

THE APPLICATION OF PERFLUOROCARBONS
AS IMPREGNANTS FOR PLASTIC FILM CAPACITORS*

G. Howard Mauldin
Division 2153
Sandia National Laboratories
Albuquerque, NM 87185
(505) 844-4260

SUMMARY

Sandia National Laboratories has developed a liquid-impregnated, plastic film (wet) capacitor that is thought to be the most reliable and space-efficient capacitor of any type ever produced for high-voltage, pulse-discharge service.

The initial design will store five times the energy of a premium-quality, Sandia-designed dry capacitor of equivalent energy and reliability, and future designs are expected to boost this energy ratio even higher.

Credit for this dramatic improvement in electrical performance is given to the near perfect attributes of the liquid chosen as the capacitor impregnant. The impregnant, a perfluorocarbon fluid, embodies all of the attributes Sandia has identified as essential to capacitor-impregnating quality. No other single fluid approaches its combination of properties. This paper will describe the technology, a production capacitor design using this technology, and the winding technology for capacitors used at Sandia National Laboratories.

THE NEAR PERFECT IMPREGNANT

A well-known relationship in the capacitor field is that the energy storage capability of any dielectric system is a squared function of the operating field stress. A doubling of the operating stress yields a fourfold increase in energy.

The high ultimate electrical strength of plastic films has long tempted workers¹ in the energy storage capacitor field. This high ultimate strength suggests the possibility of operating at higher stresses with the attendant increase in energy density. This ultimate performance has

been hard to achieve in practice because plastic films are difficult to perfectly impregnate with traditional fluids. Unless they can be perfectly impregnated or if they are left dry, trapped air pockets and other irregularities in the windings cause widely varying electrical breakdown levels. Because of this, in systems requiring high reliability the resulting capacitors must be severely derated against the average breakdown levels to assure reliable performance. This derating can be as extreme as 70 percent to 80 percent of the average performance. This results in capacitors larger than desired to ensure reliable performance.

It would appear then that in the quest for higher energy density capacitors, a search for more reliable impregnating materials would be quite productive. This has been our approach and in this we have identified what we believe to be the near perfect liquid for impregnating plastic film dielectrics.

Before discussing the details of the new capacitor technology we would like to say a few words about the search tool we use in looking for promising dielectric combinations. The main procedure used in this search we call the short-term breakdown test.

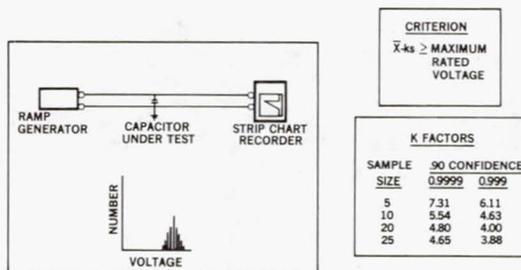


Fig. 1. The Short Term Breakdown Test

The short-term breakdown is illustrated in Figure 1. The equipment consists of a programmable power supply, a strip chart recorder, and

*This work supported by the U.S. Department of Energy.

test fixturing to connect the capacitor to this equipment as illustrated in the block diagram. The programmable power supply generates a linear ramp of voltage. The ramp rate is typically 250 V/second. The strip chart recorder is used to indicate the capacitor breakdown point on the voltage ramp and also serves as a permanent data record.

In applying this test, a quantity of samples is broken down in the above test procedure. The breakdown data is obtained and calculations of mean and standard deviation are made. A calculation of the mean minus a constant, k , times the standard deviation is made. The criterion is that this quantity must be greater than the maximum stress the dielectric system would be operated. The constant, k , is a function of sample size, reliability goals, and confidence limits as shown in Figure 1.

Some seven years ago in our continuing search for attractive film and liquid combinations, we experimented with a unique family of dielectric liquids. We believe this was the first application of these materials as capacitor impregnants. These liquids are chemically named perfluorocarbons.

