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Development Of High-Voltage Mylar Capacitors

by

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Abstract

This report contains the results of a test program to develop an impregnated mylar high-voltage capacitor. The goal was to obtain a life in excess of 2500 discharges at an energy density of 5 joules/in.^{3} at 100 kV. The work was performed in four parts: Phases I and II involved an empirical study of the dependence of the life of individual capacitor sections on voltage and stress, core size, and impregnation cycle. Phase III contained the testing of series sections, and Phase IV tested prototypes. The results obtained in Phases I and II demonstrated conclusively that the energy density and/or life of the mylar-foil capacitor windings is considerably higher than any other known energy-storage capacitor, that the goals stated are realistic, and that the life is proportional to the product $V^{-4} E^{-3.5}$, where V is the charging voltage and E the average electric field in the winding. In Phase III it was shown that the life of a series stack can be determined from the statistical distribution of failures of single windings if there are no faulty windings in the stack. A technique to eliminate faulty windings must be developed before the full potential of these capacitors can be exploited. Ten prototype 30 to 50 kV capacitors were tested in Phase IV. In the final units an average life of 1100 discharges was obtained at 5 joules/in.^{3} at 44 kV. The test data confirmed initial expectations that the use of mylar-foil capacitors will result in significant economic advantages in the construction of the energy storage banks used in large pulsed high-voltage systems.

1. Objective

The objective was to develop a 100 kV pulse-discharge capacitor, with a minimum life of 2500 discharges at 90 percent reversal, at an energy density of ~5 joules/in.^{3}. Data obtained before the start of the present program had indicated that mylar-foil capacitors would have a life in excess of 10,000 shots at 5 joules/in.^{3} in circuits where voltage reversal was small. From the practical standpoint of building large pulsed high voltage systems we feel that the stated requirement of 90 percent reversal is overly severe, and recommend that the requirement be for a capacitor rated for 50 to 75 percent reversal which will not be damaged by an occasional 90 percent reversal.

2. Discussion Of the Problem and Test Program

It is well known that the number of discharges that an energy storage capacitor can withstand is a strong function of its charging voltage. Consequently, in the construction of high-voltage capacitors, the standard procedure is to connect low-voltage sections in series and then connect as many series stacks in parallel as necessary to obtain the desired capacitance.

The life of a capacitor is basically limited by the life of the individual sections, but effects introduced by stacking sections in series may result in a significantly lower life. Other factors, such as bushing insulation, mechanical assembly, and tab connections are fairly well understood and should not normally limit the life.

The first phase of the development program was devoted to a study of the dependence of the life of individual sections on voltage and stress. Groups of capacitors, with film thickness as a parameter, were tested at selected voltages, at a fixed frequency and reversal. In a parallel testing program, (sponsored by NASA on Contract No. NAS8-20596), the variations of life with percentage reversal and frequency were studied.

The second phase of the program was directed towards improving the life of individual windings. There are many variables, such as edge margin, type of foil, winding tension, impregnation time, core size, etc., which may be important.

Two factors were chosen for investigation: core size and impregnation time. The former because of an indication that failures occur predominantly at the core, and the latter because it affects the manufacturing time and cost. Data were taken at three core sizes and for three impregnation times.

Phase III was directed toward problems associated with stacking sections in series. In principle, the lifetime of a series stack is determined by the statistical distribution of the life of the individual sections under the assumption that the voltage division throughout the stack is uniform. For times short compared to the intrinsic RC time of a section the voltage division is determined only by the capacitance. Measurements of the voltage gradient along a series stack were made, then the life of a single section was compared with two sections in series. In the next group of tests several experiments were combined. The objectives were to determine life as a function of the number of series sections for different types of windings. The windings used in this test were not optimized for life and/or energy density.

