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Recent Test Results for Advanced Ultracapacitors

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Abstract

Tests of a number of packaged electrochemical capacitors (ultracapacitors) were performed to evaluate their performance under constant current and constant power charge/discharge conditions and on the PSFUDS transient cycle. The devices tested were the Maxwell UC-1500 and UC-3600 devices, the new Panasonic 3V, 800F device, a Cap-XX 3V, 800F device, a 50V, 200F device from Superfarad, and a 60V, 6.5F device from Econd. All the devices except for the Econd device used an organic electrolyte. The devices were compared in terms of energy density, power density, resistance, round-trip efficiency on the PSFUDS cycle, and self-discharge characteristics. Data sheets were prepared for each of the devices tested in a format consistent with that prescribed by the United States Department of Energy for reporting ultracapacitor test results. The test data indicate that several of the devices have performance suitable for demonstration of ultracapacitors in electric and hybrid vehicles.

Introduction

The United States Department of Energy (DOE) initiated the development of electrochemical capacitors (ultracapacitors) for electric and hybrid vehicle applications in 1991 and the development of such devices has continued at a fast pace worldwide since then both with government support and by private companies. Many of the devices fabricated in these development programs have been unpackaged or poorly packaged devices intended only for laboratory evaluation of electrode materials and design approaches. However, within the last year or two, a number of electrochemical capacitor devices have been produced that are well packaged and could be considered for vehicle demonstration projects if their cost was low enough that the resultant cost of an energy storage unit assembled from a large number of the devices was affordable. The tests reported in this paper are intended to evaluate the performance of several of the available devices utilizing test procedures that have been developed and used by DOE in previous ultracapacitor programs (Reference 1).

The testing of the ultracapacitors was performed in the Electric Vehicle Power Systems Laboratory (EVPSL) at the University of California, Davis. Most of the devices tested were loaned to Dr. Andrew Burke by their manufacturer for evaluation as part of his on-going research program on ultracapacitors. Even though the devices are well packaged (see Figures 1-2), in most cases they are not yet produced in large quantities and are not easily procured for testing. Thus, data for most of the devices tested in this study have not been previously reported in the literature.

Most of the testing in the EVPSL was done using a Bitrode battery tester having a voltage limit of 50V and a current limit of 400A. The Bitrode is capable of running constant current and constant power charges and discharges and the PSFUDS cycle with the power steps being prescribed in one second time intervals. Some of the low current and the leakage current tests of the 3V devices were performed on an Arbin BT-2043 which is a multi-channel battery tester having a voltage limit of 20V and a current limit of 20 A. The Arbin tester is capable of measuring currents of a fraction of a mA, voltage differences of a fraction of a mV, and taking data at rates up to 5 Hz, which was particularly useful in determining the resistances of the devices. The data were analyzed and plotted using macros written for the EXCEL software.

Packaged Electrochemical Capacitors

The ultracapacitors evaluated are listed in Table 1. All of the capacitors are carbon-based and, except for the Econd (PSCap-12/60), utilize an organic electrolyte (3V/cell). The Econd device from Moscow uses an aqueous electrolyte (1V/cell). The Panasonic, Maxwell, and Cap-XX devices are single cells and the Econd and Superfard devices incorporate multiple cells with module voltages of 60V and 50V, respectively. The single cell devices were tested up to their rated voltages of 3V. The multicell modules were tested at voltages of 48V and 44V, respectively. In the case of the Econd capacitor, the module was tested at less than rated voltage primarily because of the voltage limit of the Bitrode tester. In the case of the Superfard module, the maximum voltage was limted to 44V, because of cell-to-cell variability and the desire to keep the maximum cell voltage to less than 3V. The weights and dimensions of the various capacitors were those for the fully packaged devices as they would be obtained from the manufacturers and ready for use in a vehicle.

The maximum current and power at which each of the ultracapacitors was tested was determined either by the current limit (400A) of the Bitrode or the need that the test duration be at least 4-5 seconds to be compatible with the control and data acquisition capabilities of the Bitrode. For the larger (high capacitance) devices, the 400 A limit was the determining factor. In those cases, the maximum power density of the constant power tests was greater than 1000 W/kg and the maximum power density of the high power steps in the PSFUDS was 500 W/kg. In the data analysis, the energy and power densities were calculated using the packaged weights and volumes given in Table 1.