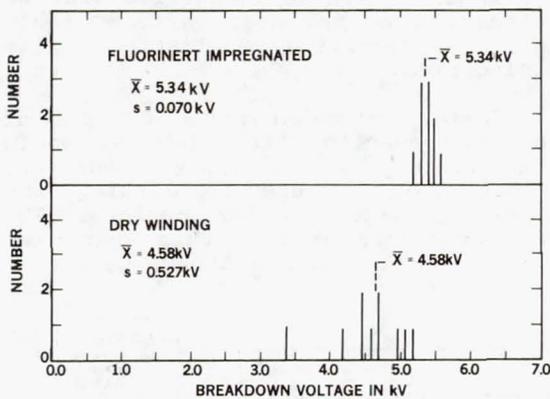


Fig. 2. A Comparison of 12 μ m Plastic Films in Dry Capacitors vs. Ones Impregnated with Fluorinert*

The first indication of things to come was observed in an experiment some years ago. Figure 2 plots the comparison of short-term breakdown of 12 μ m Mylar* in a dry condition versus

* Mylar is a trade name of the DuPont Company. Fluorinert is a trade name of the 3M Company.

the same material impregnated with one of the perfluorocarbons. Notice the significantly higher mean breakdown of the impregnated samples and the dramatic stabilization of the breakdown around the mean. This mean breakdown represents a stress of 444 MV/m. After duplicating these results a few times to demonstrate that it was not an experimental fluke, we did the tests necessary to plot Figure 3.

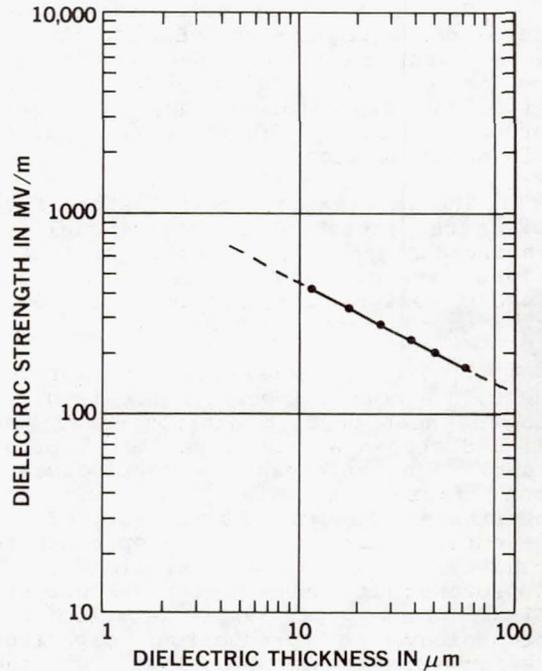


Fig. 3. Dielectric Strength vs. Thickness of Mylar Impregnated with FC-40 Fluorinert.

Figure 3 is a plot of dielectric strength versus thickness for Mylar impregnated with one of the perfluorocarbons. This curve now serves as our design guide for specific capacitors at various voltage ratings.

Credit for this dramatic improvement in electrical performance is given to the near perfect attributes of the perfluorocarbon used as the impregnant. It embodies all of the attributes Sandia has identified as essential to capacitor impregnating quality. No other single fluid approaches its combination of properties. It has a dielectric strength significantly higher than common impregnating liquids. Its surface tension is perhaps the lowest of any fluid

material. This allows it to wick into and completely wet plastic film capacitor rolls without requiring such auxiliary measures as interleaved paper wicks. The impregnant is a highly effective coolant which allows it to moderate hot spots in capacitor rolls before they lead to catastrophic failure.

A PRODUCTION CAPACITOR DESIGN

Several years ago we had a need for a high-energy density capacitor. This new technology was chosen to fulfill this need. Figure 4 contains the vital statistics of the MC3344 design that has reached production status. The key factors to note in Figure 4 are the average stress of 236 MV/m on the dielectric at rated voltage and the energy density by weight of 0.1 J/g and by volume of 0.28 J/cc. New efforts underway promise to double and perhaps triple these density figures.

Figure 4 also contains an exploded view of the details of this design. The dielectric pad is made up of two layers of 12 μm Mylar wound between two 6 μm aluminum electrode foils.

CAPACITANCE	3.0 μfd .
VOLTAGE RATING	6000 V.
ENERGY	54 J
DIELECTRIC STRESS	236 MV/m
DIAMETER	57.16 mm
LENGTH	76.2 mm
VOLUME	195.3 cc
WEIGHT	535 g
ENERGY DENSITY	
WEIGHT	0.1 J/g
VOLUME	0.28 J/cc



Fig. 4. The MC3344 High Energy Density Capacitor.

