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Technical Report
EEStor Capacitor Test Results September 2018
Rev A

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Introduction

EEStor, Inc. sent 15 types of high energy capacitors to Radiant Technologies, Inc. for evaluation of their energy efficiencies using high a resolution test instrument at high voltage. The sample descriptions, test fixture description, experiment, results, and analysis follow.

Sample Descriptions

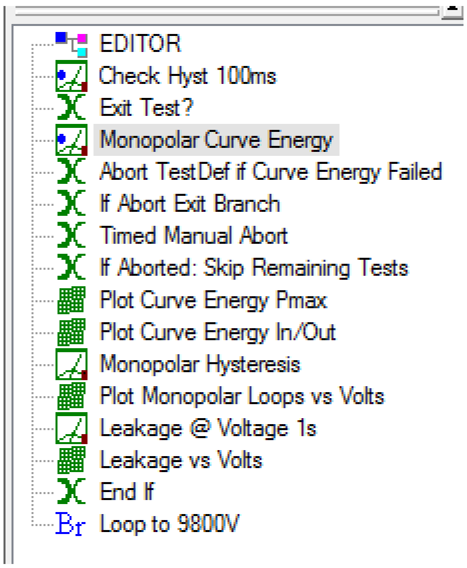
The EEStor samples provided for testing were fabricated using proprietary processes. Their compositions remain unknown to Radiant. The sample designations, their dimensions, and their areas are listed in the table below.

Sample Name	Thickness (mm)	Voltage Limit (V/um)	Test Vmax	Diameter (mm)	Area (cm2)
431-1	0.755	30	22,650	5.70	0.2552
432-6	0.665	30	19,950	5.70	0.2552
434-6	0.796	30	23,880	5.70	0.2552
361-3	0.577	30	17,310	2.50	0.0491
434-4H	0.344	30	10,320	5.20	0.2124
434-5H	0.04	90	3,600	4.00	0.1257
L2 #1053	0.567	30	17,010	5.60	0.2463
L3 #1095	0.546	30	16,380	5.75	0.2597
UL2	0.0118	150	1,770	8.90	0.6221
UL7	0.0126	150	1,890	8.60	0.5809
UH1-2	0.0165	230	3,795	8.70	0.5945
UH2-1	0.0139	300	4,170	8.90	0.6221
UH2-2	0.0146	300	4,380	8.70	0.5945
UH3-1	0.01	300	3,000	8.80	0.6082
CEL 40	0.024	30	720	8.80	0.6082

Note: 434-4H is the name of the sample labeled on its container. 431-5H was its designation in EESTOR documentation provided with the samples.

Test Definition

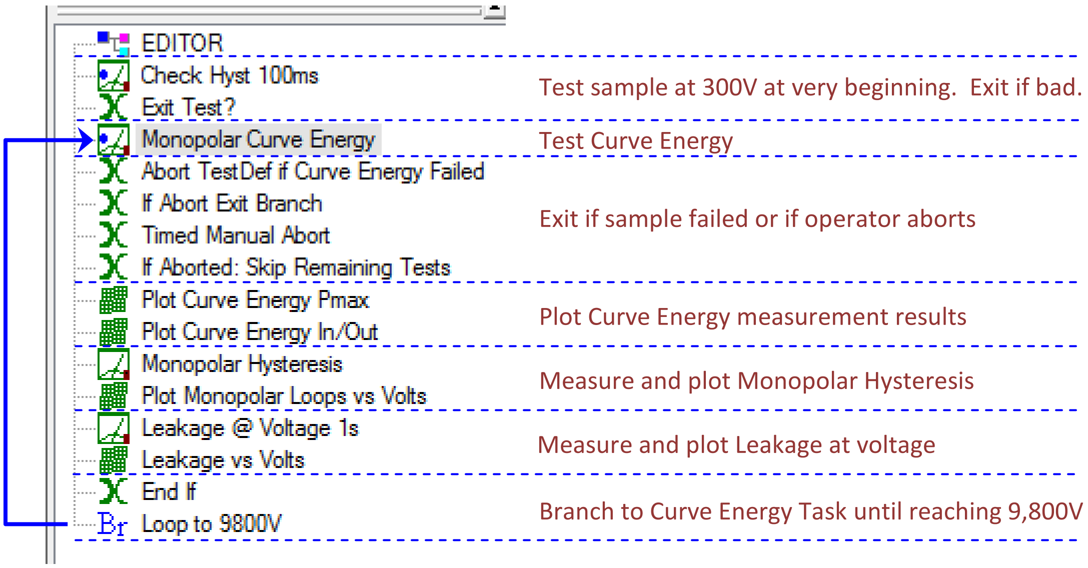
The Vision Test Management Operating System that runs Radiant Precision testers is capable of executing *custom* Test Definitions created by the operator. Vision has total control of the test instrument allowing fully automated execution of each Test Definition. A single Test Definition was executed against all samples. The Test Definition is shown below.



