ESDN9

DESIGN OF A DISK-TYPE MYLAR CAPACITOR

F29601-69-C-0035
Project 133B

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August, 1970

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ABSTRACT

This report describes the manufacture of five, very fast, high voltage capacitors. The program was a follow-on to an earlier one in which the fundamental principles of the process were demonstrated. The five capacitors are intermediate in size between the very small (1-1/2-inch diameter) early capacitors, and the size required for a real system.

The target characteristics of the capacitors are:

Charging voltage	-	200 kV
Capacity	-	4400 pF
Physical dimensions	-	24-inch diameter 1-inch thick
Internal inductance	-	0.01 nh

The limit on size of a real system are determined entirely by the size of the Mylar sheets available. A width of 1.8 meters and any length which a reasonable building would accommodate are the only absolute limitations.

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SECTION 1
INTRODUCTION

This section describes briefly the arguments behind the design of the particular type of capacitor with which the program was concerned. For the most part, it is an extract from an earlier report to the Defense Atomic Support Agency on the previous work on this type of capacitor.

1.1 General Limitations on Fast Condenser Design

We begin with a description of the main characteristics of the systems for which fast condensers are intended. Briefly, they are:

Voltage	-	1 - 20 MV
Storage Capacity	-	0.05 - 5 MJ
Energy Delivery Time	-	5 - 100 nsec

For the purposes of this section, we restrict ourselves to systems in which the primary energy store is a condenser in something like the normal sense, and ignore transmission line storage approaches.

Most such systems are "three stage" devices. That is, the primary store is made up of condensers arranged in some voltage multiplying configuration (such as a Marx). This type of capacitor can also be used in a very fast Marx configuration. They are charged to some relatively low voltage, generally about 100 kV. These condensers are switched into an auxiliary store, and this auxiliary store is switched into the load. The speed required is obtained by the design of the auxiliary store. It is easy to see why this system has two advantages, since we need only to hold megavolts for short times, and since this auxiliary store can be a transmission line and therefore very fast.

The first advantage arises from the fact that the pulse breakdown strength of oil (the common insulating medium for the auxiliary store) is much better than its dc strength at megavolt potentials.(1) Nevertheless, there remains an advantage in making the primary store as fast as one can. This subject is one of considerable complexity, but the trend over the past few years has been for system designers to strive for the fastest primary store condenser available. In part, this comes from the need for auxiliary storage in water, whose properties require that the primary store deliver its energy as fast as possible.

We turn now to the present design limitation on the rate of energy transfer, or speed of primary storage condensers.

1.1.1 The Breakdown Strength of Dielectrics

The first limitation on speed of energy delivery arises from the fact that this speed is related to the size of the condenser. The ideal condenser is one in which the energy can be delivered at a rate limited only by the speed of light in the dielectric medium of the condenser, and in which the energy is all stored very close to its output terminals. Thus, it should behave as a transmission line, its output terminals should be also in the form of a transmission line, and the energy density should be as high as possible. From these requirements, it is easy to see that the highest energy density requirement implies that the highest breakdown strength is a prime need. We observe that the energy density in a transmission line is given by:

$$e = \frac{\epsilon E^2}{8\pi} \times 10^{-12} \text{ J/cc}$$

where:

ϵ is the dielectric constant

E is the applied field strength in the dielectric

We take ϵE^2_{max} as the figure of merit of the dielectric, where E_{max} is the highest practical value which E can assume in the configuration involved.

The value of E_{max} for real dielectrics cannot be described in simple terms. The next section gives a short account of this complicated matter.

1.1.2 Area and Volume Effects on E_{max}

J. C. Martin(2) has shown that the breakdown strength of dielectrics is a function of the area or volume of the stressed dielectric. In the case of liquids, it is an area effect (complicated by higher order total voltage, gap and time variation). For solids, and in particular thin solid sheets of material, it is a volume effect. His experimental results for a variety of materials used in fast condensers is shown in Figure 1.

Figure 2 shows the required storage volume for mylar for a range of energies, assuming the mylar is stressed to its breakdown value. Figure 3, derived from Figures 1 and 2, shows the relation between energy storage and field strength for the same conditions. We note that in going from 300 J to 100 kJ, the breakdown strength has decreased by a factor of 2, and the energy density by a factor of 4.

The theoretical interpretation of these curves, of course, is no more than a refinement of the well-known fact that the statistical distribution of the failure point of any component has the effect of lowering the failure point of an assembly of components, and in fact Martin's analysis follows this argument.

Another less direct and technical reason for prefering to use the highest breakdown strength material and conditions, of course, is that by doing so we reduce the size and, therefore, the cost of a system.

1.1.3 Edge Effects

So far, we have considered only the intrinsic limitations of the materials of the condenser. Another limitation arises from the fact that all dielectric-conductor systems used in condensers have edges. (We have ruled out coaxial transmission lines, which have only ends.)

A great deal of the know-how in the design of a fast condenser concerns the correct treatment of the conductor edges. It is easy to see why this is, if we consider a simple strip line. Figure 4 shows such a line, formed from two strips of foil separated by a strip of dielectric material whose width

