CONF-810657--12

LA-UR -81-1666

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: FIELD GRADING IN CAPACITOR MARGINS

DISCLAIMER

AUTHOR(S): Thomas E. Spring, E-11
Walter J. Sarjeant, E-11
William C. Nunnally, E-11

MASTER

SUBMITTED TO: 3rd International IEEE Pulse Power Conf.,
Albuquerequ, NM, June 1-3, 1981

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FIELD GRADING IN CAPACITOR MARGINS

Thomas E. Springer, Walter J. Sarjeant, William C. Nunnally

Los Alamos National Laboratory
P. O. Box 1663, Los Alamos, NM 87545

This paper includes some of the results of modeling electric fields in the margin of a bogey plastic film liquid impregnant capacitor in which effects of foil edge shape, different impregnants, and grading wires are examined. It will be concluded that placement tolerance and connection problems make grading wires impractical and that folded foil edges are still the best solution to field grading.

High energy-density capacitors for pulse discharge are in general constructed of cylindrically wound plastic film, aluminum foil, and liquid impregnant. When quality control is exercised in manufacture,[1-3] capacitor failures tend to occur from corona discharge at the foil edges in the capacitor margin. Figure 1 shows a cross section of several layers of a plastic film liquid impregnant capacitor. The film may be several layers of polypropylene, polysulfone, or other similar material with a high dielectric strength and modest dielectric constant. The liquid insulating impregnant needed to displace all ionizable gas in the capacitor may be silicone oil, fluorinert, monoisopropyl biphenyl (MIPB), castor oil, or other fluids selected for their dielectric strength, dielectric constant, ability to impregnate, chemical compatibility in the presence of high fields, self-healing ability, propensity to form gas, and the like. In order to develop higher energy-density capacitors, it appeared appropriate initially to carry out a detailed study of maximum fields developed for various foil edge shapes with various impregnants in an otherwise specific bogey capacitor structure.

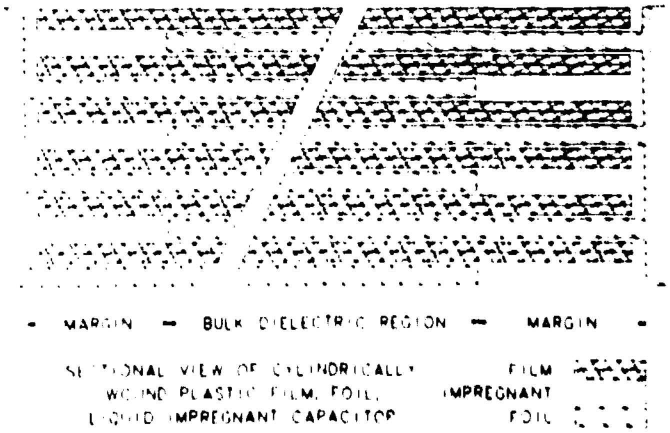


Fig. 1. Cross section of several layers of cylindrically wound capacitor.

The bogey capacitor geometry that was selected had a solid dielectric thickness of 1 mil, representing two 0.5 mil polypropylene films, and a 0.1 mil impregnant layer next to the foil. The foil thickness was fixed at 1 mil, which could represent a single cut foil or a 0.5 mil folded foil. Thus in the bulk capacitor there was a 1.2 mil spacing between foils of opposite potentials.

Foils are cut by shearing or by melting with lasers or electrical discharge. Figure 2 shows six shapes for foil edges selected as representative of most possible configurations. Each corner was rounded with a known radius to allow exact specification of the electric field on the foil edge, since perfectly sharp corners lead to singularities in the surface field. Radii of 0.01 and 0.05 mils were used and the functional variation of field with radius on the corners was also determined. The geometry for modeling is shown with corner radii of 0.05 mils at the top of Fig. 2. At the horizontal coordinate of 0 mils, the field was forced to be vertical. At 30 mils, the potential was set to zero along the vertical boundary, representing the grounded connection. The potential was zero well before 30 mils, so the solution is good for longer margin widths.