EDITOR
Check Hyst 100ms
Exit Test?
Monopolar Curve Energy
Abort TestDef if Curve Energy Failed
If Abort Exit Branch
Timed Manual Abort
If Aborted: Skip Remaining Tests
Plot Curve Energy Pmax
Plot Curve Energy In/Out
Monopolar Hysteresis
Plot Monopolar Loops vs Volts
Leakage @ Voltage 1s
Leakage vs Volts
End If
Loop to 9800V

Fig 2: Standard Test Definition for all samples.

The Test Definition is deconstructed below.



EDITOR
Check Hyst 100ms
Exit Test?
Test sample at 300V at very beginning. Exit if bad.
Monopolar Curve Energy
Test Curve Energy
Abort TestDef if Curve Energy Failed
If Abort Exit Branch
Timed Manual Abort
If Aborted: Skip Remaining Tests
Exit if sample failed or if operator aborts
Plot Curve Energy Pmax
Plot Curve Energy In/Out
Plot Curve Energy measurement results
Monopolar Hysteresis
Plot Monopolar Loops vs Volts
Measure and plot Monopolar Hysteresis
Leakage @ Voltage 1s
Leakage vs Volts
Measure and plot Leakage at voltage
End If
Loop to 9800V
Branch to Curve Energy Task until reaching 9,800V

Fig 3: Detailed explanation of the standard Test Definition.

The Curve Energy, Monopolar Hysteresis, and Leakage Tasks all started at 300 volts. Each task was programmed to increase its test voltage each time a new Branch Loop was executed. For the capacitors with high expected breakdown voltages, the assigned step was 500 volts. Thinner capacitors with lower expected breakdown voltages were assigned smaller steps to ensure enough test points were gathered before break down. All capacitors were tested to break down.

Each different sample from EEStor to be tested had a different thickness and different expected breakdown electric field. Even though the Test Definition was set to exit automatically at 9,800 volts, no sample made it past 6,800 volts except for the test fixture itself with mineral oil as already described.

Monopolar Curve Energy Task

This task applies a single half-triangle wave to the sample and records the polarization generated by the sample. From this information the Energy In, Out, and Lost can be calculated. As well, the effective capacitance can be calculated. *Effective Capacitance* is the value of a *linear* capacitor that, if substituted for the sample, would generate the same amount of charge at Vmax as did the sample. Note that this is not equivalent capacitance.

Monopolar Hysteresis Task

This task reproduces the same monopolar hysteresis loop generated by the Curve Energy Task for plotting purposes.

Leakage Task

The Leakage Task measures the charge leaking through the sample over a one-second period at each test voltage. DC leakage is a loss mechanism in energy capacitors making it an important parameter to characterize at each applied voltage. Since the leakage measurement applied a constant test voltage for one second while the other two tests only reached the same test voltage momentarily, most capacitors failed during the leakage test. Failure inserted a step in the leakage curve versus test voltage.

Dielectric Constant and Resistivity

Theoretically, the dielectric constants and resistivities of the materials under test can be calculated from these test results. However, the thickness of each sample is used to calculate these two values. The thickness of each sample was measured with a micrometer prior to testing but some were too thin to achieve any resolution. Any error in the thickness measurement would translate directly into an error in the calculation of the dielectric constant and resistivity. Therefore, those values are not reported from these tests. Energy density was calculated using thickness despite its limited precision.

Test Fixture

All samples except 434-5H were mounted in a Radiant High Voltage Test Fixture for testing. The geometry of the substrate for 434-5H was such that the sample would not fit inside the Radiant HVTF. That sample was tested in a special fixture provided by EEStor. Since all measurements were electrical only, the fixture type should have no bearing on the results.

The Radiant HVTF is a clam shell fixture constructed from Teflon of a thickness suitable to prevent electrical arcing outside the fixture up to 10,000 volts. The sample well is liquid-tight and was filled with mineral oil to reduce arcing around sample edges.