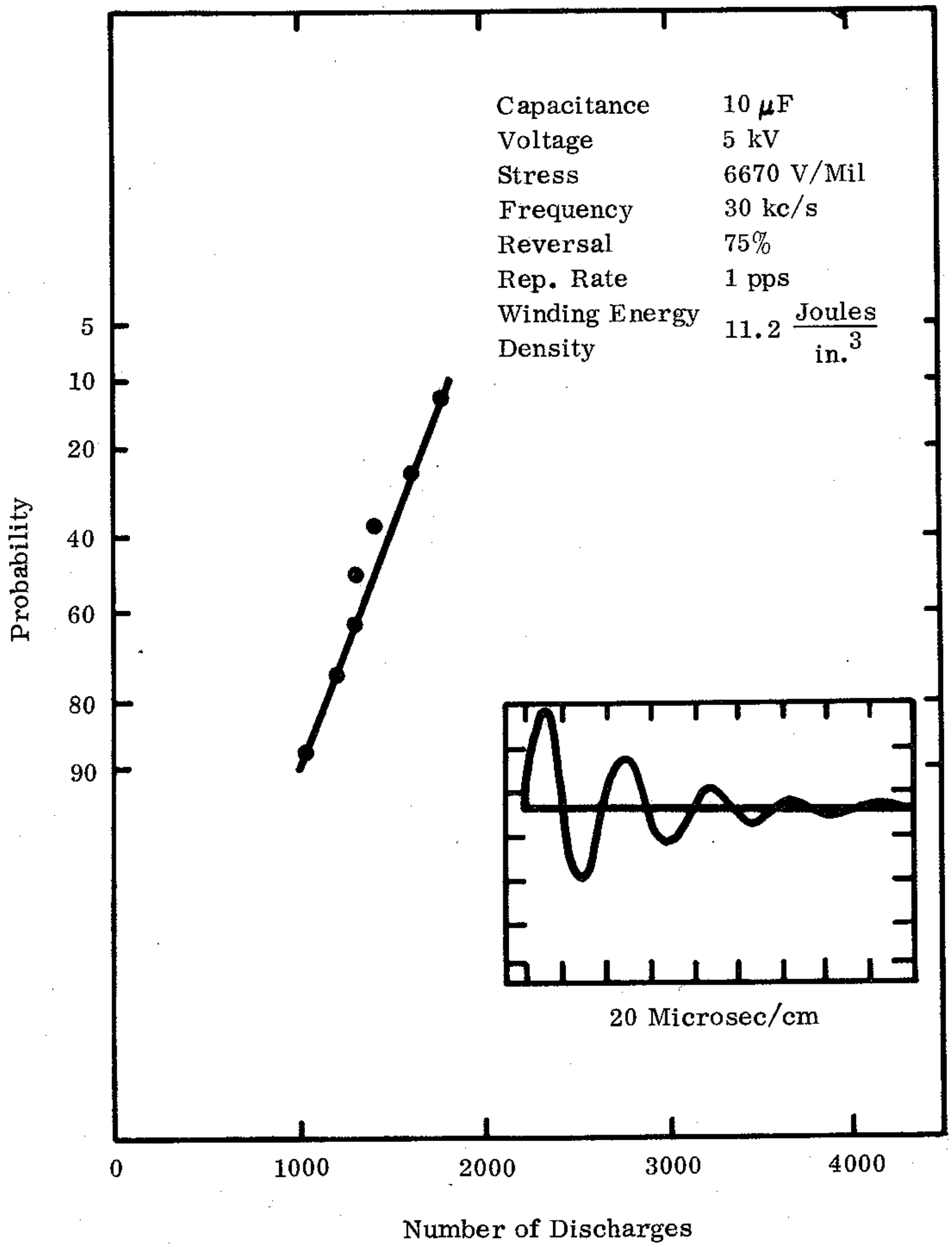
In Phase IV ten prototype 30 to 50 kV capacitors were tested.

3. Test Data

3.1. Phase I - Single Sections

The objective of this portion of the test program was to determine how the life of a single section varied with voltage and film thickness. Groups of capacitors, with film thickness as a parameter, were tested at selected voltages. The testing was performed at 30 ±10 kHz, with 75 ±5 percent reversal, at a repetition rate of 1 pps.

A typical current waveform and a typical statistical distribution of failures is shown in Figure 1. These data were obtained at 5 kV, at a stress of 6700 volts/mil, which corresponds to an energy density in the winding of 11.2 joules/in.^{3}.



Capacitance 10 μF
Voltage 5 kV
Stress 6670 V/Mil
Frequency 30 kc/s
Reversal 75%
Rep. Rate 1 pps
Winding Energy Density 11.2 Joules/in.3
20 Microsec/cm
Probability
5
10
20
40
60
80
90
0
1000
2000
3000
4000
Number of Discharges

Figure 1

The life-voltage, life-stress, and life-energy density relationships obtained are shown in Figures 2 and 3. This data shows that life of a single section is approximately proportional to the product $V^{-4} E^{-3.5}$, where V is the voltage and E the average stress on the winding.