The winding is an extended foil configuration. The winding criteria is somewhat unique in that it is wound to a specified tension on the film and foil in order to achieve a controlled looseness. The controlled looseness guarantees an optimum thickness of the liquid between the layers of the films and foils. We have found this to be a major determinant of discharge life.

We believe this is due to the better cooling performance of the thicker liquid layers.

The winding is done on a hollow mandrel whose interior is used to house a welded stainless steel bellows. The bellows is used to compensate for the change in volume of the liquid over the wide operating temperature range (-55° to +74°C). We believe that it is essential to compensate for this liquid volume change in order to provide a void-free condition at all times in the assembly. The bellows also provides pressure on the liquid over all temperature conditions.

Another somewhat unique feature of this design is the electroding system. At the 25 kA discharge current peak required by the application the current density in the electrodes is some 1500 A/cm². Considerable development effort was required to achieve a system that would repeatedly withstand this condition. The system finally chosen uses silver conductive epoxy as the basic interconnect but also uses a copper screen to act as mechanical reinforcement and provide increased conductivity.

The case is formed from a stainless steel tube to which are welded end caps to complete the closure. Electron beam or laser welding is used for their superior hermetic sealing capabilities. The high-voltage bushing and ground ring are oven-brazed to the top cover. The copper fill tubes are oven-brazed to the stainless steel case. The final closure after assembly is an electron beam weld joint between the high-voltage terminal and a sleeve on the high-voltage bushing. Through this assembly process, we have achieved an all welded closure system with its superior hermetic sealing properties.

We use an individual filling process with each unit connected to a vacuum and liquid manifold through separate fill tubes. The dry assemblies are vacuum degassed until they meet a maximum outgas rate. At the same time, the liquid is being degassed in a thin film configuration and filtered. Once these intermediate steps are completed, the assembly is impregnated while still under vacuum and sealed by a mechanical pinch-off procedure. Final sealing of the pinch-off tubes is accomplished by an ultrasonic welding procedure.

WINDING TECHNOLOGY

Perhaps the major learning experience on this program was in the area of roll winding. Others² have reported similar experiences. We started out with what could be characterized as traditional winding technology and soon found it to be inadequate for the task. We then evolved the winding technology adequate for the requirements.

In the quest for higher and higher energy density such mechanical factors as end margin length and foil extension for outside connection became important. Mechanical wander of either of these parameters becomes important since both of them affect the active region in the roll and hence the energy density. One would like to operate at as small end margins as possible, but excessive wander requires a conservative nominal value to prevent wander from encroaching on a critical dimension. Essentially the same can be said about foil end extension with one additional factor. Excessive wander of the foil extension also makes for a difficult electroding problem. The solution to excess wander lies in the precision of the film and foil handling systems on a particular winder. In solving this problem on our machine we have gone to precision instrument bearings on all film and foil rollers. In some of the roller positions we have experienced film or foil slippage over the roller instead of continuous rolling. This has been due to inadequate contact with the rollers due to a shallow angle of engagement. Slippage rather than rolling can cause excessive wander and film wrinkling. This was solved by using two rollers at each position where an S-shaped wraparound could be obtained for greater engagement. With these improvements we have reduced wander and wrinkling to an insignificant level.

Perhaps the most critical factor has to do with the tightness of the winding. It has been so critical to our performance that we have labeled it the "tight winding syndrome." As the name implies, this is a condition involving the tightness of the winding. Figure 5 indicates its effect on discharge life performance. We define winding tightness by a parameter called space factor. Space factor is the ratio of the space between foil and film layers expressed as a percentage

of the total film thickness. A large space factor indicates a loose winding and a small space factor represents a tight winding. In Figure 5, the numbers associated with each space factor curve is a tabulation of discharge life from samples representative of that type winding. The units with space factors at or above ten percent exhibit far superior discharge lives than those in the seven percent or lower range. We have solved this problem by replacing the mechanical tension (Prony brake) system with electric motor tensioning devices.