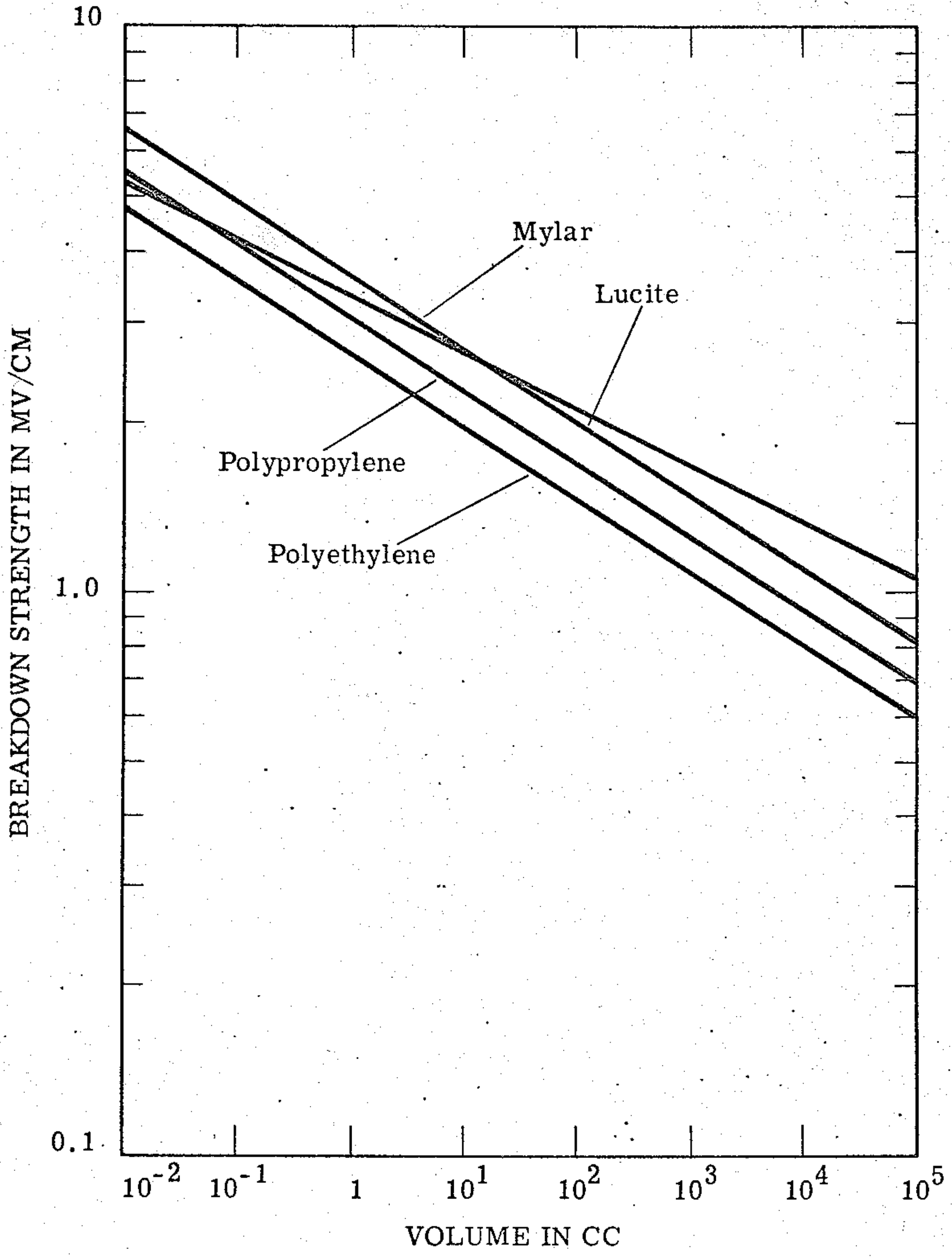

Figure 1. The Strength of a Variety of Dielectrics as a Function of Volume. Reference J. C. Martin, Private Communication.

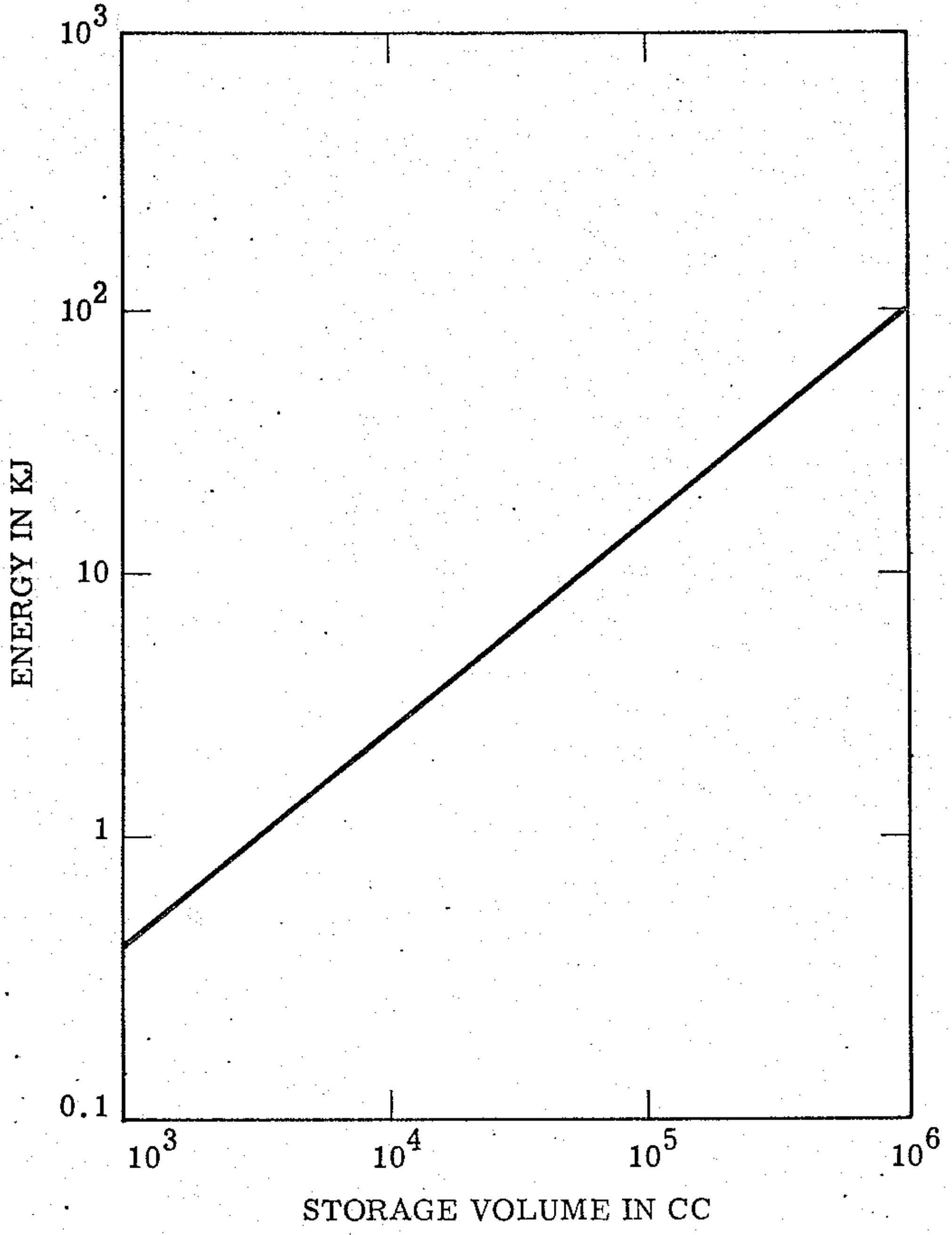

Figure 2. The Energy, Storage of Mylar as a Function of Energy.