The parallel testing for NASA was performed at a fixed voltage and stress, with frequency and percentage reversal as parameters. The test data at 3500 volts/mil (~3.5 joules/in.^{3} in the winding) at 3.5 kV is tabulated below:

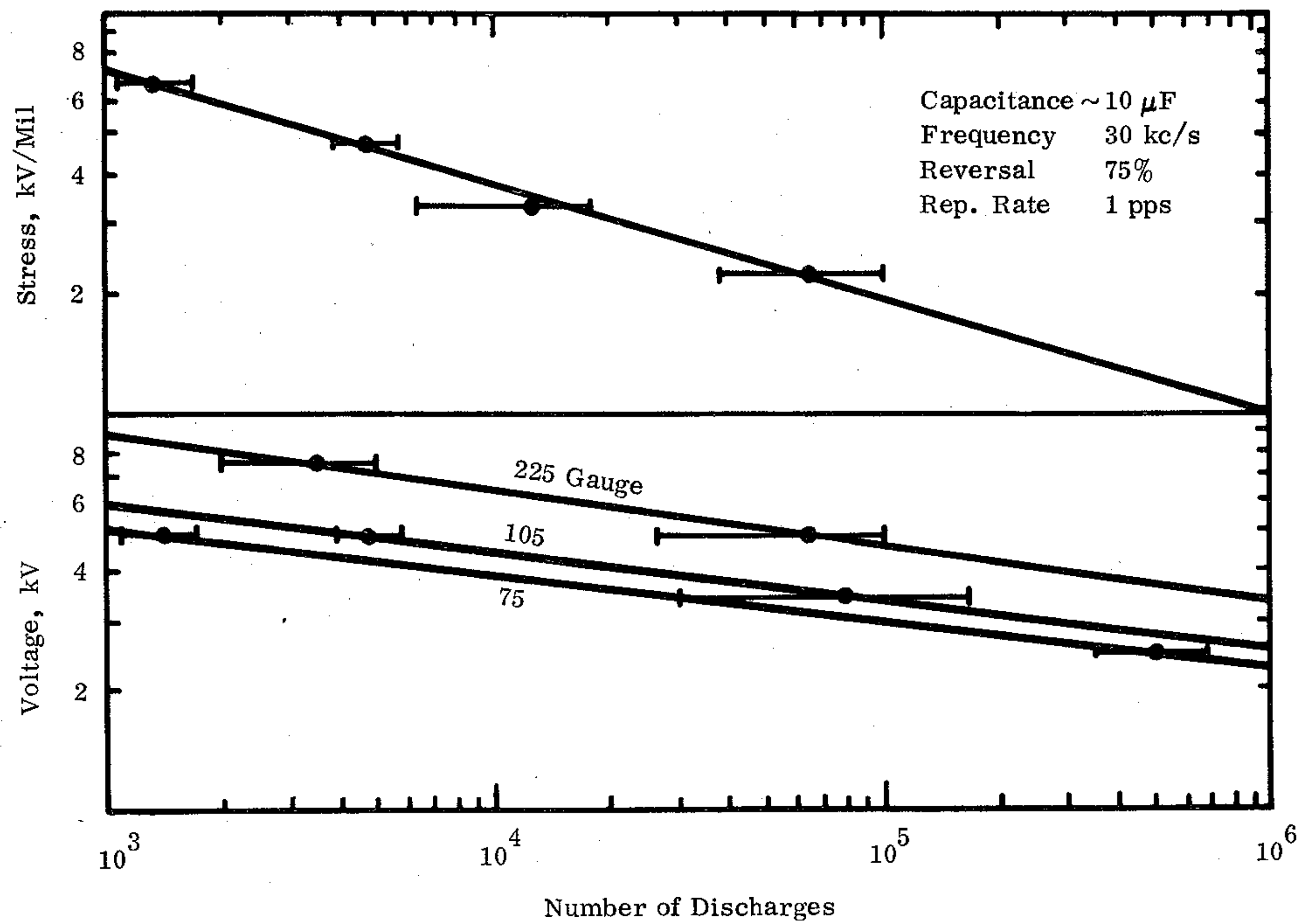
Frequency (kHz)	Percent Reversal	Life (x 10^3 Discharges)
30 ±5	90 ±5	10^{+9}_{-5}
30 ±5	70 ±10	160^{+140}_{-120}
30 ±5	50 ±10	>700 (No failures in 7 samples)
10 ±3	70 ±10	120 ±70
100 ±10	90 ±5	7 ±3

These data demonstrate that capacitor life is a strong function of reversal above 70 percent and not particularly sensitive to frequency over the range 10 to 100 kHz. The large spread on the test data is caused by small differences in the percent reversal between the samples of a particular test group. This data must be repeated with much greater precision before firm conclusions can be drawn.