Summary of Test Results

The test results for each of the ultracapacitors are summarized in Tables 2-7, which are in a format similar to that suggested in Reference 1. Each of the tables contains information on the capacitance, resistance, energy density, power density, round-trip efficiency, and self-discharge characteristics of the device for various charge and discharge rates. For a complete description of the performance of a particular device, the reader should study the table for that device. Comparisons of the relative performance of the devices will be discussed in the following paragraphs.

The energy densities of the organic electrolyte devices as a function of discharge current (A) and power (W/kg) are given in Figures 3 and 4. The Superfarad and Cap-XX devices had energy densities of 4-5 Wh/kg at discharge currents less than 100 A, but both devices indicated a lower energy density at higher currents. Both Maxwell devices had energy densities of about 3.5 Wh/kg independent of current up to 300-400A. The energy densities (Figure 4) of the devices for constant power discharges are lower than those for the constant current discharges (Figure 3) because the constant power discharges were terminated at one-half rated voltage rather than 0.0 V as in the case of the constant current discharges. Both Maxwell devices had constant power energy densities of 2.5-3.0 Wh/kg for power densities up to 700-800 W/kg. All the other devices exhibited a significant decrease in energy density for power densities greater than 150 W/kg. Note that the maximum voltage for the 16-cell Superfarad device was 2.75V/cell rather than the 3.0V/cell used for the other organic electrolyte devices. This accounts for the lower energy density of Superfarad device relative to the other devices at the lower discharge powers. The energy density of the Econd device that used an aqueous electrolyte was only about 0.1 Wh/kg independent of the discharge rate making it unsuitable for vehicle applications. It was designed as a pulse power device for stationary applications with low resistance (high efficiency) rather than energy density being the primary design objective.

Resistance data for the devices tested are given in Tables 2-7 for various charge and discharge currents. The resistance was calculated from the initial voltage step at the beginning of a charge or discharge. The initial step was corrected for the capacitive voltage change (I*t/C) that occurs during the time before the acquisition of the first data point in the charge or discharge. This procedure for the calculation of the resistance from the IR step at the initiation of the charge or discharge assumes a quasi-steady response of the device and neglects any transients in the establishment of the ion diffusion currents. The resistances per cell in discharge as a function of current are given in Figure 5 for the devices using an organic electrolyte. All the devices have a resistance per cell in the mOhm range. It is of interest to correlate the resistance per cell to the capacitance (F) per cell of the device as one would expect the devices with larger capacitance to have lower resistance due to their larger electrode area per cell. The parameter of interest is R*C (Ohm-F) of the device or cell, which is the time constant (second) for the device. On this basis, the Maxwell capacitors have the lowest resistance electrodes with a time constant of .6 sec and the Superfarad capacitors have the highest resistance electrodes with a value of 5.7 sec. The corresponding values are 3.8 sec for the Cap-XX and 1.7 sec for the Panasonic devices, respectively. These differences in the resistance characteristics (time constants) of the various devices are the reason that the variation of their energy density with discharge current and power (see Figures 3 and 4) are so different. The Econd device has very low resistance electrodes with a time constant of .13 sec. This would be expected as the Econd device uses an aqueous electrolyte and bipolar cell design.