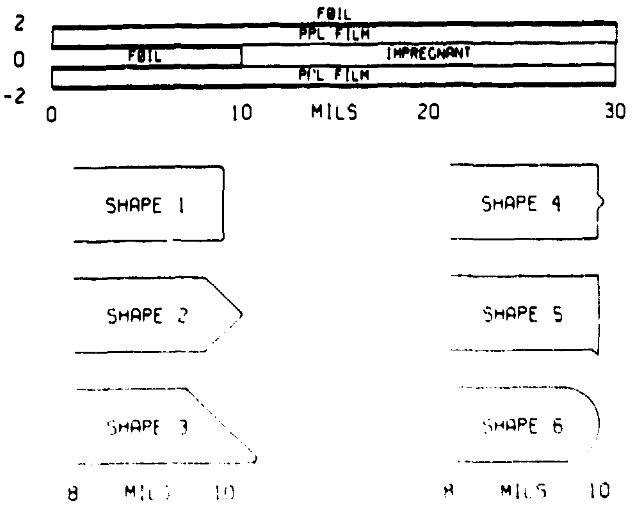


Fig. 2. Capacitor model with six foil edges.

The energy density achievable in the bulk plastic film has been shown to be limited by the maximum electric field present in the impregnant,[2,3] since the sharpest edges occur on the foil edge. Fields in the impregnant can be suppressed to the extent the impregnant's dielectric constant is greater than that of the plastic film. Likewise, appropriate shaping of the foil edge or addition of smooth conducting material in the margin near the foil edge can serve to grade the field. In order to model these effects in a realistic capacitor, it is necessary to be able to calculate electric fields in the dielectric materials present.

For the representative geometries selected, no analytic solution exists for the electric fields, thus requiring computer solutions to the problem. Fortunately in a problem such as this, containing multiple regions with uniform permitivity in each region, experience to date indicates the maximum field in each region must occur on the boundary. Thus it is only necessary to compute the electric field along the foil edges and along the interface between the impregnant and plastic film.

The solution of the Laplace equation yielding the potential and electric fields inside the capacitor section was obtained using Green's third formula,[4] which gives the potential, ϕ, in a closed region as a function of the potential and its normal derivative around the boundary, S.

$$\phi(x,y) = \frac{1}{2\pi} \int_S \left[\ln\left(\frac{1}{r}\right) \frac{\partial\phi}{\partial n} - \phi \frac{\partial}{\partial n} \ln\left(\frac{1}{r}\right) \right] dS \qquad (1)$$

This work is being performed under the auspices of the US Department of Energy.

Here r is the distance from the point x,y to a point on the boundary and n is the coordinate normal to the boundary. The computer program (LAPLDDC) written by John Hayes[5] was utilized to calculate the fields on the boundary of each dielectric region, where the maximum field must occur. All boundary segments used were straight lines, circles, or arcs of circles. Potentials and their normal derivatives were represented along the boundary at a finite number of points. Typically several hundred points were used on the boundaries to represent the complete capacitor.

For boundary conditions either the potential or the normal derivative of potentials must be specified. Where two dielectrics interface, the dielectric constants of each are needed to force the normal component of displacement to be continuous. The code applies Equation (1) at every point along the boundaries to determine $\frac{\partial\phi}{\partial n}$ if ϕ is given or ϕ if $\frac{\partial\phi}{\partial n}$ is given. Once ϕ and $\frac{\partial\phi}{\partial n}$ are known at every point on the boundaries, the potential and the field components $-\frac{\partial\phi}{\partial x}$ and $-\frac{\partial\phi}{\partial y}$ may be determined anywhere inside a dielectric region. However, the fields along conductive boundaries, namely $\frac{\partial\phi}{\partial n}$, are already available and the fields along dielectric interfaces can be computed from the tangential field $\frac{\partial\phi}{\partial \tau}$ and normal field $\frac{\partial\phi}{\partial n}$. To make contour potential plots, the potential is evaluated at points on a rectangular lattice from which the contours are plotted.

To visualize explicitly the effects of different foil edges and different impregnants in a film capacitor, polypropylene film of 1 mil total thickness was used with 1 mil foil thickness and 0.1 mil impregnant between film and foil. Impregnant also filled the margin.

For each choice of impregnant there is an assumed dielectric strength that the maximum field should not exceed, or breakdown occurs. This limit sets the electric field in the polypropylene film, wherein the bulk of the energy is stored.

