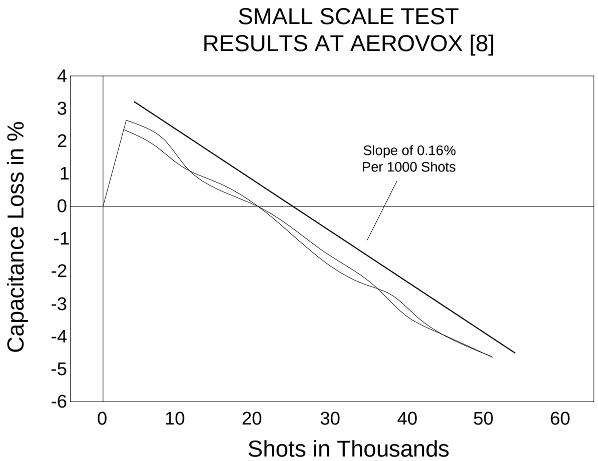

Figure 11

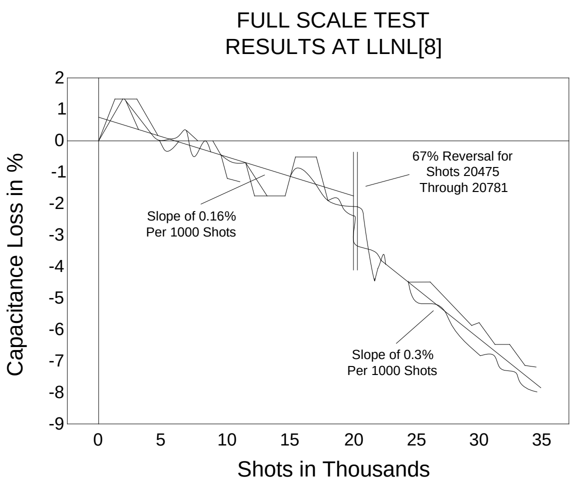

Figure 12

Superimposed over the data is a line that is sloped at 0.16%/1000 shots. The slope of the small work that was done about a year before the full scale capacitors were built shows a slope identical to the full sized capacitor testing.

With a self clearing capacitor, one small scale capacitor can be tested under a number of different conditions. Thousands of breakdowns could be recorded at each test condition before the capacitor will have reached end of life.

Since the loss of capacitance is closely related to the number of breakdowns, the rate of capacitance loss under different test conditions can be observed and used to predict the performance of the capacitor under the test conditions of concern.

This ability to monitor many breakdowns in one sample, accounts for the ease at which small scale results translate to full sized capacitor tests. Granted, testing one capacitor does not account for variations in manufacturing or base materials but it does provide significant data on a capacitor built as the sample was built. The argument can be made that tracking the capacitance loss is equivalent to tracking thousands of dielectric breakdowns in small capacitors. In large capacitors it represents tracking hundreds of thousands of dielectric breakdowns. The difference in the levels of confidence gained from plotting thousands of data points vs. hundreds of thousands of data points is small.

An important factor in the ability to scale is the ease of testing. The test equipment, power, people and time requirements, all are drastically reduced. Small scale capacitor testing done for 10,000 shot requirement can usually be completed in four or five days.

The data in Figure 12 demonstrate another point. The capacitor is run through a series of fault tests and after this has lost about 5% of the initial capacitance. As would be expected, the rate of capacitance loss increased as the capacitor approached the end of life. In this case, the rate of capacitance loss had doubled from 0.16% to 0.3% per 1000 shots. The capacitor passed the 5% capacitance loss mark and continued on for another 10,000 shots still failing in a graceful manner.

THE LIMITING FACTOR FOR METALLIZED ELECTRODE CAPACITORS

There is one significant drawback to the metallized electrode capacitors. The peak current that they can handle is less than an equivalent extended foil capacitor. This is driven by two factors. First, the electrode of a metallized electrode capacitor is about 1/1,000 the thickness of a foil capacitor and does not have the ability to carry like a foil capacitor electrode. Secondly, the capacitors are usually about 1/2 the size of an equivalent foil capacitor resulting in higher internal concentrations of current.