Parasitic Charge and Leakage Contributed by the Test Fixture

A test was executed on an 870 micrometer-thick nylon washer in mineral oil to evaluate the characteristics of the oil as an insulator in the HVTF. Does it leak more than the samples at 9,800 volts? The nylon washer separated the two electrodes of the fixture since the top electrode is free floating. The plot below shows twelve monopolar hysteresis loops measured with the same test used on the EEStor samples. The test started at 4,300 volts and stepped up to 9,800 volts in 500V steps. Note that each subsequent test aligns its slope of the lower voltages.

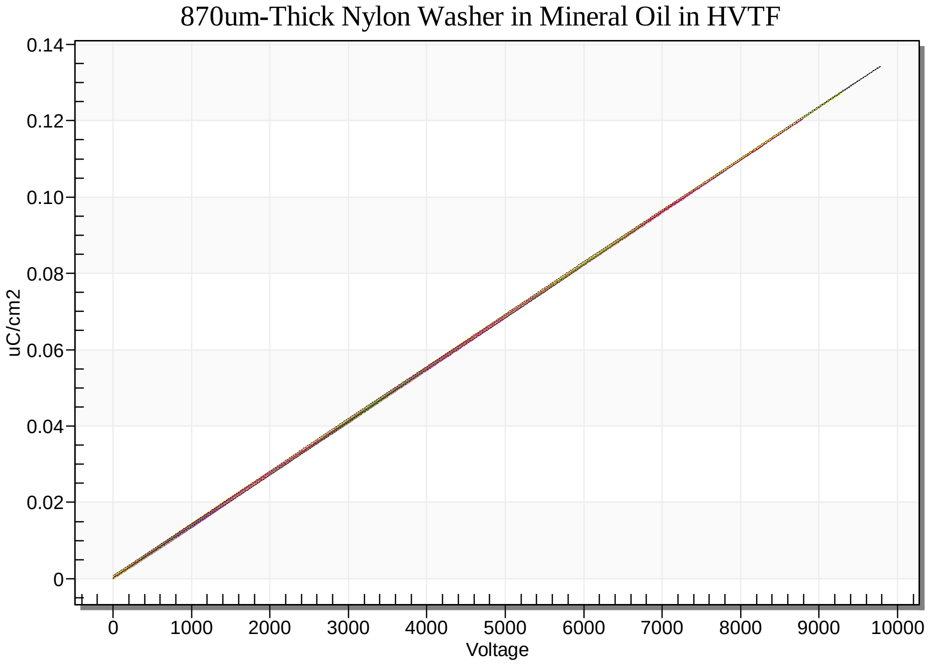


Fig 1: Monopolar hysteresis of a nylon washer in mineral oil in the HVTF. Period = 100 ms.

The peak polarization at 9,800 volts for this electrode separation was 0.134 µC/cm^2 using an area of 0.2552 cm^2. Leakage was minimal. Parasitic charge was not inconsequential.

The complication with parasitic charge is that it does not have area. Its adds *pure charge* to a measurement. That additional charge is constant independent of the area of the sample being tested. Since sample measurements are reported as *polarization*, the fixed parasitic charge captured during a measurement will vary its effect on the sample's measured polarization results depending upon the area of the sample and the Vmax of the test. Being linear, the parasitic charge contribution can be calculated from the test voltage. It must then be converted to polarization by dividing by that sample's area before being subtracted from the results.

The polarization plot in Figure 1 is converted to charge in Figure 1a.

