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**A Newly Discovered Failure Mode in
High Energy Density,
Energy Storage Capacitors**

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A NEWLY DISCOVERED FAILURE MODE IN HIGH ENERGY DENSITY, ENERGY STORAGE CAPACITORS

by

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ABSTRACT

High energy density pulse capacitors, typified by the 10-kV, 170- μ F unit, have become widely used in recent years. These units primarily were designed for lower cost and higher energy per unit volume. The life characteristics of these units have never been determined fully, but they have already been shown capable of lives much longer than originally expected.

The Los Alamos Scientific Laboratory is now conducting an extended program to determine the long-term capabilities of these capacitors. This program is aimed not only at finding the statistical parameters of the failure distribution but also at determining the physical failure modes characteristic of such units.

Recently, a new failure mode was found. This failure mode has prevented test samples of polypropylene-paper-diocetyl phthalate units from actually reaching the true potential life of the insulation.

In this report, the new failure mechanism is examined and suggestions are made that could eliminate the failure mode.

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I. INTRODUCTION

High energy density capacitors have become widely used in controlled thermonuclear experiments. They are preferred not only because they cost less per joule but also because less space is required for the bank. The continued development of these units is highly desirable because units similar to the present-day high-density capacitors are likely to be the "workhorse" capacitors used in eventual fusion devices. Capacitors for such devices should be inexpensive, should have very long lives, and should be as compact as possible.

Little solid information is now available on the true long-term capabilities of currently available units. The Los Alamos Scientific Laboratory (LASL) has carried on a long-term development program on the 10-kV, 170- μ F capacitor.^{1,2} Initially, this effort was aimed at obtaining capacitors that would operate reliably only for as long as required for the experimental devices then proposed. This set the requirement for a life of only about 30 000

operations. As a result, complete life testing of this capacitor type was never carried out.

Because LASL has received many inquiries concerning the expected life of the 170- μ F, 10-kV capacitor, we have undertaken a program to produce life data under controlled conditions. This program has the following aims:

1. Better estimation of the life of standard paper-castor oil units.
2. Evaluation of nonstandard units using different dielectric sandwiches and impregnants that might improve the life, cost, or size of the units.
3. Determination of the statistical parameters of the failure distributions characterizing the life of standard and nonstandard units.
4. Investigation of the failure modes of these units with the hope of discovering design changes that would result in longer life.

One of the first results of this program has been the discovery of a capacitor failure mode not previously seen. To understand the significance of

this mode, it is first necessary to describe the "normal" failure mode of standard 170- μ F, 10-kV capacitors.

II. DESCRIPTION OF THE EXPECTED FAILURE MODE

Capacitors fail for many reasons. Close examination of failed units in the past years has convinced us that most causes of capacitor failure can be eliminated. In fact, the only noneliminatable failure cause should be the electrical fatigue of the dielectric caused by repeated electrical stressing. Failure from this cause is what we call normal end of life.

Normal end of life in most capacitors is easy to spot because most capacitors are constructed in a way that produces selected regions of high stress. These high-stress regions are the margins where the edge of the foil lies. It has been estimated that the electric field at the foil edge is at least a factor of 2.2 greater than the stress in the body of the capacitor.³ Observation shows that most failures, even in multisection windings, are initiated at a margin. Consequently, if a failure pattern is found that does not correspond to most of the failures being at the margins, then an abnormal failure mechanism should be suspected. If this mechanism can be found and eliminated, longer lived capacitors will result.

III. DESCRIPTION OF THE NEW FAILURE MODE

A nonstandard failure pattern was found during the post-mortem examination of a group of developmental polypropylene-paper-diocetyl phthalate capacitors. In these units most of the failures occurred in the bulk of the active portion of the capacitor away from the margins. Examination of the windings revealed discoloration resembling arc burning in many places in the dielectric sandwich. This arc burning appears to be caused by the presence of holes in the aluminum foil. Figure 1 shows three pictures of samples taken from these capacitors. Figure 1.a shows a portion taken from the body of a winding where the burning is obvious; Fig. 1.b is of the same section but with the back part of the sandwich removed to make the holes plainly visible; Fig. 1.c is taken from a similar position in a capacitor that received a substantially smaller number of shots. The last picture illustrates the

fact that in the newer capacitor the holes are smaller and that the arcing must enlarge the holes.

When all windings in these units were examined to get a clear picture of the distribution of the burning, a definite pattern was noted. In the windings on the outside of the group, the burning was less extensive and was about equally distributed between the flat portion of the winding and on the edge fold produced by the flattening of the winding during assembly. The burning was almost entirely

Fig. 1.a. Photograph of burning on an edge fold. The darkening around the peripheries of the holes is due to products produced by the burning.

Fig. 1.b. Same section as Fig. 1.a with back part of sandwich removed to silhouette holes.

Fig. 1.c. Edge fold holes typical of holes after a few thousand shots.

confined to the outer one-third of the windings. In the windings situated to the inside of the grouping, the burning was situated mainly on the edge fold. Again it was found confined to the outer one-third of the windings.

Because failure in these units results in substantial damage to the guilty winding, no irrefutable connection between the failures and the burning could be established. However, as well as could be determined, the failures did appear to be associated with the presence of burning.

The distribution of holes in the windings was also noted. Holes were found throughout the windings. These holes were almost invariably in places where some flexing and wrinkling of the foil had occurred.

IV. POSTULATED MECHANISM OF FAILURE

As stated above, the failures seem to be connected with arc burning across holes in the foil. There are several questions to be answered concerning these holes. The most obvious are: How do the holes originate? *Given the holes, how does arc burning occur?* Others are: Why does their presence lead to failure? Why doesn't this mode also appear in paper-castor oil units? and What design changes can be made to either eliminate this failure mode or postpone it?