The early metallized electrode capacitors built in 1990 had a significant current limitation [4]. As the capacitors evolved, the current output capability increased by a factor of two by 1993 when the Beamlet bank was built [8]. The current output doubled again by 1995 when the Feuerstellung 2000 bank was built [9]. For pulsed power applications, the current limitation of metallized capacitors is a practical design limit rather than an absolute number expressed in terms of peak current, dv/dt or I2t. At some point, it becomes less expensive to use an extended foil capacitor when dealing with high currents. That point keeps moving in a direction that favors metallized electrode capacitors.

When defining current requirements for pulsed discharge capacitors, it is necessary to consider both the normal and fault conditions. If the fault current can be limited to about 10% of the shots and 3 times the normal peak current, the normal conditions will drive the capacitor design.

In most applications, the benefits of using metallized electrodes in pulse discharge applications far outweigh the current penalty. Because of this, metallized electrode capacitors are replacing the foil capacitors as the design of choice for most applications.

FIELD EXPERIENCE WITH METALLIZED ELECTRODE PULSED POWER CAPACITOR BANKS

Over the past 5 years, there have been a number of large metallized electrode capacitors built, deployed, and operated. Large banks of metallized electrodecapacitors have been built with Aerovox® type KM capacitors and Aerovox® type LM capacitors. Both types of capacitors have been used in high energy density experimental weapon systems. As a result, there are some restrictions on what can be said about theinternal make up of the capacitors. It can be said that both types of capacitors are built with self clearing metallized electrodes and have demonstrated a soft failure mode. Also, the major energy storage media in the type KM capacitors is polypropylene while it is PVDF in the type LM capacitors.

A summary of the references is offered in Table 1. The list of references has information on the performance of some of the successfully deployed metallized electrode capacitor banks.

Table 1

METALLIZED ELECTRODE CAPACITOR BANKS DEPLOYED IN PULSED POWER APPLICATIONS							
Item	Bank Size MJ	Capacitor					
		Size kJ	Rated kV	M Joules/ Cu. Meter	Type	Description/ Operator	Ref. No.
1	10	50	16	0.77	KM	*FMC now Defense Research	[4]
2	1	52	44	0.71	KM	TZN	[7]
3	13.5	52	22	0.90	KM	Beamlet/LLNL	[8]
4	30	67	22	0.86	KM	Feuerstellung 2000/ TZN-Rhelnmetal	[9]
5	8.5	85	16	2.40	LM	Transportable/ ARL – NSWC	[10]
* The capacitor described in the paper was used in the bank							

CAPACITOR PERFORMANCE

Capacitor performance can be evaluated many different ways. Here an effort is made to evaluate the comparative performance of four types of oil impregnated capacitors under common pulsed power conditions. The types of capacitors that will be addressed have a solid dielectric made up of:

Kraft (Kr) + Foil Electrodes
Kraft + Polypropylene (PP) + Foil Electrodes
Polypropylene + Metallized Electrodes
(Aerovox Type KM)
PVDF + Metallized Electrodes
(Aerovox Type LM)

APPLICATION RANGE

The application range for the capacitors is defined by the factors that drive the capacitor design decisions. One of these is operation voltage. For high voltage applications where the operating voltage is over 50,000 volts, only the foil electrode capacitors have demonstrated their capability to perform reliably [3].

Evaluating the ampere limits for capacitors is an interesting task. For non-continuous pulsed discharge applications, where the expected life is less than 20,000 shots, the pulse width is a good indicator. Current concentration inside the capacitor goes up when the pulse width goes down. The foil electrode capacitors are usually chosen when the pulse width is less than 20 μsec long.