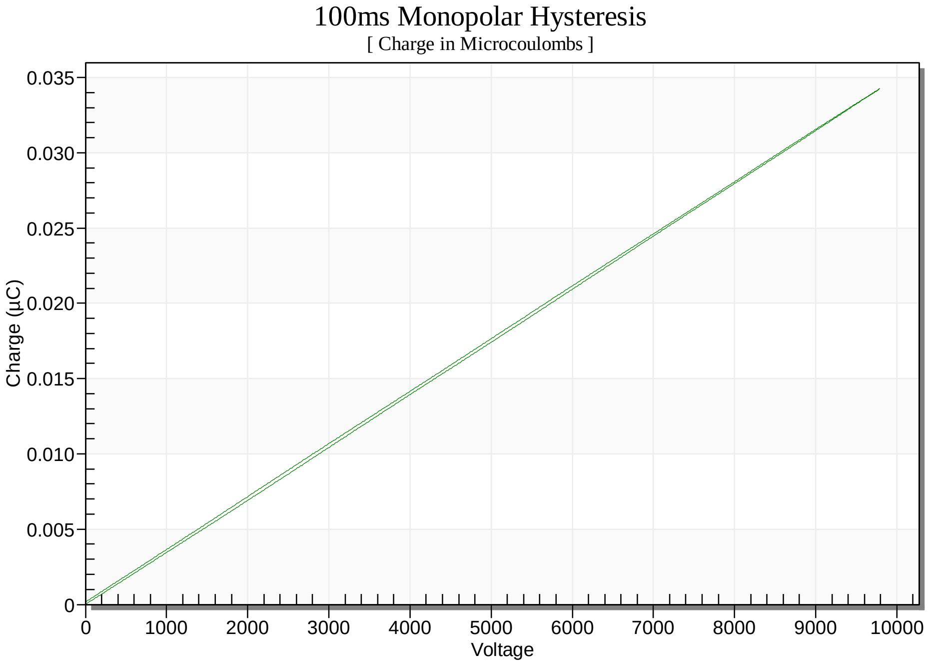


Fig 1a: Monopolar hysteresis of Figure 1 plotted as charge (µC)

The peak charge generated at 9800 volts was 34.28nC. Since 9782 volts generated that charge and the parasitic response was linear, the parasitic charge at any voltage can be calculated using the classic capacitor equation:

$$Parasitic\ Capacitance\ (Cp) = \frac{34.28\,nC}{9782V} = 3.5pF$$

$$Parasitic\ Polarization\ (Pp) = \frac{(Vmax\ \times 3.5pF)}{Sample\ Area}$$

The Pmax value reported for each sample must be adjusted for this parasitic. As well, the energy densities for each sample must be adjusted. Energy density is the polarization of the sample multiplied by the electric field that generated the polarization. Each energy density value must be divided by its electric field to convert it to polarization, the parasitic polarization must be subtracted, and the result multiplied by electric field again.

$$Corrected\ Energy\ Density = \left[\left(\frac{ED(original)\ \times Thickness}{Vmax}\right) - \ Pp\right] \times \frac{Vmax}{thickness}$$

$$Corrected\ Energy\ Density = ED(original) - \frac{Pp\ \times\ Vmax}{thickness}$$

$$Corrected\ Energy\ Density = ED(original) - \frac{(Vmax\ \times 3.5pF)\ \times\ Vmax}{Sample\ Area\ \times\ thickness}$$

Finally, the Effective Capacitance for each sample should be lowered by 3.5pF.

Results

The table below summarizes the test results for all fifteen capacitors. See the appended data pages for plots of each parameter.

Sample	Vbd	BD Source	Vmax	Pmax (μC/cm^2)	Cap (pF)	Energy In (J/cm^3)	Energy Out (J/cm^3)	Energy Lost (J/cm^3)	Eff. %	k	R (GΩ)
431-1	5300	CE	4800	4.945	263	0.157	0.118	0.039	75.1%	879	14.78
432-6	5800	CE	5300	6.727	324	0.249	0.231	0.019	92.6%	954	148.70
434-6	7300	LK	6800	4.397	316	0.323	0.310	0.014	95.8%	582	247.90
361-3	1800	MH	1300	16.544	625	0.108	0.072	0.036	66.6%	8297	10.02
434-4H	4050	CE	3800	6.100	341	0.395	0.119	0.276	30.1%	624	4.32
434-5H	1400	LK	1300	16.353	1582	2.071	1.134	0.937	54.8%	569	0.05
L2 #1053	4700	LK	4600	19.708	1056	0.336	0.300	0.037	89.1%	2745	142.37
L3 #1095	5200	LK	5100	17.822	908	0.443	0.409	0.034	92.3%	2156	973.85
UL2	1800	CE	1700	3.739	1369	2.721	2.096	0.625	77.0%	29	0.80
UL7	850	LK	800	3.453	2508	1.106	0.868	0.238	78.5%	61	1.51
UH1-2	2500	LK	2450	3.952	959	3.069	2.176	0.893	70.9%	30	0.75
UH2-1	1800	LK	1650	3.672	1385	2.313	1.543	0.770	66.7%	35	0.44
UH2-2	1925	LK	1800	3.589	1186	2.333	1.599	0.734	68.5%	33	0.63
UH3-1	925	LK	800	2.526	1921	1.064	0.771	0.293	72.5%	36	0.50
CEL 40	540	CE	520	0.879	1028	0.106	0.056	0.049	53.4%	46	0.62