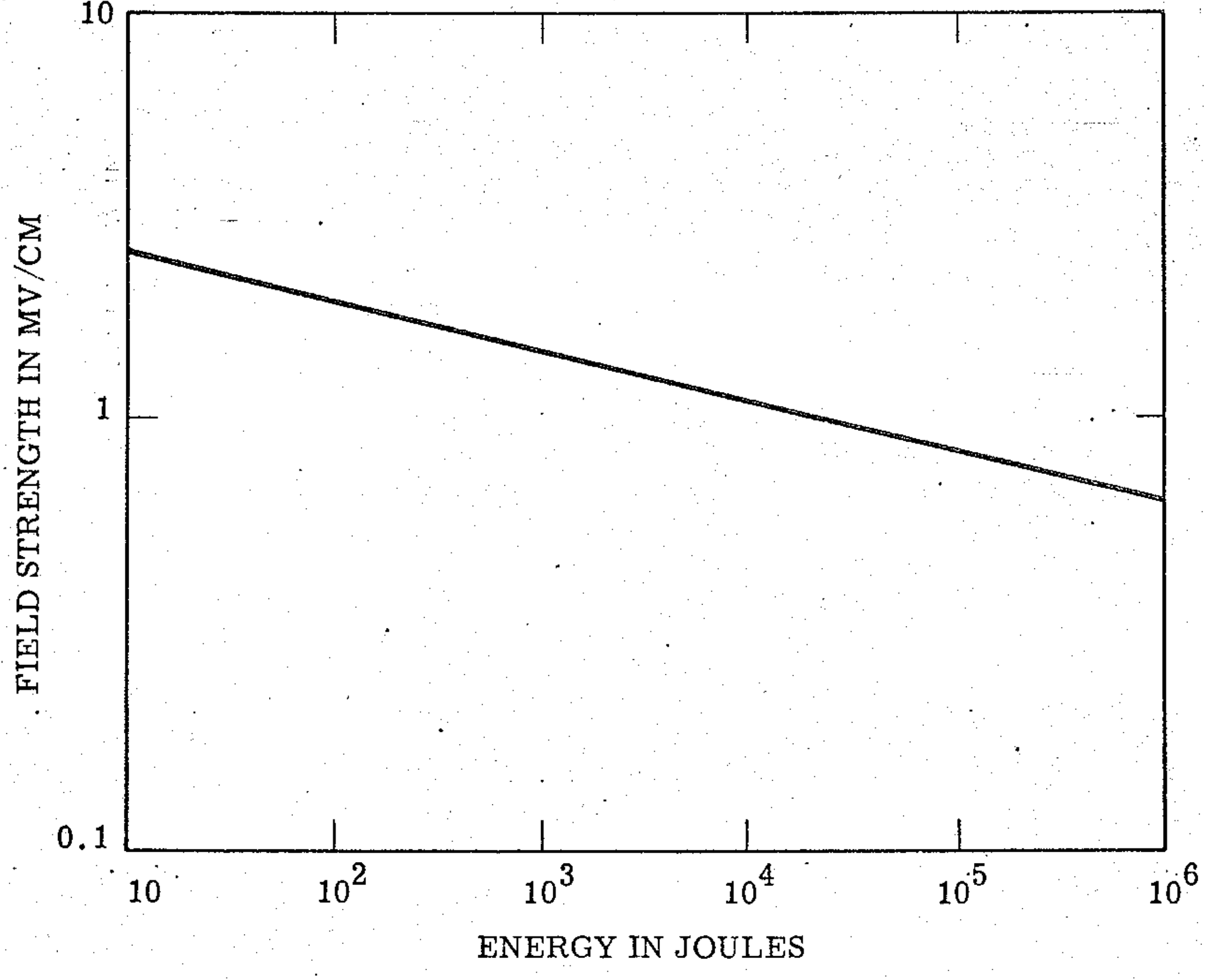

Figure 3. The Electrical Stress Supportable by Mylar as a Function of the Energy Stored. Reference J. C. Martin, Private Communication.

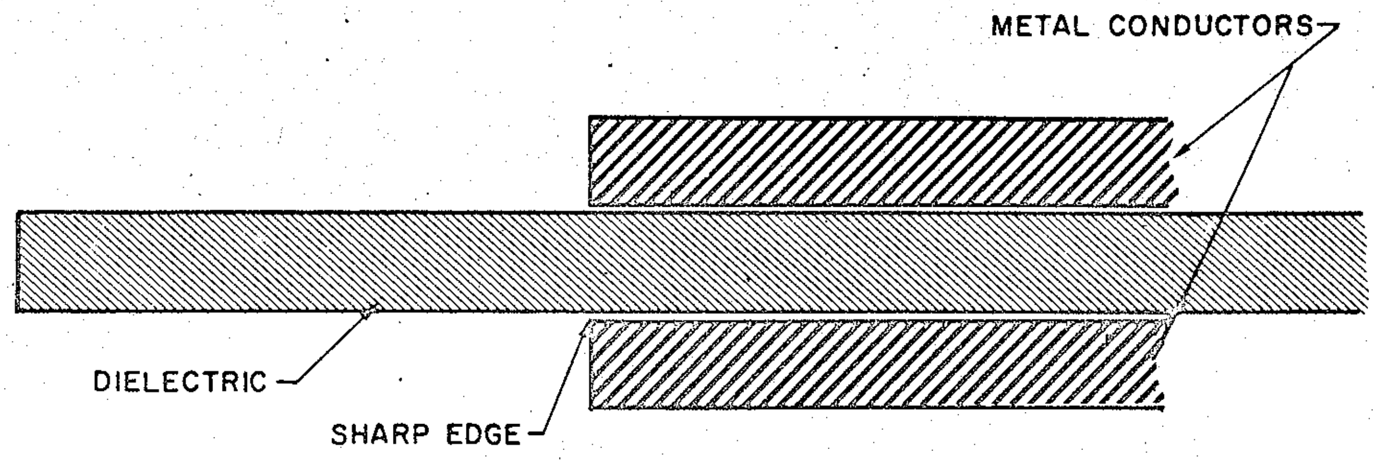

Figure 4. Edges of a Strip Line

is wider than the metal foils. If the foils are thin, their edges will have very small radii and many imperfections. The field enhancement due to these edges will be great.

Nevertheless, the volume of stressed dielectric will be small, and Martin's analysis shows that breakdown through the dielectric at these edges should not be as likely as one might at first imagine. The author's experience with such strip lines tends to confirm this view. A hypothesis which might explain the mechanism of failure due to edges arises from the fact that streamers can grow rather readily along the interface of two dielectrics. Thus, the first enhancement will cause a streamer to move out from a point on the edge of one foil, and along the surface of the strip line dielectric. See Figure 5. After the streamer has grown a little, it will produce its own field enhancement, and a streamer will grow from the other foil. As these two streamers on either side of the dielectric move away from the foils, they produce a very large field across the dielectric, particularly at their tips. At some point, this field is large enough to puncture the dielectric, and the strip line fails. The author has observed this for many simple strip lines formed of 0.005-inch copper foils and 0.020-inch mylar sheet. The strip lines were in air (generally wet English air) and their mode of failure was clearly visible. Frequently, the mylar failed about 0.5-inch from the edges of the foils. This failure occurred at voltages of 5 to 10 kV, which produced only a few percent of the estimated breakdown field in the body of the mylar.

There are many ways of reducing the effect of edges in condenser systems. Martin describes one in which the fields at the edges are reduced by the use of conducting papers or solutions.(2) Many manufacturers of condensers have their own, undisclosed, techniques for mitigating this problem.

1.2 The Effect of Condenser Construction on its Speed

So far, the condenser has only been considered as a strip line with a volume of stressed dielectric and some edges. To be useful, it must also have output terminals, to which output leads may be attached.