For rep-rate applications, the internal heating of the capacitor becomes critical. If the capacitor becomes thermally unstable, it will fail very early. From a heat dissipation standpoint, the KR+ PP + Foil capacitors perform the best. The higher the ratio of PP to KR, the lower the dielectric losses. The lowest loss capacitors use no KR in the dielectric system. A second choice for rep-rare applications is the PP + metallized electrode capacitor. The losses are low and the capacitors often significantly smaller. Metallized capacitor designs have been specifically for use in this application [5].

When energy density is the only consideration, the PVDF + Metallized electrode capacitor provide the smallest package with an energy density of 2.4 J/cc. Unfortunately, this is an expensive capacitor to build with high internal losses and nonlinear operation. A good second choice here is the PP + metallized electrode capacitors with 1 J/cc.

Operating temperature is another consideration. From the choices in the list, the Kr + PP + Foil capacitors are normally chosen. In some cases, high temperature films are used instead of polypropylene.

LIFE EXPECTANCY VS OPERATING VOLTAGE

One major factor in the life of a pulsed power capacitor is the operating voltage. Here the performance is usually described in terms of a power law where:

Life at V2 = (Life at V1) x (V1/V2)n.

Where V2 is the operating voltage of interest and V1 is the operating voltage where the life characteristics are known. In this formula "n" represents the power law that has been established for that particular capacitor. The power laws that are used to describe this relationship have been empirically determined over the years. The power laws attributed to the systems under discussion here are:

n = 5th for Kr + Foil Electrodes,

7th to 9th for Kr+PP+Foil Electrodes,

15th for PP + Metallized Electrodes,

15th for PVDF + Metallized Electrodes,

For a capacitor to follow the particular power rule, it is necessary that the capacitor continue to operate in the same failure mode. As voltage is increased on a capacitor, new failure modes are introduced and the power rule increases. Likewise the 15th power rule assigned to highly stressed metallized electrode capacitors may not hold true at very low voltage. The relationship between stress and volume for a capacitor of a given energy level is approximately:

$Volume_2 = Volume_1 *(Stress2/Stress1)^2$

Since the cost of building capacitors is directly related to the size or volume of the capacitor, this relationship can be expanded to evaluate the relationship between capacitor cost and life expectancy. A capacitor that follows the 15th power of stress vs. life would be following the 15/2 or 7.5 power of size vs. life. This would mean that for approximately 10% more money the life of a capacitor that follows the 15th power could be doubled.

LIFE vs. VOLTAGE STRESS
FOR CAPACITORS

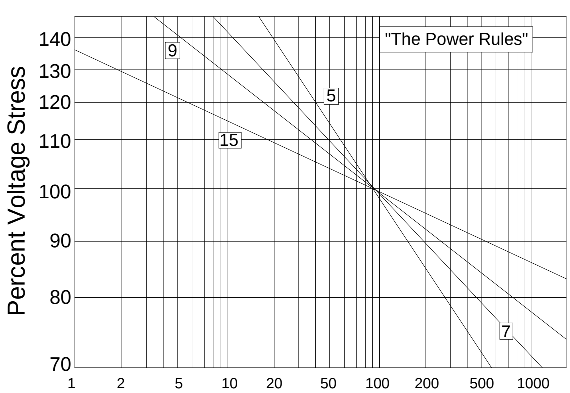

Figure 13

VOLTAGE REVERSAL AND LIFE

The effect of voltage reversal on life has been studied on the four types of capacitors under discussion. For three out of the four, the relationship seems to be about the same. As the voltage reversal is increased above a certain point, the life of the capacitor starts to decrease. The relationship is graphically displayed on the semi-log chart of Figure 14.

The effect of voltage reversal on pulsed discharge capacitors is small below 20%, although some capacitors have been proven to be sensitive to reversals as low as 10%. The reversal of voltage in a capacitor is a voltage stress mechanism. Like voltage stress, it drives different failure modes. When a capacitor enters or leaves a particular failure mode regime, the rate of change in life with respect to voltage reversal changes. Because of this, the voltage reversal chart of Figure 14 shows a wide path over which the expected results will vary.