Table 2: Sample Performance corrected for fixture parasitics

Notes:

1. *Vbd is the test voltage at which the sample self destructed.*
2. *Vmax is the highest voltage for which valid data was measured for all three tests.*
3. *Pmax is the polarization at Vmax measured for the sample.*
4. *Cap is the effective capacitance calculated as [Pmax x Area]/Vmax.*
5. *Eff(%) is the energy efficiency of the capacitor: Energy Out / Energy In*
6. *R is the linear resistance for 1 second at Vmax*
7. *CEL 40 was an unusual case. It did not break down in the traditional sense almost to 800 volts. However, at 540 volts a noticeable distortion occurred in the hysteresis loop that continued at higher voltages. Therefore, 540 volts was declared as the breakdown voltage.*

Analysis
Four samples performed at far higher efficiencies with high resistivities than the others:

1. 432-6 93% efficient with 149 GΩ resistance.
2. 434-6 96% efficient with 248 GΩ resistance.
3. L-2 89% efficient with 142 GΩ resistance.
4. L-3 92% efficient with ~1TΩ resistance.

Sample 434-6 had the highest efficiency. It also has excellent resistivity

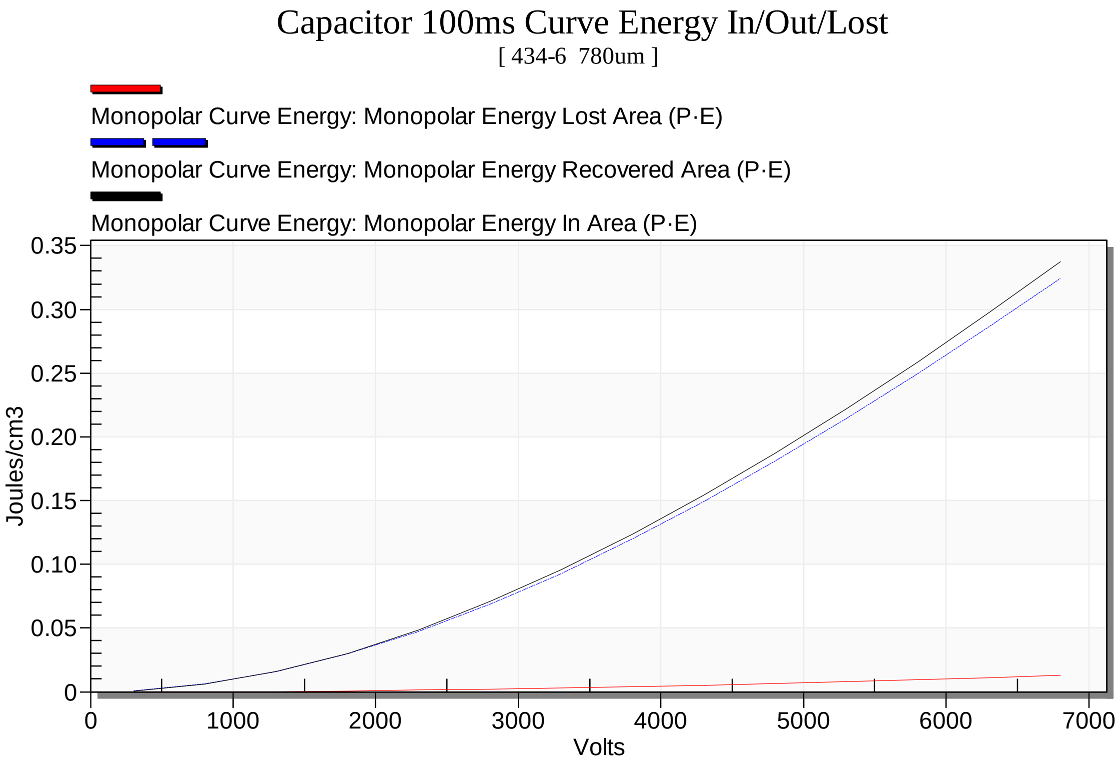


Fig 4: Energy Plot for 434-6

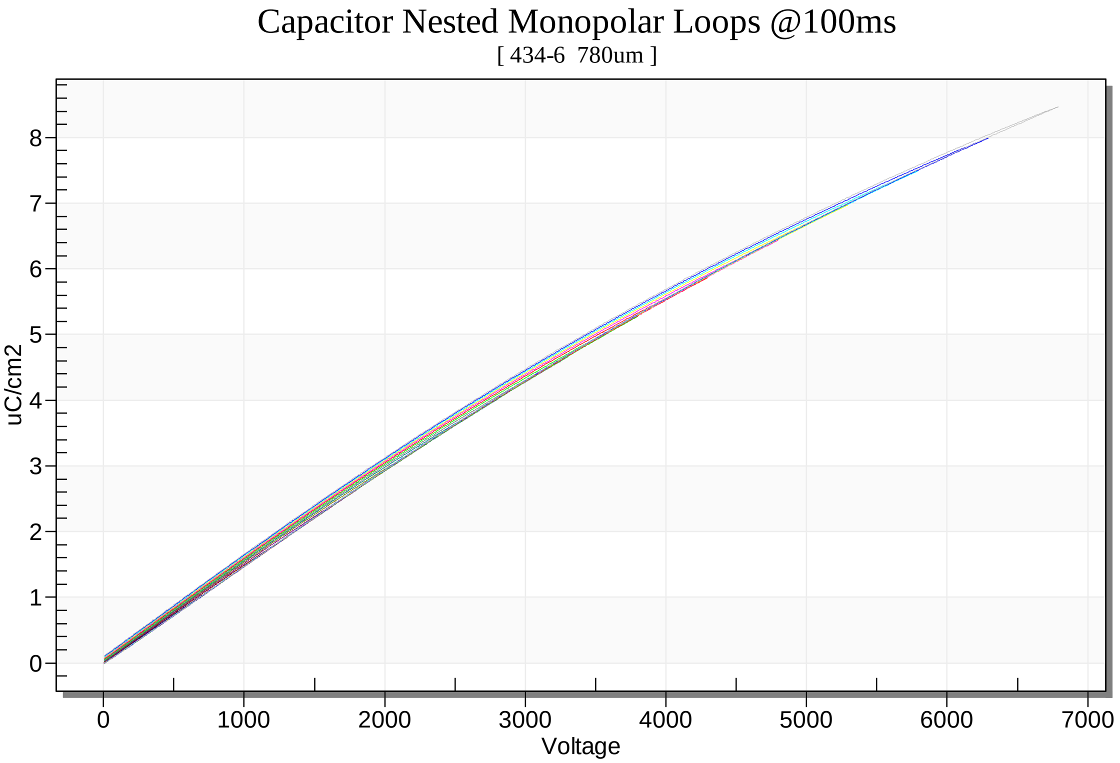


Fig 5: Monopolar hysteresis 434-6. Period = 100 ms.

Monopolar loops at Vmax for all samples are plotted together below.