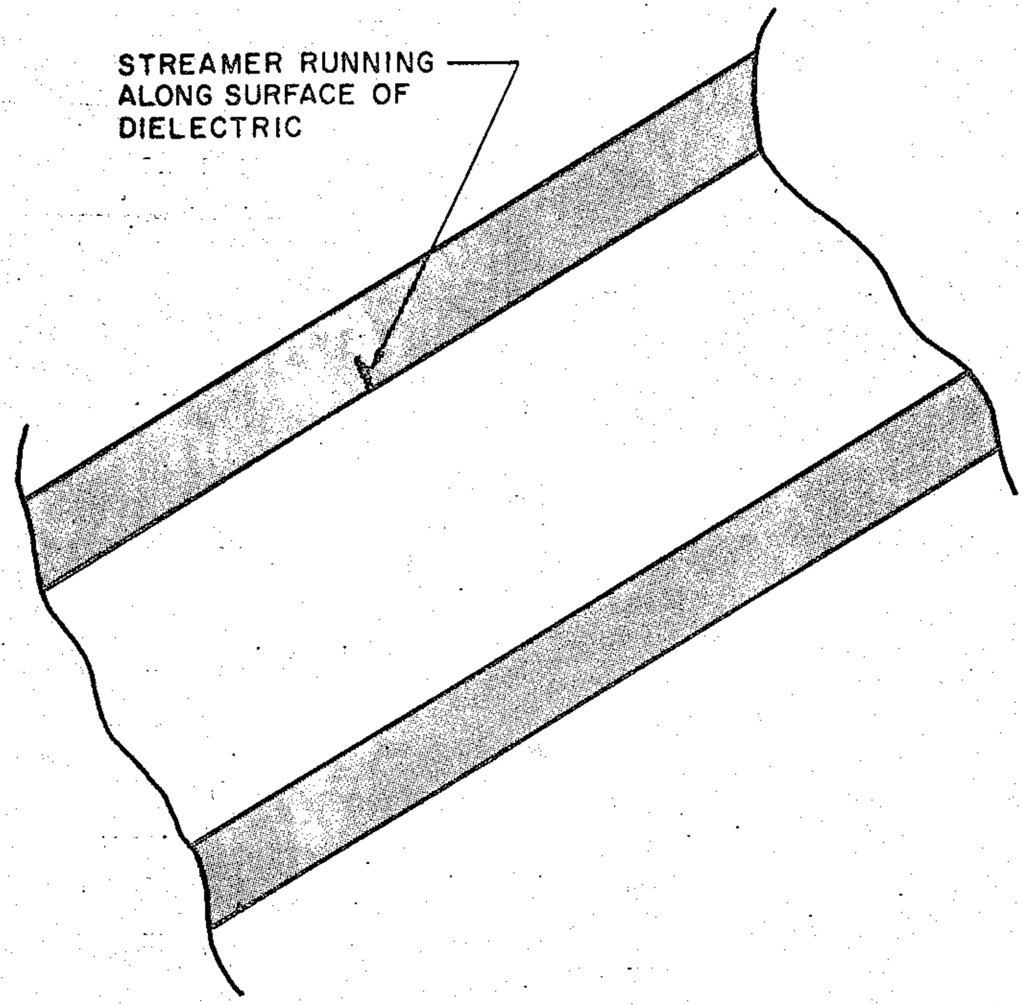

Figure 5. Streamer Moving Out From Edge of Foil

This has its own problems. For a practical condenser, one must have a joint between the condenser dielectric and the output lead dielectric. The leads may go to another condenser unit in the same case, or to the output leads of the condenser case.

In real condensers, the greater part of the total "undistributed" inductance is in these leads. By "undistributed" is meant that inductance which is not associated with capacitance in the correct strip line relationship. This inductance acts as a lumped quantity in the discharge of the condenser and prevents the unit discharging as a pure transmission line. It has a vital effect on the speed of the condenser.

The remainder of the "undistributed" inductance arises from the need to connect short sections of strip line in parallel in order to avoid having too long a line. For example, suppose we designed a 10 kV, 1 μF condenser from a simple strip line. Take the operating field strength as being 500 v/mil, a conservative value. If the foil conductor is 15 cm wide, the strip line becomes 160 nsec long. Thus, even if we discharge it into its characteristic impedance (0.045 ohm), its discharge time would be 160 nsec. (Its output voltage would be, of course, 5 kV.) All other terminations would result in longer discharge times. Thus, we cannot allow a condenser strip line to become long electrically. The construction, therefore, must be some form of multiple connection.

Rapidly, the condenser becomes, not a transmission line, but a component with lumped constants. A great part of the secret of constructing fast condensers lies in the design of these multiple connections, and their feeds to the output terminals.

1.3 High Voltage Condensers

The normal operating voltage of one winding of a fast condenser is generally limited to 8 to 10 kV. The reason for this presumably arises from difficulties with edges and multiple connections at higher voltages. Thus, a 100 kV condenser must be made up of a number of such windings connected in series. Again, a penalty must be paid here for the many internal inductive connections.

Overall the figure of merit of a fast condenser can be taken to be:

$$S = \sqrt{LC}$$

A typical good modern high voltage condenser might have the following characteristics:

Operating Voltage - 80 kV
Capacity - 9 μF
Inductance - 8 nanohenries
Figure of Merit - S = 0.27 microseconds

Such a condenser, being multiply connected in its windings, will behave substantially as a component having lumped circuit constants.

If we build a large system of such units we could expect to deliver the energy to a load in about a microsecond.

SECTION 2

THE HIGH POTENTIAL FAST CONDENSER (HIPUF)

We have described earlier that present fast condensers are characterized by being lumped constant components, having multiple internal connections. The intrinsic strength of the dielectric material cannot be utilized for maximum energy storage because of the field intensification at the edges of the conduction. (This last characteristic may become absent from at least one condenser design.) The rest of this report describes a condenser design which has different characteristics from those described above, and the first steps toward its realization.

It is emphasized here, and it will be repeated later, that the HIPUF design has special features which make it attractive for certain special needs. It is not to be regarded as a condenser in competition with others for any but these special fields.

2.1 The Volume Effect

In Section 1.1.2, we described the decrease in breakdown strength of thin sheets of dielectric as the volume of stressed dielectric increases. About a year ago J. C. Martin(2) reported measurements on Mylar films which showed that this decrease, under certain circumstances, could be prevented.

He showed that if one took many sheets of 0.00025-inch Mylar and made a many layered sandwich with water between the sheets, the pulse breakdown strength curve flattened off at about 100 nanoseconds of film.

Martin believed that the phenomenology of this effect arose from the fact that the layers of water between the Mylar films were effectively field free, because of the high dielectric constant of water. It is common knowledge that the dc breakdown strength of small volumes of film increases with decreasing thickness of film (Figure 6). This is probably due to the fact that avalanches have a finite length of travel before they initiate breakdown streamers, and if the thickness of dielectric is comparable to this length, an avalanche will not necessarily initiate breakdown. Thus, we see that if we use many very thin films