VOLTAGE REVERSAL
EFFECT ON CAPACITOR LIFE

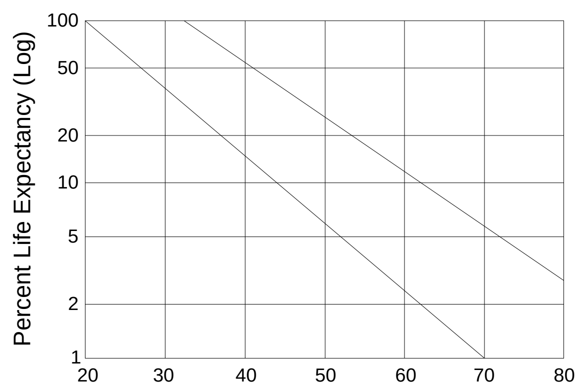

Figure 14

One of the four capacitors under discussion does not follow the voltage reversal criteria of Figure 14. This is the PVDF capacitor with metallized electrodes. Here, the nonlinear characteristics of the capacitor control the circuit. During the first charge cycle, these capacitors tend to absorb a significant amount of energy [10]. The amount of energy absorbed on subsequent cycles decreases. During a fault discharge into a high reversal circuit, the energy stored during the charge cycle must be over-come. This results in the behavior shown in Figure 15. For circuits where the expected re-versal is less than 30%, there is no reversal at all. On circuits were there is 90% reversal ex-pected, the voltage reversal is limited to 30%. Also it has been determined that the life of the capacitor is little effected by being discharged into any high reversal circuit.

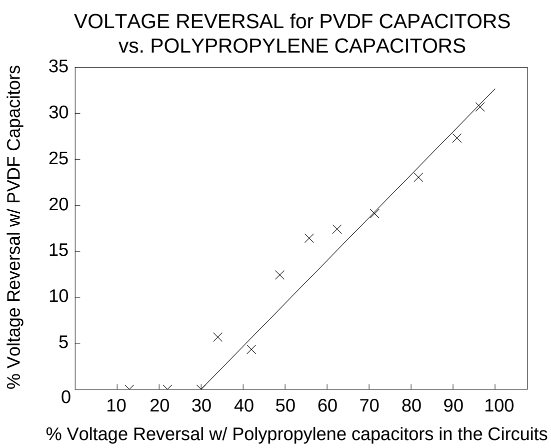

Figure 15

High reversal on a high energy density PVDF metallized electrode capacitor for a source outside the capacitors can result in fast degra-dation. Significant damage will be done to the capacitor if it is charged to 50% in the wrong direction.

SURVIVAL OF FAULT CONDITIONS

One item that deserves close scrutiny is the capacitor's ability to survive faults. Here, the metallized electrode capacitors have a signifi-cant advantage. In the case of the PVDF capacitors the fault conditions studied [10] have no meas-urable effect on the performance of the capaci-tor. In September of 1995, the 30 MJ facility, Feuerstellung 2000 [9] had gone through the worst case fault. The fault occurred inside one of the capacitors. The peak current was calculated at 215,000 amps in the 22kV module. The polypropylene capacitors with metallized electrodes all survived without damage except for the capacitor directly below the fault. That capacitor lost some capacitance and the paint was burned off the cover but it continued to function normally.

The current capability of a metallized electrode capacitor can be exceeded in a fault. Experi-ence in this area has shown that it is possible to destroy a capacitor by attempting to drive too much current through the capacitor. If this occurs under conditions where the capacitor can maintain the soft failure mode, the elec-trode will burn open, the peak power delivered will by severely limited by the increasing impedance of the capacitor, and some of the charge will re-main inside the capacitor. After such an event, the capacitor will no longer accept or deliver a charge and must be replaced. Caution should be used when handling a capacitor that has gone through this event since stored charge can remain in the capacitor for years.