Figure 3 shows a potential map of Shape 3, the 45° shear with 0.01 mil corner radii and shows representative fields going around the foil edge for 1000 V across the opposite foils. The field enhancement factor of the foil edge is defined as the ratio of the maximum field to the field in the impregnant in the parallel section. In Figure 3 the enhancement factor is 7791/1092 or 7.13. This factor, as will be seen, is useful in comparing different foil edges in the same impregnant but not in comparing different impregnants.

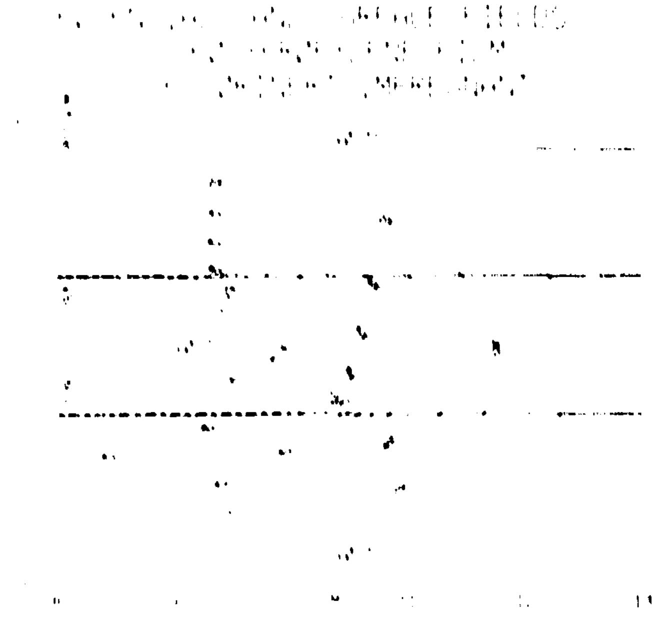


Fig. 3. Potentials and representative fields near foil edge for 1000 V on Shape 3.

Calculations similar to those illustrated in Fig. 3 were executed for the six foil edge shapes with two different corner radii and for five representative impregnants: fluorinert, transformer oil, MIPB, silicone oil, castor oil, and glycol. Figure 4 shows how glycol with a dielectric constant of 39 would reduce the field in the margin. Tables I and II show the bulk field in the polypropylene and energy density including foil mass but excluding

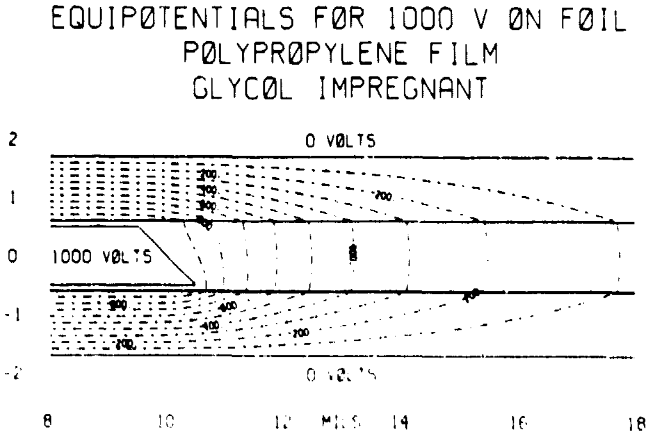


Fig. 4. Effect of a high dielectric constant (K=39.) on potentials around Shape 3.

TABLE I

SHAPE	RADIUS	FLUORINERT K = 1.88 D_s = 11000 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg	TRANSFORMER OIL K = 2.20 D_s = 1000 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg	MIPB K = 2.66 D_s = 400 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg
1	.01	1580.	14.0	159.9	.146	73.1	.030
	.05	2646.	39.2	267.9	.410	122.4	.083
2	.01	1844.	19.1	177.7	.180	76.5	.032
	.05	3112.	54.3	299.9	.513	129.1	.092
3	.01	1143.	7.3	113.2	.073	50.3	.014
	.05	2261.	28.7	224.2	.287	99.7	.055
4	.01	1609.	14.5	163.0	.152	74.7	.031
	.05	2669.	39.9	270.5	.418	123.8	.085
5	.01	1164.	7.6	121.8	.085	58.0	.019
	.05	N/A	N/A	N/A	N/A	N/A	N/A
6		5297.	157.2	548.2	1.715	256.0	.362