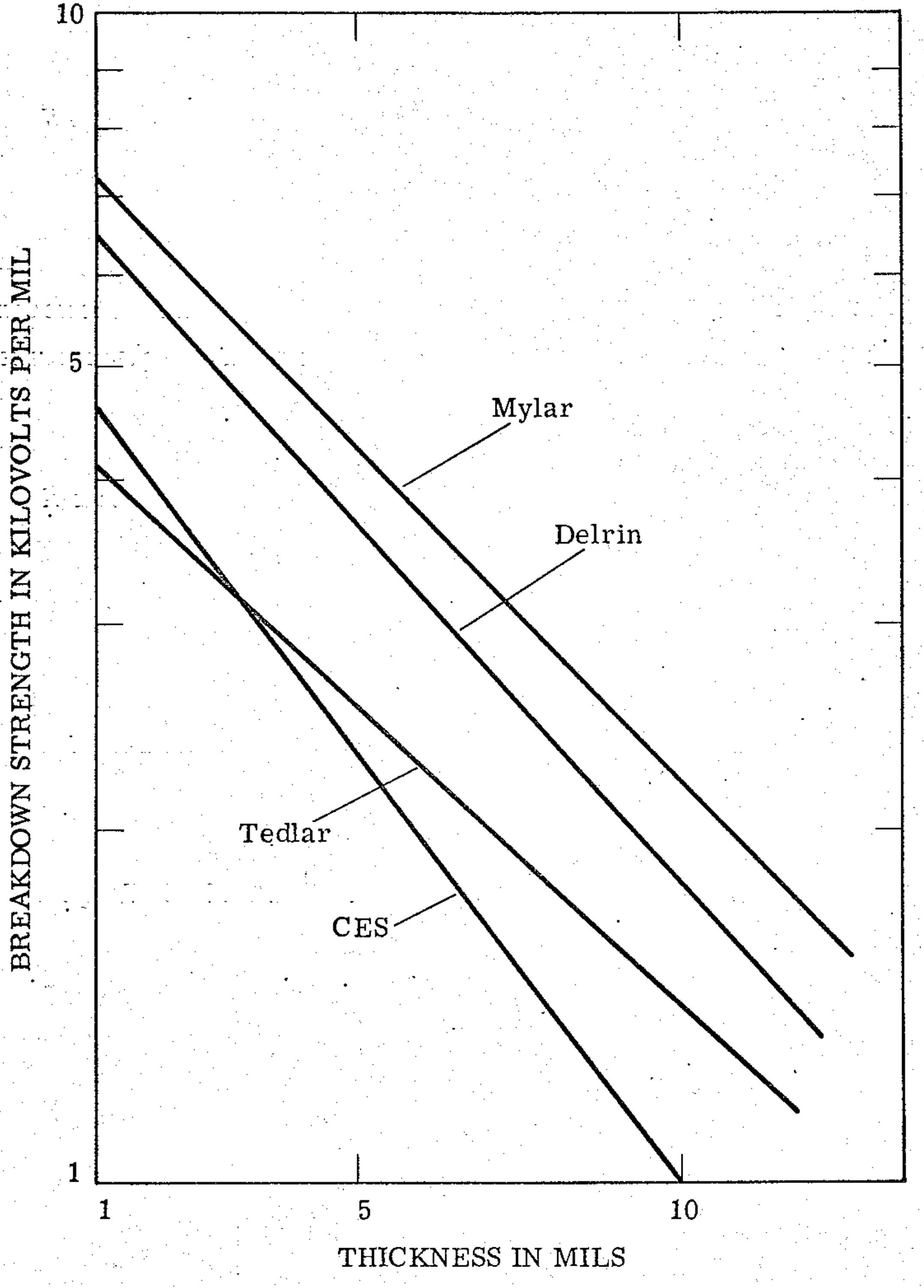

Figure 6. The Strength of Plastic Film as a Function of Thickness.

separated by field free regions we may retain the high strength of the thin films in effectively thick sections. Using Martin's results we add the knowledge that this effect can be extrapolated to large volumes. In a verbal communication, Martin remarked that he believed that this effect was common to all thin dielectric films, and arose, again, from the statistical theory of breakdown. It seems likely that if we take 20 layers, say, separated by high dielectric constants material, we shall retain the breakdown strength of only one layer of dielectric. Note that there is probably a volume effect with the "one layer", but it seems likely to be much less violent than the volume effect with the 20. This arises from the fact that each layer can have its independent strength, since a streamer breakdown never propagates from one layer to the rest through the field free layer.

2.2 The HIPUF Edge Grading

We cannot take advantage of Martin's results to their fullest unless we can tame the edge effects. We see this immediately if we consider the result of using, say, 100 layers of 0.00025-inch Mylar in an attempt to obtain high energy density. We might hope to operate at about 3 MV/cm stress. The voltage across the sandwich becomes 200 kV. The stress at the edges of the conductors would be tens of megavolts per centimeter.

High Voltage Engineering Corporation, the parent of Ion Physics Corporation, has developed a special condenser for use in their Insulating Core Transformer machines. This condenser is formed of a pressed disc of polyethylene with a Rogowski profile defining a central energy storage area into which the electrodes are applied. Figure 7 shows this condenser.

This technique allows the condenser to operate reliably at 200 kV charging voltage, although the flashover path at the edge is only 3-inches.

This technique can be applied to the HIPUF condenser, by molding a resin profile around the edges of the Mylar laminate.

Figure 8 shows how this may be done. The choice of resin is important, since it must have about the same dielectric constant as the Mylar, be strong electrically, and have good molding and handling properties.