Typical paper capacitors are guaranteed for 10^4 to 10^5 shots at ~1 joule/in.^{3} and 75 percent reversal. It is apparent from these data that with the MLI technology, one can obtain significantly higher energy densities and/or longer life.

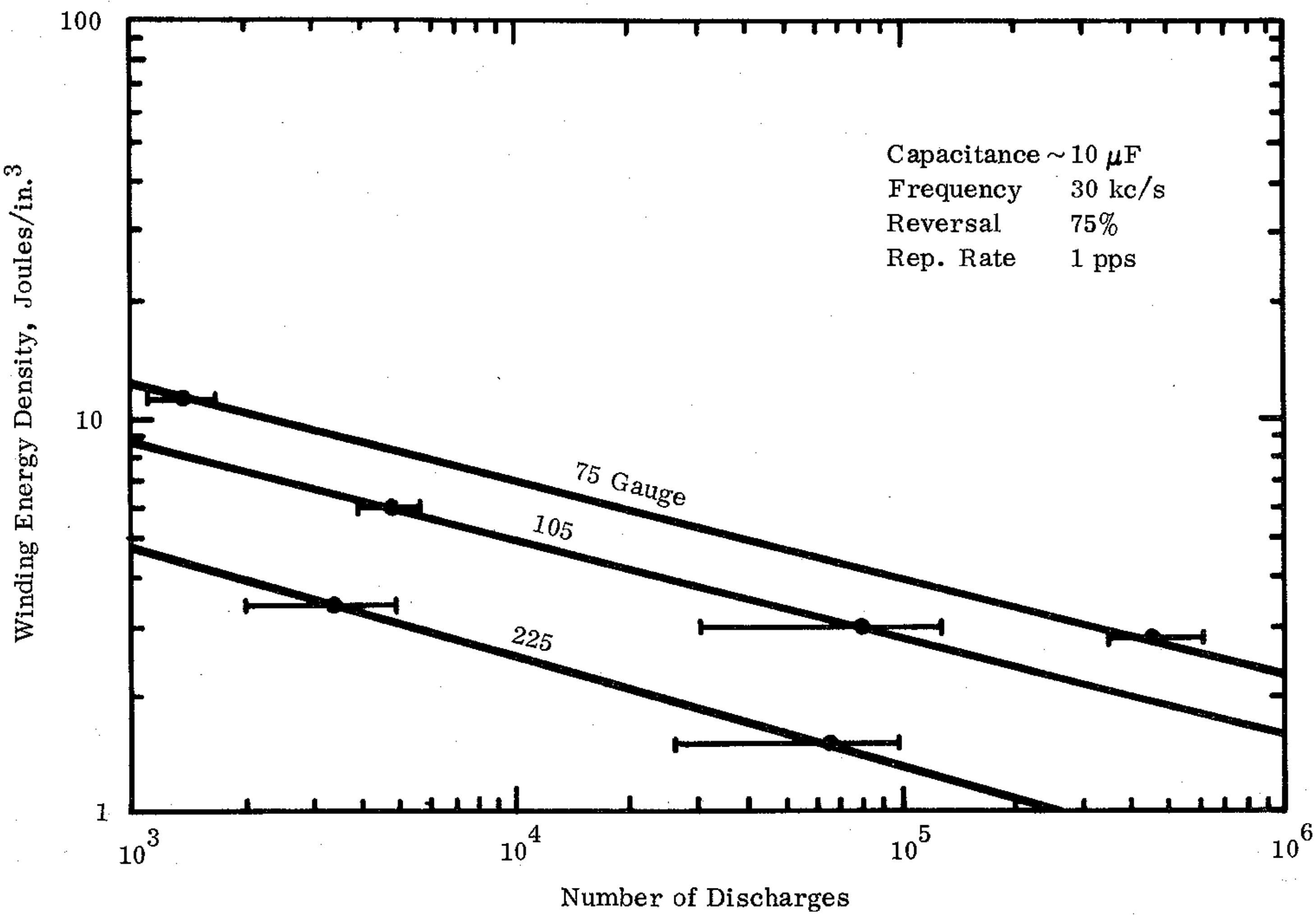
3.2. Phase II - Single Section Improvements