TABLE II

SHAPE	RADIUS	SILICONE OIL K = 2.8 D_s = 350 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg	CASTOR OIL K = 3.7 D_s = 350 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg	GLYCOL K = 39 D_s = 500 V/mil PPL BULK FIELD V/mil	CAPACITOR ENERGY DENSITY J/kg
1	.01	66.	.024	80.5	.034	528.1	1.29
	.05	111.	.067	134.5	.095	812.7	3.07
2	.01	68	.025	70.1	.030	302.1	.42
	.05	115.	.073	128.4	.087	509.4	1.20
3	.01	45.	.011	52.7	.015	254.4	.30
	.05	90.	.044	104.0	.057	476.3	1.05
4	.01	68.	.025	82.5	.036	554.3	1.43
	.05	112	.069	136.4	.098	849.3	3.35
5	.01	53.	.016	68.5	.025	529.7	1.30
	.05	N/A	N/A	N/A	N/A	N/A	N/A
6		232.	.294	265.9	.372	1032.2	4.94

margin and container mass when the maximum impregnant field is equal to the assumed dielectric strength, D_s, indicated in the tables.[2] The bulk energy density, W, can be shown to be given by

$$W = \frac{\frac{1}{2}\,\epsilon_p E_p^{\,2}\left[t_p + \left(\epsilon_p/\epsilon_I\right) t_I\right]}{\rho_p t_p + \rho_I t_I + \rho_f t_f} \tag{2}$$

where the subscripts refer to p - polypropylene, I - impregnant, and f - foil; ϵ is the permitivity; t the thickness; and E the field. The dielectric strength of certain impregnants is a strong function of thickness.[6] For example, recent experiments utilizing fluorinert yield data consistent with around 11000 V/mil breakdown strength in impregnant thicknesses of less than 1 mil decreasing to 500 V/mil in 1-cm thickness.[3,6] Standard dielectric strength tests with 1 inch spheres at 1 cm spacing are not applicable for thicknesses less than 1 mil. The data used for dielectric strengths are what were available then.

From the results of Tables I and II, the importance of a high dielectric strength for the impregnant is clearly evident. Even with the best impregnant and the rounded Shape 6, the ultimate dielectric strength of 9600 V/mil in polypropylene is not exceeded. Note also that differences between 0.01 and 0.05 mil radii of curvature on corners on the different shapes can affect the energy density by factors of 2.7 to 3.9. The folded foil, as was pointed out by Mandelcorn[7] and Parker,[1] has a substantial improvement in energy density over bare cut edges.

The energy densities in Tables I and II are on the order of a hundred times greater for fluorinert than for the other impregnants because of the high dielectric strength assumed (11000 V/mil). Since effective dielectric strengths for other impregnants in thin thicknesses may be substantially higher than bulk strengths, the effects of foil edges and dielectric constant were analyzed several other ways. In Table III the field in the PPL film was taken to be 1000 V/mil, as used in many high-repetition-rate plastic film liquid impregnant capacitors. Here we see how the maximum field in the impregnant varies with the different shapes and with different dielectric constants. Several conclusions may be drawn.

TABLE III

ENERGY DENSITY IN PPL (J/kg)
for 4000 V/mil maximum impregnant field

SHAPE		K_{imp} = 1.89	2.2	2.66	2.8	3.7	39.
1	.01	6.40	7.93	10.36	11.13	16.42	345.
	.05	17.94	22.25	29.05	31.20	45.79	819.
2	.01	8.71	9.79	11.33	11.79	14.66	113.
	.05	24.82	27.89	32.28	33.59	41.75	321.
3	.01	3.35	3.97	4.90	5.19	7.02	80.
	.05	13.11	15.59	19.25	20.36	27.39	281.
4	.01	6.64	8.24	10.80	11.62	17.23	381.
	.05	18.25	22.68	29.70	31.92	47.07	894.
5	.01	3.47	4.60	6.53	7.17	11.89	348.
	.05	N/A	N/A	N/A	N/A	N/A	N/A
6		71.9	93.2	127.0	136.1	179.0	1321
RADIUS MILS							