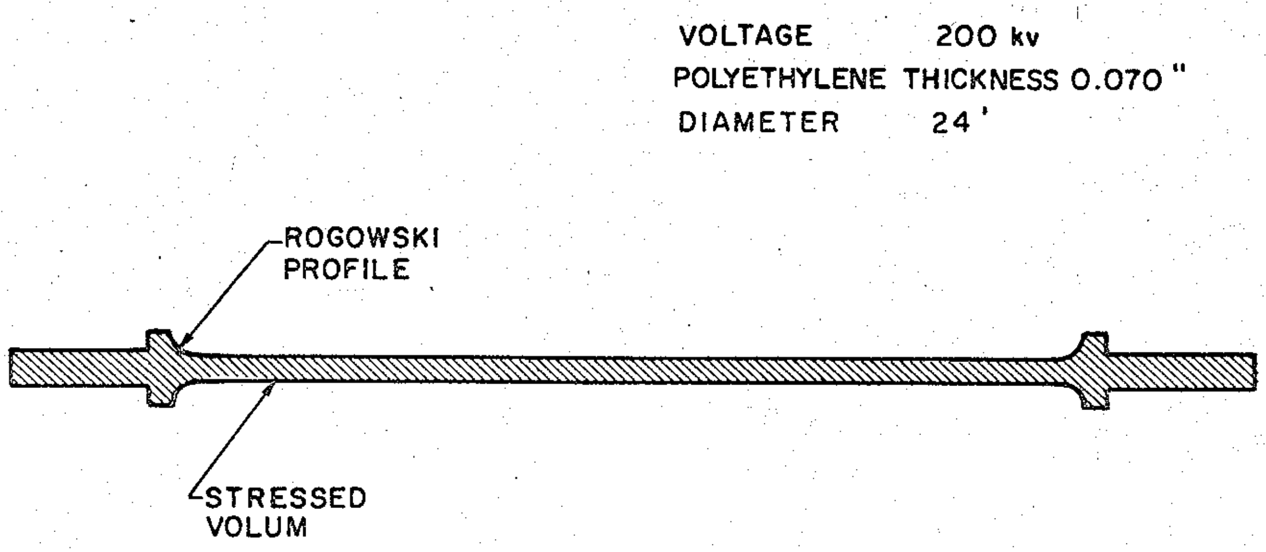

Figure 7. The HVEC Polyethylene Condenser

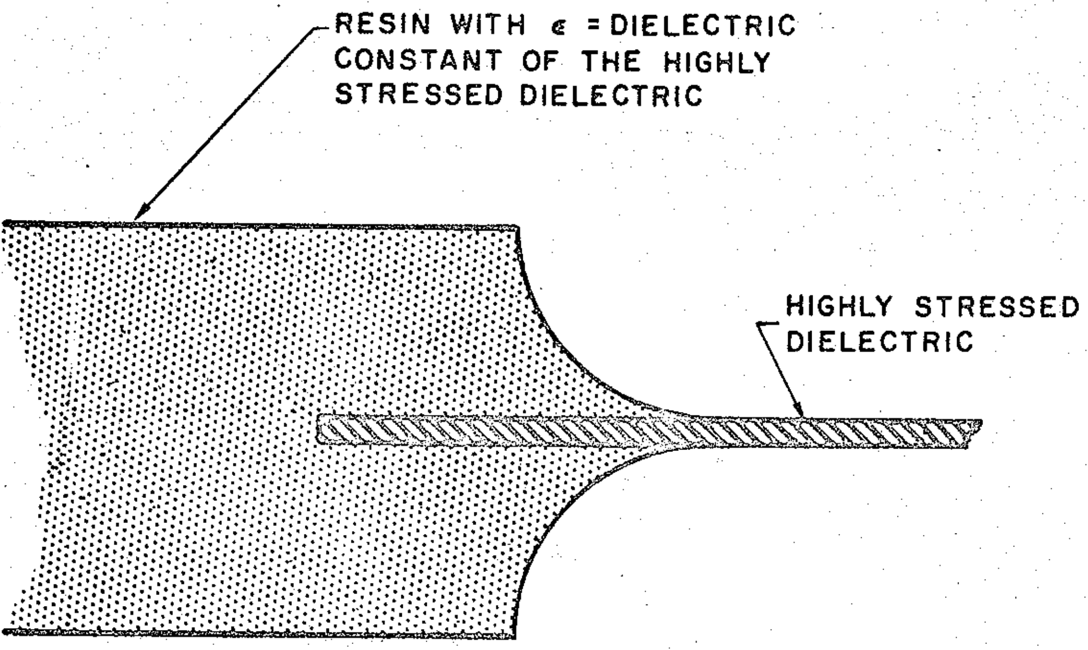

Figure 8. Resin Molded Edge for Mylar Condenser

2.3 Feasible HIPUF Systems

In principle, we can make HIPUF to any size or shape we wish, within the limitation that one dimension is no greater than 72-inches, which is the width of a Mylar roll.

The basic capacity and energy storage is:

Capacity per square centimeter = 6 pF for 24-1/2 mil layers
Energy storage per square centimeter = 0.12 J at 200 kV

The following are a few capacitors which are of future interest. The thickness in all cases is 0.5-inch, which is the thickness of the resin frame.

A. Circular Capacitor, 24-inch OD

C = 10,000 pF
E = 200 J

This (A) would be a suitable substitute for the ALEC type capacitor, increased to ARES size.

B. Circular Capacitor, Maximum Diameter 6 feet

C = 0.13 μF
E = 2.6 kJ

C. Strip Line, 3 feet wide, 50 nsec Double Transit Time Long

Length = 12 feet
Energy Stored = 3.4 kJ

D. Maximum Width Strip Line, 6 feet wide, 50 nsec Long

Energy stored = 7 kJ

The impedance of the strip lines is very low. For C it is 0.12 ohms, for D, 0.06 ohms. If we make a Marx generator of 2 MV open circuit voltage, the impedance will only be about 1 ohm. This assumes, of course, that the switches are distributed, and ignores the problem of the load return conductor.

We conclude that the strip line configuration is of no obvious value for Marx generators. The bulk of the Marx will be hardly less than a normal arrangement, and the impedance is so low that we cannot use it.

This adds point to the description of the HIPUF capacitor as a very special capacitor, for very special uses.

The strip line version has interesting properties for a distributed source wave launcher. Note that we may flare the line out, and transform its impedance at will. Little energy will be stored in the high impedance region, and we can easily attain a 50 ohm level at the output. It is ideal for a distributed switching configuration. Note too, that its environment need be only one atmosphere of SF_6. No pressure vessels or oil tanks are required.

SECTION 3

THE EXPERIMENTAL PROGRAM

The experimental program has been determined largely by the molding components available at the start of the program.

IPC has a number of electrodes which had been used for breakdown studies in vacuum. Their use as molding components did them no harm, so it was decided that their use in this program would expedite the work considerably. These electrodes were in two sizes, 1-1/2-inch diameter and 14-inch diameter. The first was well suited to a preliminary examination of the concept, and the 14-inch diameter electrodes allowed us to make a condenser of some value. The best of these was a pair of electrodes 14-inches in diameter. This determined the size of the capacitors.

The next choice of component was the high dielectric constant layer between the Mylar sheets. This material must have a dielectric constant greater than 20, a reasonable breakdown strength, and a conductivity as low as possible and certainly below 10^{-10} mhos/cm. In addition, it should be of a nature which allows us to make a void free sandwich with the Mylar. Such a material is cyanoethylsucrose. It has the following properties.

Dielectric Constant	- about 30
Breakdown Strength	- see Figure 6
Resistivity	- 10^{12} - 10^{13} ohm-cm
Viscosity at Room Temperature	- 5 x 10^5 cp
Solubility	- soluble in acetone, MEK

The resin chosen to mold the edge must have a good breakdown strength, high resistivity, a dielectric constant about equal to that of Mylar and some flexibility. The resin chosen was Emerson and Cumings' 1264 Stycast. Its properties are:

Dielectric Constant	- 3.6 - 4.0
Resistivity	- 10^{14} ohm-cm
Breakdown Strength (ASA)	- 400 v/mil
Mechanical Properties	- "semi-flexible"

3.1 Laminating

The laminating process was one which had been developed during the earlier program. In principle it is a very simple process, but it has proved completely adequate for the manufacturing of a limited number of units.

A photograph of the apparatus is shown in Figure 9 and a drawing in Figure 10.

The Mylar is unrolled from the spool, inspected for imperfections and secured at one end of the metal tray. A retaining barrier is laid on the sheet at the secured end and a roller passed over the sheet from one end to the other. By this means all bubbles of air are excluded from the Mylar, and a uniform layer of CES-Acetone solution trapped beneath the sheet. 24 layers of 1/2 mil Mylar were so laminated.

When the requisite number of sheets has been laid down, the tray is drained of solution and the composite sandwich hung up to dry. Mylar is very permeable to Acetone, and within two days the sandwich is ready to be made into a capacitor.

Care was taken to exclude all foreign matter from the solution, which was filtered between each manufacturing exercise. Since the Mylar was only exposed to the atmosphere for a short time (about 30 seconds) no foreign matter had time to settle on it.