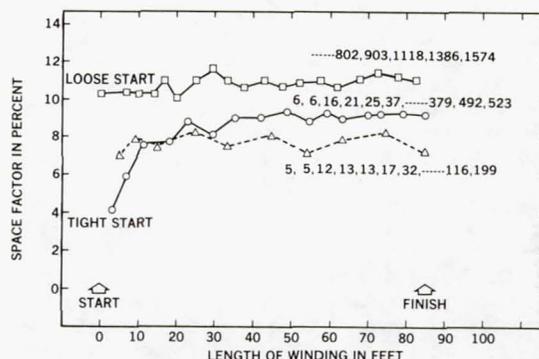


Fig. 5. The Effect of Winding Tightness on Discharge Life.

Figure 6 is a photograph of this modified winder. This is a twelve-supply spindle machine with electric motor tension control. It employs an electronic system using force transducers and meters to continuously monitor the tension being applied on the material from all twelve spindles. This machine also employs instrument grade bearings in all feed rollers and double rollers in those locations where greater roller engagement is required. With this system we have been able to wind wrinkle-free windings at tensions as low as 50 grams. The foil and film wander is held under 5 mils.

SUMMARY AND CONCLUSIONS

We have reached production status on the MC3344 having completed the first production lot. In our system we go through distinct phases to achieve production status. These are design prove-in, manufacturing feasibility, and production. Table I summarizes the data up to and including the first production lot. Significant factors to note in Table I are the very uniform Xs and sigmas as well as the calculation X - ks. The uniformity

of these parameters is maintained over different lots of film, different lots of liquid, and fabrication by different personnel. We conclude, then, that the technology is highly predictable and reliable and fabrication processes can be well controlled with standard production practices.

ACKNOWLEDGMENT

The author would like to thank C. B. McCampbell, D. H. Weingarten, K. J. Urquhart, and M. L. Reichenbach of Sandia National Laboratories, and W. E. Packer, N. A. Sidneil, and C. I. Biver of the General Electric Neutron Devices Department for continuing support and assistance.

REFERENCES

1. R. D. Parker, "Technological Development of High Energy Density Capacitors," NASA Lewis Research Center, Cleveland, Ohio, NASA CR 124926, February 1976.
2. R. D. Parker, "Capacitors for Aircraft High Power," Air Force Aero Propulsion Laboratory/POD, Wright-Patterson AFB, Ohio, Tech Report AFAPL-TR-77-40, December 1976.

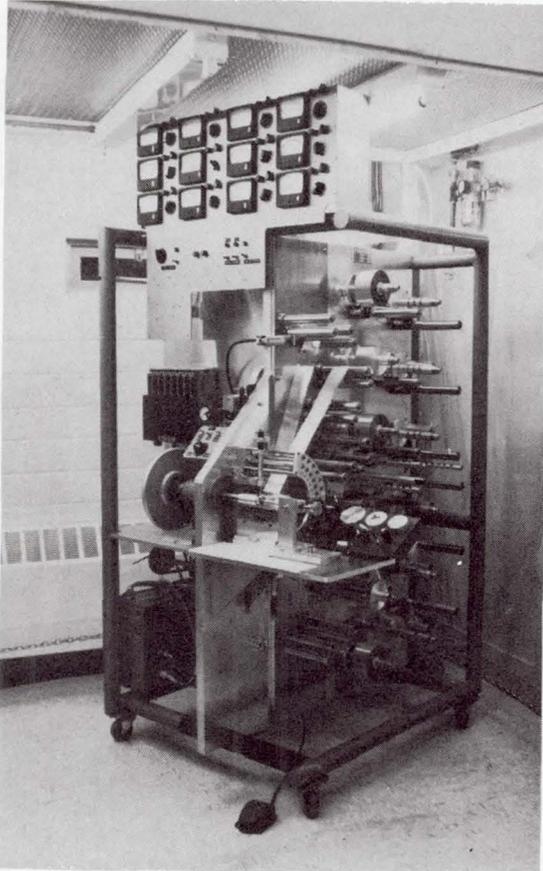


Fig. 6. Modified Twelve Spindle Winder.

TABLE I

Summary of MC3344 History

Phase	Short-Term Breakdown			Discharge Life
	X	s	X - ks	
Design Prove-in	7.53 kV	.265 kV	6.30 kV	10 units passed 500 discharges
Manufacturing Feasibility	7.55 kV	.299 kV	6.38 kV	23 units passed 500 discharges
First Production	7.55 kV	.248 kV	6.38 kV	20 units passed 500 discharges