The highest field for a given dielectric constant occurs at the 45° angle of Shape 3. Shape 2 acts to reduce the maximum field from that of a square cut (Shape 1). The maximum field on Shape 2 occurs in the 90° corner in the center. The projection at the center of the foil edge in Shape 4 extending 0.1 mil at 45° and meeting in a 90° corner, serves to slightly shield the charge build-up on the two corners as the projection itself is shielded by the surrounding edge. Thus, the peak field, though still at the outside corners, is reduced from that of Shape 1 and the PPL energy density is slightly higher. The 45° projection at the lower corner in Shape 5 makes the maximum field higher than on the 90° corner in Shape 1 but less than the 45° corner of Shape 3 where there are no nearby concave corners to shield the tip. As expected, Shape 6 allows the highest energy density.

TABLE IV

ENHANCEMENT FACTOR

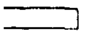
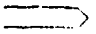
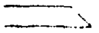
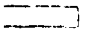
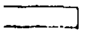
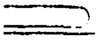
SHAPE		K_{imp} = 1.89	2.2	2.66	2.8	3.7	39.
 1	.01	5.16	5.39	5.71	5.80	6.30	14.5
	.05	3.08	3.22	3.41	3.46	3.78	9.4
 2	.01	4.42	4.85	5.46	5.63	6.67	25.3
	.05	2.62	2.88	3.23	3.34	3.95	15.0
 3	.01	7.13	7.62	8.30	8.49	9.64	30.1
	.05	3.61	3.85	4.19	4.29	4.88	16.1
 4	.01	5.07	5.29	5.59	5.67	6.16	13.8
	.05	3.06	3.19	3.37	3.42	3.72	9.0
 5	.01	7.01	7.08	7.19	7.22	7.41	14.4
	.05	N/A	N/A	N/A	N/A	N/A	N/A
 6		1.54	1.57	1.63	1.66	1.91	7.4
RADIUS MILS							

Table IV shows the enhancement factor, the ratio of maximum impregnant field to bulk impregnant field, for the various shapes. For a given dielectric constant, this factor serves well to compare effects of foil edge shape; however, it gives a distorted view of effects of different dielectric constants relative to the plastic film since the higher dielectric constant tends to suppress the impregnant field more in the bulk than around the foil edge. As the impregnant dielectric constant increases relative to that of the film, the field in the impregnant is suppressed. Thus for a given dielectric stress, a higher impregnant dielectric constant will allow higher energy densities.

While maximum fields in the impregnant have been presented for two radii of curvature and for several specific dielectric constants, in examining the results for other radii and dielectric constants, the maximum field, E_{max}, for Shapes 1 to 5 could be approximately expressed as a function

$$E_{max} = A\left(\frac{K_{imp}}{K_{film}}\right)^{-B}\left(\frac{r}{0.01}\right)^{-\alpha} \tag{3}$$

where K_{imp}/K_{film} is the impregnant to film dielectric constant ratio and r is the radius of curvature in mils. Table V gives values of A, B, and α for the five shapes. The fields on the 45° projection of Shapes 3 and 5 have a stronger inverse dependence on radius (α=0.42) than on the 90° projections of Shapes 1, 2, and 4 (α=0.32).

TABLE V

Parameter Values for Equation 3

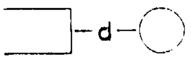
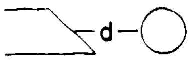
Shape	A (V/mil)	B	α
1	4682	0.623	0.32
2	4409	0.386	0.325
3	6773	0.488	0.424
4	4593	0.633	0.314
5	5986	0.728	0.431

While a high permittivity impregnant will grade the field at a foil edge, such impregnants may not have other necessary characteristics. Glycol, for instance, does not wet or impregnate the capacitor well (refer to Figs. 3 and 4).

The effect of placing a conducting wire whose diameter equaled the foil thickness in the margin parallel to the edge was computed for Shapes 1 and 3 in fluorinert. Table VI gives the maximum field on the foil edge or wire as a function of distance from center foil edge to wire edge. Note that it would be necessary to position the wire with a tolerance of a few tenths of a mil to insure limiting the maximum field.