3.2 The Casting Process

When the sandwich had been prepared, it was cut into a circle slightly larger than the 14-inch diameter electrodes. The casting process was carried out in two stages, in molds. Figures 11 and 12 show the form of the molds.

Care was taken to exclude any bubbles, particularly from the area of the Rogowski profile, by running repeatedly a small sliver of 0.010-inch Mylar around under the profile.

After two days the resin had hardened enough to break the mold, and the final process of spray-coating the capacitor was carried out. The resin was masked off around the top of the profile, and the electrodes sprayed on using ECCOCOAT silver paint.

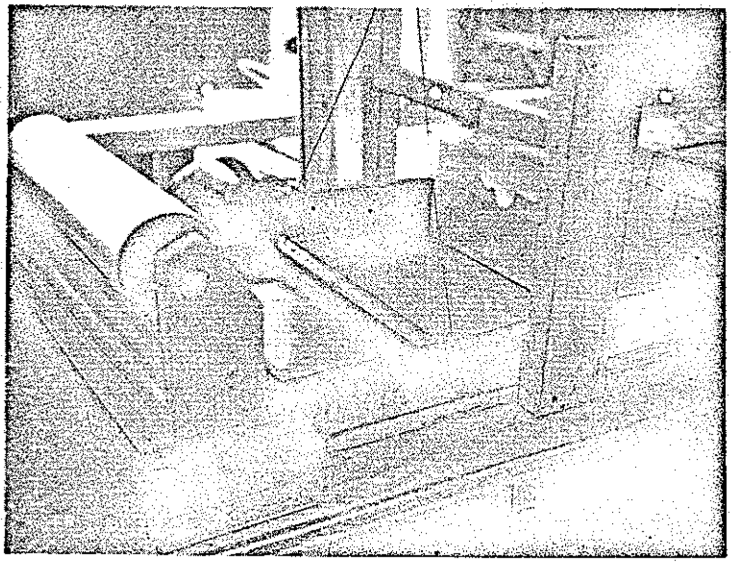

Figure 9. Lamination Apparatus.

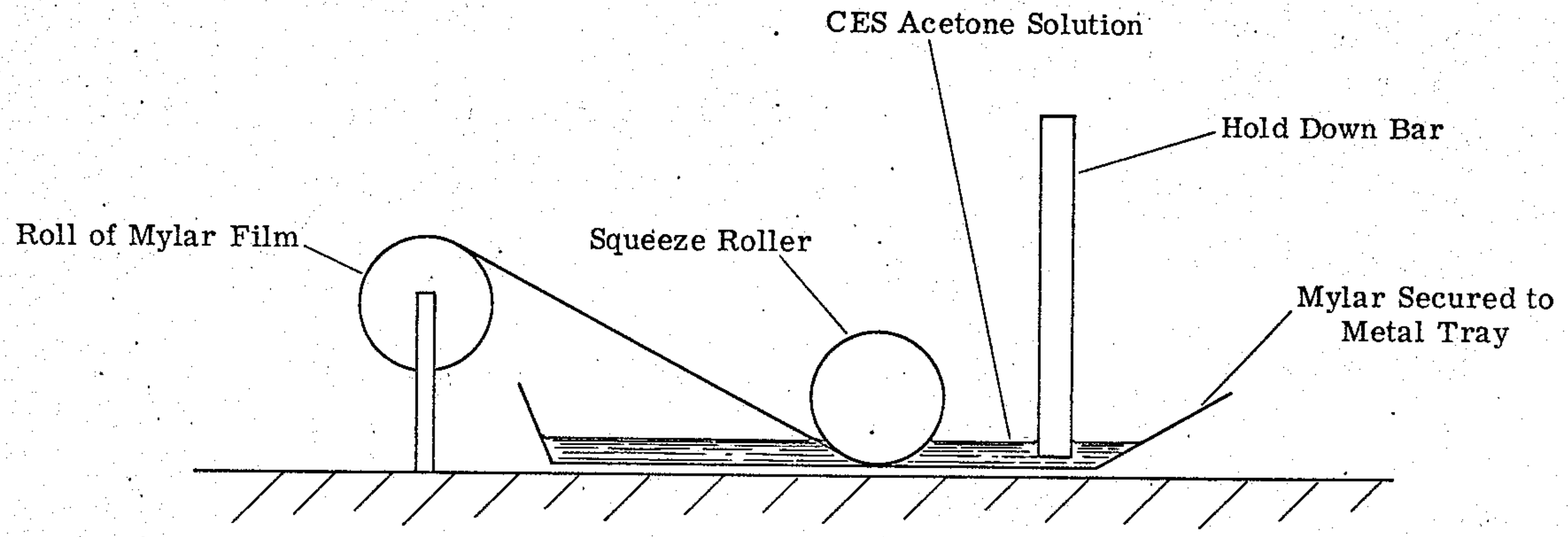

Figure 10. Lamination Apparatus.

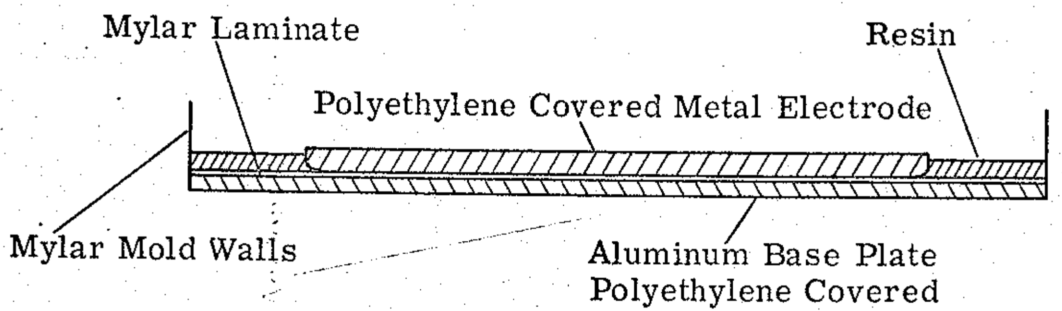

Figure 11. First Mold.

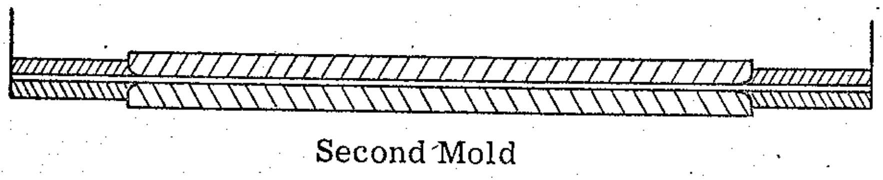

Figure 12. Second Mold.

3.3 The Capacitor Testing

The apparatus available for testing the capacitors consisted of a small 0.25 MV Van de Graaff generator, and a 585 Tektronix oscilloscope.