In many of our tests there appears to be a prodominance of failures at foil edges near the core. This effect is probably related to core diameter, winding tension, film gauge and many other variables. It was not possible to study all of these effects within the time or budget allocated, however the simplest test, core size, was performed. This test was combined with an impregnation time study.



Capacitance ~ 10 μF
Frequency 30 kc/s
Reversal 75%
Rep. Rate 1 pps
Stress, kV/Mil
Voltage, kV
225 Gauge
105
75
Number of Discharges

Figure 2



Capacitance ~ 10 μF
Frequency 30 kc/s
Reversal 75%
Rep. Rate 1 pps
75 Gauge
105
225
100
10
1
Winding Energy Density, Joules/in.^{3}
10^3
10^4
10^5
10^6
Number of Discharges

Figure 3

The results obtained are not conclusive, and to some extent confusing, but are included for reference at the request of AFWL. The test data at 3 joules/in.^{3}, 30 kHz, ~95 percent reversal are as follows:

Core Size	Short Cycle	Medium	Long
1/2 inch	49,700 discharges	9,400	22,300
	78,400	29,700	22,700
	139,400	30,800	28,700
	152,200	33,200	32,900
	174,000	127,900	78,600
1-5/16 inch	10,400	16,900	3,800
	14,500	48,900	12,100
	19,000	97,600	20,400
	41,000	109,700	27,700
	132,800	169,200	103,600
2-3/4 inch	6,800	8,700	12,200
	6,800	9,100	12,500
	17,000	12,600	16,600
	27,200	27,000	17,200
	29,000	41,900	20,200

Again the large statistical spread is caused by small variations in the percent reversal between samples of a test group.

The indication is that the short cycle, with the small core or the medium cycle with medium size core are optimum. These data are not conclusive and the test must be repeated.

3.3. Phase III - Series Sections

The objective of this phase of the program was to determine the life of a stack of series sections. In a preliminary experiment the voltage gradient along a series stack was measured under dc and pulsed discharge conditions and found to be constant within the limits of experimental accuracy, ~5 percent. The dc voltage division was measured with an electrostatic voltmeter and the ac division with a high-voltage probe.

A comparison of the life of a single section and two sections in series is shown in the following table. These data were obtained at 4 kV (7.2 joules/in.^{3}), discharging into a resistive load, so that the current did not reverse and the waveforms could be matched identically.

Test Conditions

	Single sections	Two sections in series
Capacitance	22 μF	11 μF
Voltage	4 kV	8 kV
Load	1 Ω	2 Ω

Test Data

Single sections	Two sections in series
0 (failed on hi pot)	48,500
80,914	55,500
93,956	84,300
93,036	87,787
144,000	108,646

When one section of a two-series stack fails, the other is severely overvolted and it fails. Consequently, the average life is weighted toward the low end of the statistical distribution. The lower life of the two sections in series is within the

In the next group of tests several experiments were combined. About 44 capacitors were tested at voltages between 5 and 50 kV, at 100 kHz and 90 to 95 percent reversal. The objective was to determine the dependence of life on the number of series sections, for different types of windings. The windings used were not optimized for life and/or energy density.

Four types of windings were considered, single sections and two sections wound in series, with both mylar and a mylar-paper combination dielectric. The test data is as follows:

Single Section Windings, Mylar

No. of Windings per can	1	3	5
Test Voltage, kV	5	15	25
Life, shots	8500	3750	1190
	9000	7200	2460
	10,300	7250	3130
	12,500	7900	5400
	12,500	8100	5910

Double Section Windings, Mylar

No. of Windings per can	1	3	5
Test Voltage, kV	10	30	50
Life, shots	3250	3630	2000
	3560	4650	(plus 9200
	4770	5150	without reversal)
	6070	5700	3350
	6620	5850	4390

	Single Section Windings, Mylar-paper		Double Section Windings, Mylar-paper	
No. of Windings per can	1	3	1	3
Test Voltage, kV	5	15	10	30
Life, shots	21,600	5040	5200	3900
	29,000	7320	6075	
	29,500	7500	6620	
	30,500	8950	7165	
	31,400	10,250	8330	

In most cases the failures were not caused by normal dielectric wearout. The tabs, connecting the winding to the core and bushing come off. This problem frequently occurs at very high frequencies and large voltage reversals. This is an engineering problem which can be eliminated entirely with additional developmental effort. It does not occur at lower frequencies and/or lower current reversals.