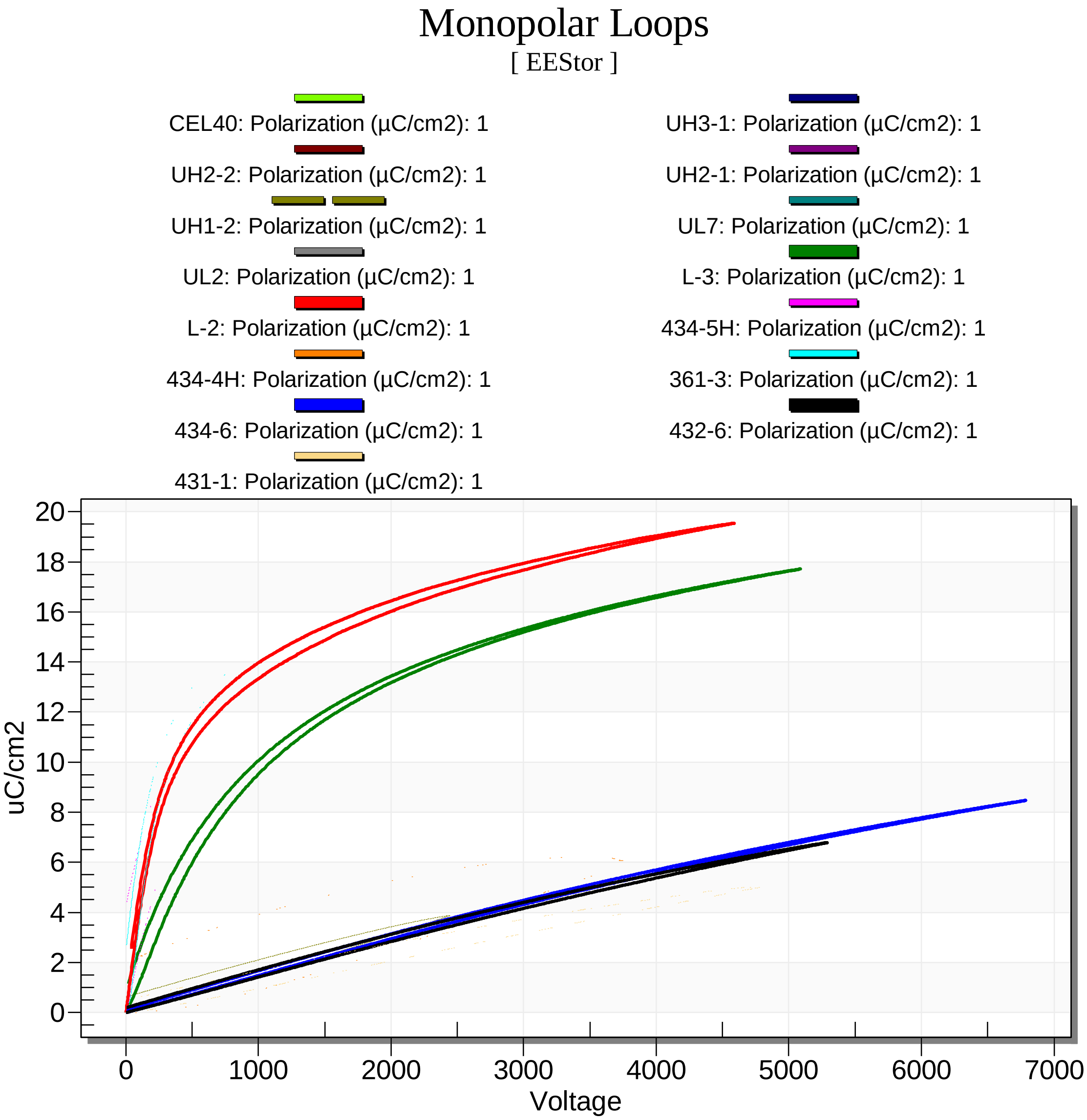


Fig 6: All monopolar hysteresis loops of the sample set. The four best samples are highlighted with thicker lines which are black, blue, red, and green.

L-2 and L-3 would be optimally applied below 1000 volts for highest capacitance density per volt.

The results in Table 2 should normalized by area and thickness for comparison of technologies. The four primary parameters of interest are normalized in Table 3.

	Area	**Cdense**	**σ**	**k**	**Eff.**	**Vbd**	**Thick**	**Ebd**
Sample	**(cm^2)**	**(nF/cm^2)**	**(GΩ-cm)**		**%**		**(cm)**	**(kV/cm)**
431-1	0.255	1.03	49.95	879	75.1%	5300	0.0755	70
432-6	0.255	1.27	570.60	954	92.6%	5800	0.0665	87
434-6	0.255	1.24	794.70	582	95.8%	7300	0.0796	92
361-3	0.049	12.72	8.52	8297	66.6%	1800	0.0577	31
434-4H	0.212	1.60	26.67	624	30.1%	4050	0.0344	118
434-5H	0.126	12.59	1.57	569	54.8%	1400	0.004	350
L2 #1053	0.246	4.29	618.45	2745	89.1%	4700	0.0567	83
L3 #1095	0.260	3.49	4631.54	2156	92.3%	5200	0.0546	95
UL2	0.622	2.20	421.77	29	77.0%	1800	0.00118	1525
UL7	0.581	4.32	696.13	61	78.5%	850	0.00126	675
UH1-2	0.594	1.61	270.21	30	70.9%	2500	0.00165	1515
UH2-1	0.622	2.23	196.93	35	66.7%	1800	0.00139	1295
UH2-2	0.594	1.99	257.33	33	68.5%	1925	0.00146	1318
UH3-1	0.608	3.16	304.11	36	72.5%	925	0.001	925
CEL 40	0.608	1.69	157.12	46	53.4%	540	0.0024	225

Table 3: Summary table of properties per unit area at Vmax

Assuming that efficiency is the most important parameter followed in order by dielectric constant and resistance density, L-3 is the most suitable material type for manufacturing. It has slightly lower efficiency than does 434-6 but more than three times the dielectric constant area with the same excellent resistivity. Breakdown voltage for 434-6 and L3 are almost identical.