Three capacitors were selected for testing. The capacitances of these were measured by shock exciting a resonant circuit comprised of the capacitor and a coil of calculable inductance. The frequency of ringing was measured using the oscilloscope. The inductance of the coil was calculated from

$$L = \frac{0.0395\, a^2 n^2 k}{b} \quad \text{microhenries}$$

taken from the Handbook of Physics and Chemistry.

a - is the radius
b - the length
n - the number of turns, and
k - a function of $\frac{2a}{b}$

The results of the measurements are tabulated in Table I below:

Table I

Capacitor	Capacitance
No. 2	4440 pf
No. 5	4810 pf
No. 9	4610 pf

The inductance poses a few problems. If we assume that the terminals are the edges of the conducting Bruce profiles, we may use the relation for an annular ring in the radial conduction form.

$$L = \frac{2h\,\delta r}{r} \times 10^{-10} \text{ henries}$$

where

r - is the radius
h - the separation, and
δr - the width of the ring

If we integrate this for the present capacitor, we obtain

$$L = 0.04 \text{ nanohenries}$$

This is the "internal" inductance.

The capacitors were tested for high voltage strength using the equipment shown in Figures 13 and 14. The voltage was measured by a sphere gap filled with SF_6. The spheres were 4-inches in diameter, in a Lucite enclosure. The breakdown strength of SF_6 was taken from Reference (3), using the Paschen's Law correction for Albuquerque pressure, and another correction was made for the non uniform field. It is estimated that the measured voltage was correct to about ±10 percent.

Two capacitors reached 200 kV without failure. One failed during the charging period (some two minutes).

One of the remaining capacitors was put through a short circuit pulse test. The sphere gap was set for a certain voltage with the earth side of the gap connected to the earth side of the capacitor through approximately 0.2 microhenries. Thus when the gap broke down at 200 kV, approximately 60 kiloamps passed through the circuit at peak, and it rang with a frequency of 14 Mc. The oscilloscope proved unable to write with the necessary speed to record the ringing, but an estimate from the length of the pulse indicated at least 10 oscillations greater than half the initial cycle were present. Thus one breakdown could be said to be equivalent to at least 5 cycles.

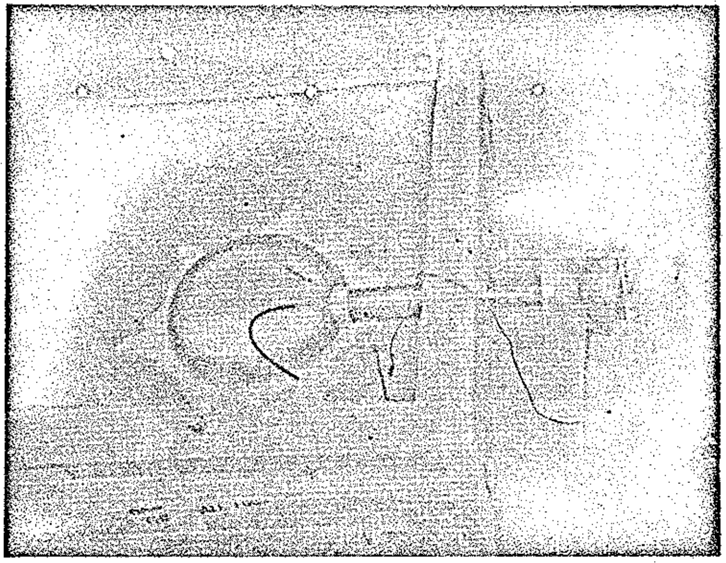

Figure 13. High Voltage Test Rig.

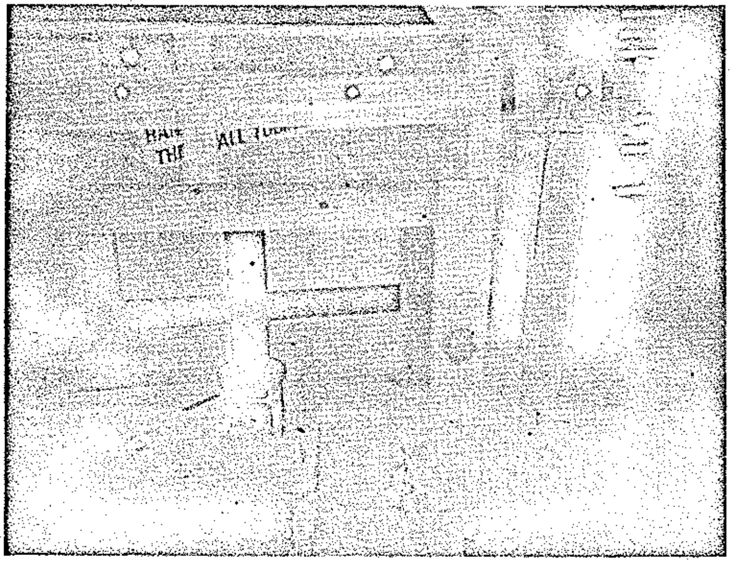

Figure 14. High Voltage Test Rig.

The capacitor was charged to approximately 200 kV and discharged 38 times, at which point it failed. An examination of the capacitor showed many fine brown discolorations in the conducting surface, indicating very uneven current flow. The mold electrode used to provide electrical contact to the conducting surface was not a very good fit due to distortion of the resin edges after casting, and it is felt that the current flow across the surface of the capacitor was uneven. This had obviously led to burning of the conducting paint, and probably to the failure at one edge, probably where the metal electrode happened to touch near the failure point.

This method of testing is a very severe one, and the imperfections of the electrode attachment were, with hindsight, likely to lead to unfair testing.

We might conclude that the capacitor could withstand at least 200 pulse discharges with greater than 25% field reversal.

An attempt was made to measure the leakage and internal resistance. A 30 kV power supply was connected across a capacitor through a micromicroammeter. At 10 kV a current of 0.03 microamperes was recorded, giving a resistance of 3×10^{11} ohms. However, this resistance appeared to be voltage sensitive, going down with increasing voltage. This gave rise to the suspicion that the current might be due, in part at least, to corona currents.

In addition, the measurement could not separate leakage currents from internal currents. The surface leakage resistance could be voltage sensitive.

It was concluded that more sophisticated methods would be needed to measure these quantities.

The power factor was measured using the oscilloscope to measure the phase angle between current and voltage when the capacitor was driven by a 10 kc signal generator. The voltage across the capacitor was applied to the vertical deflection plates and the voltage developed across a resistor in series with the capacitor was applied to the Y plates. The resultant waveform allowed a measurement of the power factor. However, the power factor

$$\cos \emptyset = R_S C \omega$$

where R_s is the series resistance, C the capacitance and ω the angular frequency. The series resistance is merely the resistance of the conducting layer and cannot be more than a few ohms. Thus at any frequency less than about 10 Mc the power factor will be extremely small. And thus it proved that the power factor was less than the measurement was capable of giving.

SECTION 4

THE USES OF THE CAPACITOR

With most capacitors the system in which they are used is to a large extent independent of the capacitor; for example, one may conceive of a Marx generator and merely indicate the capacitors as boxes. The electrical characteristics of the system will, of course, depend on the capacitors, but the basic design will not.

In the present case, the capacitor must be, to a great extent, the system. To achieve the speed of which the capacitor is capable the capacitors must be connected by strip lines. Thus the capacitors, connectors, switches and load must be an integrated whole.

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