3.4. Phase IV - Prototypes

With the present manufacturing facilities, the maximum number of series sections that can be stacked in one can is about ten. To obtain reliability at high energy density, the voltage per section must be less than 5 kV, which limits the maximum voltage to ~50 kV at the present time. Thus, it was decided to build 30 to 50 kV units, and to connect them in series externally to obtain a terminal voltage of 100 kV.

A total of ten prototype capacitors have been tested. The first two were designed to test the high-voltage insulation and to check general engineering design. The windings were not optimized for energy density. These units were tested at 50 kV, at 100 kHz, with 90 percent reversal. The first unit failed at 3350 shots, and the second one at 4400 shots. In both cases, the failures occurred at the tabs, and the results were not representative of the true life of the dielectric. In the next three units more tabs were added, and the windings were optimized. The details of the test are as follows:

Test Sample:

Capacitance	1.8 μF
Voltage	33 kV
Stored energy	~1 kJ
Insulation resistance at 500 volts	950 ±200 MΩ
Dissipation factor at 1 kHz	0.006 (0.6%)
Case dimensions	O.D. 4 in. length 36 in.
Energy density in the dielectric	5 joules/in.^{3}
Overall energy density*	2.2 joules/in.^{3}

*In an improved case, an overall energy density of approximately 3 joules/in.^{3} could be achieved.

Test Conditions:

Voltage	33 kV
Frequency	30 kHz
Reversal	50 percent

Test Results:

Unit No. 1	12,100 discharges
Unit No. 2	13,000 discharges
Unit No. 3	(14,000) - not failed at close of test

Thus, MLI has obtained a lifetime in excess of 10,000 ringing discharges (50 percent reversal) at an energy density of 5 joules/in.^{3} in the windings, which corresponds to an overall energy density of 3 joules/in.^{3} in an optimized can. Already this energy density is ~3 times greater than other high-voltage capacitors designed for ~10,000 shot life.

The above results, and the scaling laws obtained for single sections, indicate that the 2000 to 3000 shot life goal should be realizable at 5 joules/in.^{3}. Accordingly, 5 units of the same type described above were fabricated. The overall energy density was ~5 joules/in.^{3} at 44 kV. The units failed after 1125, 1118, 1350, 945 and 1090 discharges. This life is within a factor of 2 of the design goal.

However, in all these units only 1 out of 10 sections failed and the other sections showed no sign of degradation.

After this test was completed, a high pot test of 20 windings at 2.2 kV revealed that it may be possible to detect defective windings before final assembly. It is expected that there were defective windings in the 5 prototypes tested at 5 joules/in.^{3}, and that the failure rate due to dielectric degradation is less than that indicated by the prototype tests.

Some additional testing will be required, but MLI has every reason to believe that the design goals are indeed realistic (and may be conservative).

4. Conclusions

The following conclusions can be drawn from this test program:

1. The energy density and/or life of mylar-foil capacitor windings is considerably higher than any other known energy-storage capacitor.
2. For high voltage applications, a large number of series sections is required for optimum performance. The actual number of sections depends on the life and/or energy density desired.
3. When windings are stacked in series axially, the maximum practical voltage that can be attained is ~30 to 50 kV. In order to attain 100 kV, lower voltage modules must be placed in series, or an alternate method of stacking must be employed.
4. The lifetime of a series stack of windings can be determined from the statistical failure distribution of single sections, provided that there are no faulty windings in the stack. A technique for eliminating faulty windings must be developed before the full potential of a mylar dielectric can be utilized.
5. The goal of this program has been approached, and it appears that further increases in energy density and/or life are attainable with additional engineering development.

This program has provided a valuable insight into the technical problems involved in the construction of high voltage capacitors. It is immediately obvious that, by the use of the new Maxwell film capacitors, economic advantages can be obtained in the construction of the energy storage banks used in large pulsed high-voltage systems.