The holes could arise in one or more of three ways. They could be present in the virgin foil;

they could be introduced into the foil during the construction process; or they could be produced during electrical operation of the capacitor. Examination of new, unflexed foil shows that it does have holes in it, but not very many. Mechanical flexing of new foil, however, produces holes quite easily in the thickness of foil used in the sample units. This suggests that the prime cause of the holes is the mechanical stress accompanying the winding of the pack. The post-mortems showed that almost all of the holes were in regions subjected to mechanical stress. This was evidenced by greater than normal wrinkling of the foil in regions of high hole density. In fact, most of the holes were on the fold edge of the winding, which probably is the most mechanically stressed point in the winding. Figure 1.c, which is of a sample taken from a unit that received less than 10 000 shots, seems to confirm that the holes are in the unit from the beginning.

The arc burning must occur when the current density near the hole becomes great enough to cause the current to jump across part of the hole. There are several items that substantiate this. First, the holes in units with few shots are smaller than in those with many shots, as illustrated by a comparison of Figs. 1.b and 1.c. The enlargement of the holes could be expected to accompany arcing due to mechanical forces produced by the arc. Second, similar low-voltage arcing is often seen near high-current experiments where high eddy currents are induced in shielding. And, third, the peculiar burning pattern can be explained by assuming the burning is caused by high current density-caused arc jumping.

A consideration of the magnetic field configuration inside the unit shows that it must be somewhat as illustrated in Fig. 2. The magnetic field that passes between the windings situated toward the inside of the group is mostly canceled by the fields of the adjacent windings. More field manages to pass through the separation between the last and next-to-last windings, but a large field passes completely around the entire group. Where there is changing magnetic field next to a conductor, there must be current proportional to it in the conductor. Thus we must have the highest current densities in the capacitor occurring on the edge of the windings (that is, on the edge folds) and on the outside of

the outside windings. These are precisely the positions of the highest burning concentrations. The field, hence the current density, must fall off as it penetrates the winding and this explains the general limitation of the burning to the outer one-third of the packs.

It would appear that the holes do not cause failure. The failures must be attributed to the chemical and physical damage caused by the arcing.

The arc burning failure mode also contributes to the failures of paper-castor oil capacitors, but it appears at about 500 000 shots instead of 250 000. This explains why this new mode was first found in PPL-paper-DOP units. Only recently have we run any paper-castor oil units past a half million shots. The reason for the later onset of failures probably lies in the difference in the molecular structure of the impregnants. Dioctyl phthalate is a saturated ester, whereas castor oil has mostly unsaturated molecules. Because of this unsaturation, castor oil can chemically absorb a substantial amount of the decay products produced by the arcing⁴ thus reducing the probability of chemical damage.

Fig. 2. General pattern of the magnetic field near the windings in a capacitor during discharge. The field is strongest around the outside of the grouping.

This ability is illustrated in Fig. 3, which shows a large unfailed (not shorted) burn area taken from a half-million shot paper-castor oil capacitor made with 0.00584-mm (23 gauge) aluminum foil. Burns even one-fifth of the size of this one are never seen in PPL-paper-DOP units. This shows that for some reason the paper-castor oil unit is able to withstand the deleterious effects of the decomposition products from the arcing.* The picture also shows how it does this. On the left side, the trained eye can find large globs of hydrogenated castor oil. The hydrogenation process--the saturation of the originally unsaturated castor oil bonds--takes place by the chemical combination of unsaturated bonds with the decay products preventing these products from attacking the solid dielectric.

This points to one possibility for the improvement of PPL-paper-DOP units. The test units of this type had only a small percentage of inhibitor added to the DOP; the addition of more or better inhibitors could slow down the rate of damage caused by the chemical products of the arc.

However, the best way to improve the life of these units is to attack the cause head on, and this is to reduce or eliminate the holes in the foil.

The foil used in the PPL-paper-DOP capacitors is 23 gauge (0.00584 mm). A comparison with the next thicker standard foil, 35 gauge (0.00889 mm), shows that the number of holes produced during foil manufacture is substantially lower; but, more important, the number of stress-produced holes is at least 50% less. The holes produced by mechanical flexing also tend to be substantially smaller in the thicker foil.

IASL has procured a sample group of PPL-paper-DOP capacitors made with the thicker foil. The results of life testing on these units will show whether the thicker foil is sufficient to eliminate the arc burning. If so, it will allow us to get a better estimate of the ultimate life of this

* It is true that the PPL-paper-DOP units are stressed higher than the paper-castor oil units. We believe that the arc burning is only related to current density and is virtually independent of the stress. This conclusion appears to be borne out by the experimental fact that the life of lower density PPL-paper-DOP units seems to correlate more with the current density than with the stress.

Fig. 3. Such large burn areas as in this example from a paper-castor oil unit show the inhibiting effect of the unsaturated esters in castor oil. They produce a longer lived unit by chemically bonding to the decay products. Hydrogenation blobs can be seen on the left side of the picture.

insulation combination. At present, the arc-burning failure mode is dominant; therefore, all we know is that we have not reached the natural end of life for the PPL-paper-DOP unit.

V. SUMMARY

A new failure mode has been identified in 10-kV, 170- μ F capacitors. This mode is arc burning across holes in the foil. The holes are mainly the result of mechanical flexing during winding of the packs.

This failure mode is the present predominant failure mode in PPL-paper-DOP capacitors, but it is

not of serious importance in paper-castor oil units. This indicates that the maximum life of PPL-paper-DOP capacitors has not yet been attained.

The use of more or better inhibitor additives in the DOP and thicker foil could decrease the importance of or even eliminate this mode.

Sample capacitors, made with thicker foil, have been procured and will be tested.

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