RELIABILITY

Reliable, dependable and trustworthy are all synonyms. Here the metallized electrode capacitors again have the edge. The fact that they are defect tolerant improves the yield in manufacturing as well as in the field. While it is not unusual to get 7% to 12% failures at manufacturing test for high energy density capacitors with foils while the number is less than 1% for metallized electrode capacitors.

In the field, the performance of the metallized electrode capacitors continues to be outstanding. There was one minor design limitation that caused an internal connector to break under high peak currents or due to fatigue from thousands of pulses. This problem caused one of the three capacitors in Figure 12 to fail after 10,543 shots. Since this problem was eliminated, there have been no reports of field failures of the two types of metallized electrode capacitors discussed here.

The best statistical comparison of the performance of metallized electrode capacitors with conventional capacitors was done at LLNL where Douglas W. Larson compared the performance of the Nova bank, which used foil capacitors, with the performance of the Beamlet [8]. For this comparison, the combined test data from qualification and acceptance testing of the capacitors was analyzed using Weibull statistics. The resulting Weibull function parameters were a analyzed using Weibull statistics. The resulting Weibull function parameters were a slope of 3.4 for the foil capacitors vs 1.1 for the metallized electrode capacitors.

The MTBF at 5000 shots for the bank was 316 shots for the foil capacitors and 2100 shots for the metallized electrode capacitors.

A tabulation of typical, comparable performance characteristics is offered below in Table 2.

PERFORMANCE COMPARISON FOR FOUR TYPES OF PULSED POWER CAPACITORS				
	FOIL ELECTRODE		METALLIZED ELECTRODE	
Item	**Kraft/PolyP Type NM**	**Kraft Type PM**	**PolyP Type KM**	**PVDF Type LM**
Typical Ratings				
Voltage Range	500V – 120 kV	500 V – 120 kV	5 kV – 44 kV	5 kV – 44 kV
Voltage Reversal	< 10%	< 10%	< 20%	< 20%
Maximum Repetition Rate for a 100 Shot Burst in Hz	> 5	1	>5	1
Output Energy Density				
@ 1k Shot Life or 100 Hr.				
Joules/gram	0.35	0.4	0.90	1.54
MJoules/m3	0.3	0.45	1.17	2.51
@ 10k Shot Life or 100 Hr.				
Joules/gram	0.2	0.16	0.77	1.32
MJoules/m3	0.17	0.18	1.00	2.15
Efficiency				
On the first shot	98%	95%	94%	65%
On the 30th Shot	98%	95%	94%	80%
Internal Rise °C				
First 10 shots	0.04	0.08	0.08	8
Following 10 shots				6
Temperature Range				
Operating				
Minimum in Deg. C	<-20	<-20	<-20	<10
Maximum in Deg. C	>75	>50	>75	>55
Storage				
Minimum in Deg. C	<-20	<-20	<-20	<10
Maximum in Deg. C	>85	>85	>85	>85
Peak Current in kA @ 50 kJ, 16 kV	350	250	200	120
Life w/Reversal				
for 20% Vr	100.0%	100.0%	100.0%	1
for 58% Vr	15.0%	10.0%	16.0%	N/A
for 80% Vr	0.2%	0.1%	0.9%	N/A

SUMMARY

Progress in capacitors for pulsed power applications is evident. In the past 5 years, the reliability of capacitors for large systems has im-proved drastically. Most of this improvement is a result of the metallized electrode capacitors now available to the Pulsed Power Industry. The capacitors combine high energy densities and high reliability in a way that makes even the largest banks under consideration, feasible. The problem of violent failures has been eliminated for many applications. The available product achieves end of life in a soft mode that allows the capacitors to be monitored with normal maintenance procedures with the confidence that the information obtained is accurate.

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