TABLE VI

MAXIMUM FIELD WITH 1 MIL GUARD WIRE
RADIUS = 0.01

	 d	 d
d(mils)	E_{max} (V/mil)	E_{max} (V/mil)
0.25	3288	----
0.5	3623	3074
0.75	3916	3659
1.0	4189	4238
1.25	4436	4801
1.5	4649	5311
2.5	5243	6775
20.0	5637	7792

The potential of the wire was held to the center foil potential of 1000 V in these calculations If the wire is allowed to float, the potential drops to much lower value increasing the field. Figure 5 demonstrates for a wire 0.25 mil edge to edge from Shape 1 that a floating wire will have a potential of 530 V and will allow a maximum field of 5851 V/mil, up from 3288 V/mils. Unfortunately, one cannot tie the wire at foil potential during a transient since the current flows at right angles to the wire in the foil, but must be constrained to follow the wire to a connection to the foil.

It is concluded that wires are an impractical solution to field grading both from position tolerance and from electrical connection aspects. While high dielectric constant impregnants will grade the field, no suitable material is known at present. Thus folded foils are the best solution presently available.

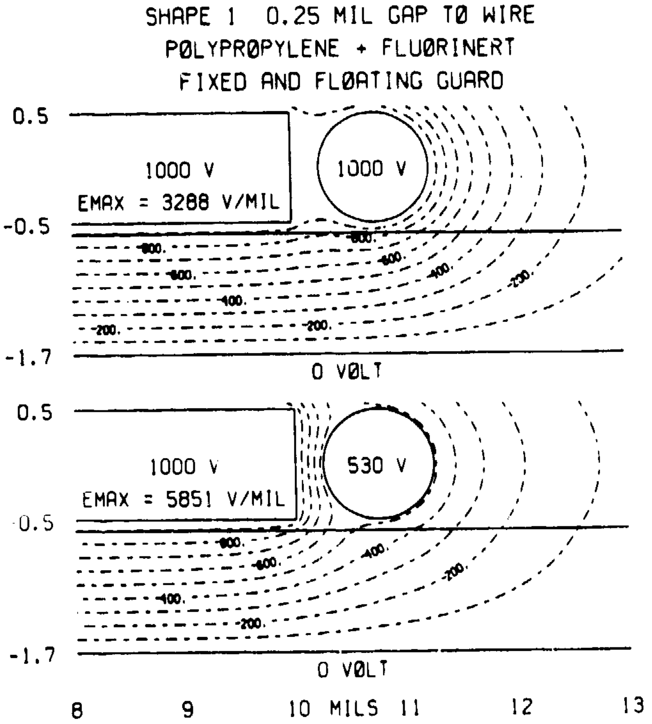


Fig. 5. Equipotentials and maximum field for Shape 1 with guard wire.

References

1. R. D. Parker, "Effect of Foil Edge Modifications and Configurations Changes on Energy Storage Capacitor Weight," IEEE Trans. on Parts, Hybrids, and Packaging, Vol. PHP-13,3, Sept. 1977.

2. G. H. Mauldin, "The Application of Perfluorocarbons as Impregnants for Plastic Film Capacitors," to be published in the Proc. of the NASA Symposium, Huntsville, AL, February 14, 1981.

3. G. H. Mauldin, "The High Energy Density Capacitor Program at Sandia National Laboratories," invited paper to be published in the Proc. of the Special Symposium on High Energy Density Capacitors and Dielectric Materials at the 1980 National Academy of Sciences Conference on Electrical Insulation and Dielectric Phenomena, Boston, MA, October 26-28, 1980.

4. W. Sternberg and T. Smith, The Theory of Potentials and Spherical Harmonics, 2nd Ed., The University of Toronto Press, Toronto, 1952.

5. J. H. Hayes, "Four Computer Programs Using Green's Third Formula to Numerically Solve Laplace's Equation in Inhomogeneous Media," Los Alamos report LA-4423, June, 1970.

6. W. G. Dunbar, J. W. Seabrook, "High Voltage Design Guide for Airborne Equipment," Boeing Aerospace Co., technical report AD-A029, June 1976.

7. L. Mandelcorn, T. W. Dakin, R. L. Miller, and G. F. Mercier, "High Voltage Power Capacitor Dielectrics: Recent Developments," Proc. of the 14th Electrical/Electronics Conference, Boston, MA, October 9-11, 1979.