Where break down voltage is the key parameter, UL-2 and UH1-2 are optimal but there is a steep price to pay in lower energy density, resistivity, and energy efficiency. UL2 has the best combination of breakdown field and efficiency.

Relationships Between Parameters

The two most important parameters for an energy capacitor will be the capacitance density of the device and its energy efficiency. Capacitance density is the capacitance of that capacitor per unit area. Double the area of the capacitor and the *capacitance* doubles. For energy systems, the desire is to store as much energy per *system volume* as possible. Materials with higher capacitance density require smaller capacitors for storing the same energy than competing materials so they take up less volume in the system. Capacitance density derives from the dielectric constant "k" of the dielectric from which the capacitor is constructed *and* the thickness of that dielectric. Two capacitors fabricated from different dielectrics can have the same *capacitance density* even if the two dielectrics have radically different dielectric constants if the material with the lower dielectric constant is thinner. This is where the breakdown electric field becomes a limit. The system application determines its operating voltage and capacitors used in that system must have a minimum thickness according to its E_{BD} limit so they never breakdown at the operating voltage.

Energy efficiency is the second critical factor for selecting the appropriate material. The energy efficiency describes how much of the energy stored in the material is returned from the capacitor. The rest is lost as heat. Clearly the energy efficiency translates directly into the efficiency of the energy management system. However, its more subtle effect is that the heating of the capacitor by the lost energy will decrease the capacitor's resistance to electrical breakdown.

The critical design parameter is the operating voltage of the system into which the energy capacitor is to be embedded. With that value, the minimum thickness can be calculated for each composition to not breakdown at that operating voltage plus a safety margin. Typically when human safety is involved, the safety margin is 100% or higher.

For example, assume a minimum system operating voltage of 1kV and a minimum breakdown voltage of 2kV. Substituting these values into Table 3 and assuming a fixed 1cm^2 capacitor area, Table 4 is created.

	Cdense	**R**	**τ_{RC}**	**k**	**Eff.**	**Vbd**	**Thick$_{min}$**	**Ebd**
Sample	**(nF/cm^2)**	**(GΩ/cm^2)**	**(s)**		**%**		**(cm)**	**(kV/cm)**
431-1	2.73	1.42	3.89	879	75.1%	2000	0.02849	70
432-6	3.68	13.08	48.16	954	92.6%	2000	0.02293	87
434-6	2.36	17.33	40.90	582	95.8%	2000	0.02181	92
361-3	11.45	0.55	6.26	8297	66.6%	2000	0.06411	31
434-4H	3.25	0.45	1.47	624	30.1%	2000	0.01699	118
434-5H	8.81	0.01	0.08	569	54.8%	2000	0.00571	350
L2 #1053	10.07	14.92	150.23	2745	89.1%	2000	0.02413	83
L3 #1095	9.09	97.26	883.71	2156	92.3%	2000	0.02100	95
UL2	1.98	0.55	1.09	29	77.0%	2000	0.00131	1525
UL7	1.83	2.06	3.79	61	78.5%	2000	0.00296	675
UH1-2	2.02	0.36	0.72	30	70.9%	2000	0.00132	1515
UH2-1	2.00	0.30	0.61	35	66.7%	2000	0.00154	1295
UH2-2	1.92	0.39	0.75	33	68.5%	2000	0.00152	1318
UH3-1	1.46	0.66	0.96	36	72.5%	2000	0.00216	925
CEL 40	0.46	1.40	0.64	46	53.4%	2000	0.00889	225

Table 4: Material performance with the minimum breakdown voltage equal to 2kV

Notes:

1. *τ_{RC} is RC time constant for a 1cm^2 capacitor in Table 4 to discharge itself through its own resistance.*

In Table 4, L3 is clearly the optimal choice due to its large capacitance density, high efficiency, and very long self-discharge time constant.

UL-2 actually fares poorly against L3 despite its large breakdown voltage. It will be much thinner than L3 to achieve the same breakdown safety margin but its low dielectric constant severely limits is capacitance density and increases its self-discharge rate.