PSFUDS tests were performed for each of the capacitors. These tests were intended to determine the round-trip efficiency for a sequence of charge/discharge steps (Reference 1) at power densities up to 500 W/kg (see Table 8 for the test cycle). For PSFUDS testing of most devices in the past, it was necessary to reduce the maximum power and/or the time interval for the high power step in order that the device could sustain the test cycle with a voltage above one-half its maximum operating voltage. In the present tests, the Maxwell and the Superfarad devices were sufficiently large and had high enough energy density that the original test cycle given in Table 8 could be used. For the other devices, a less demanding cycle was used (maximum power of 300 W/kg for 5 seconds). The results of the PSFUDS tests are given in Table 9. The round-trip efficiency is the ratio of the sum of the energy (W-sec) taken from the device during discharge steps to the sum of the energy into the device during charging steps of the cycle. In general, the measured round-trip efficiencies correlate well with the RC time constant of the devices with the devices having small RC values having the highest efficiencies. The Maxwell devices with RC time constants less than one second had roundtrip efficiencies near 90% even for the most demanding test cycle (a maximum power step of 500 W/kg for 8 seconds). The Superfarad device, which consisted of 16 cells in series, had a lower round-trip efficiency than the Maxwell devices both because of its higher resistance (greater RC time constant) and the need for a reduce voltage (2.75 V/cell) due to cell-to-cell variability in the multicell module. The high efficiency of the Econd device was due primarily to its low resistance and resultant low RC time constant of .13 seconds. The PSFUDS or similar test cycle is a good procedure for determining the efficiency of electrochemical capacitors under realistic charge/discharge conditions like the devices would encounter in vehicle applications.

The final set of tests performed on the packaged ultracapacitor devices were self-discharge tests, in which the device was charged to its maximum operating voltage, held at that voltage for 120 seconds, and then disconnected from the tester (current set equal to zero). The voltage of the device was then measured for 48-60 hours as it self-discharged. The self-discharge characteristics of the organic electrolyte devices are shown in Figure 6. In general, the devices show a high self-discharge for the first several hours and a much lower self-discharge for longer times with a well defined "knee" in the self-discharge curve. Most ultracapacitor manufacturers rate their devices for long-term use at a voltage near the "knee". At this voltage, the leakage current would be low and the capacitor could be held at that voltage almost indefinitely without damage to the device by gas buildup (overpressure and mechanical failure of the case). The capacitors can be used to 3V per cell for short periods (seconds or minutes) as was done in the present tests without damage, but it requires a significant current to maintain that voltage. Figure 6 indicates the self-discharge characteristics of the various devices vary significantly. For the devices tested in this study, the Maxwell UC-3600 device exhibted the most favorable self-discharge characteristic. It is surprising that the other Maxwell device - UC-1500 - showed the worst self-discharge characteristic. The multicell Superfarad device showed greater self-discharge than expected based on earlier tests of a single cell device using the same carbon and electrolyte (Reference 2). The differences between the self-discharge of single cell and multicell devices should be investigated in future studies of ultracapacitors.

References

1. Miller, J.R. and Burke, A.F., Electric Vehicle Capacitor Test Procedures Manual, Idaho National Laboratory Report DOE/ID-10491, October 1994
2. Burke, A.F., Miller, M., and Guerin, J.T., Recent Test Results for Aqueous and Organic Electrolyte Ultracapacitors, Proceedings of the Sixth International Seminar on Double-layer Capacitors and Similar Energy Storage Devices, Deerfield Beach, Florida, December 1996

Table 1: Packaged Ultracapacitor Devices and Their Characteristics

Device	Country	Rated Voltage	Rated Capacitance	Electrolyte	Packaged Weight (kg)	Packaged Volume (l)
Maxwell	USA					
UC-1500		3V	1000F	organic	.39	.288
UC-3600		3V	2700F	organic	.85	.612
Superfarad	Sweden	50V	200F	organic	17.	17.
Panasonic	Japan	3V	800F	organic	.321	.236
Cap-XX	Australia	3V	800F	organic	.173	.132
Econd	Russia	60V	6.5F	KOH	19.5	7.82

Table 2: Summary of Test Data for the Maxwell UC-3600 Device

Device Name:	UC 3600 (Model #: 34715; Serial #: 9721-14-01)
Manufacturer	Maxwell
Electrolyte Type	Organic
Electrode	Carbon
Comments	Packaged Dimensions: Width X Height X Length = (6 X 6 X 17)cm^3
# Cells	1
Area / Cell	NA
Mass	850 grams (Packaged)
Volume	612 cm^3
Voltage	Maximum => 3.0 volts; Working => 2.3 volts

Table 2. Device Performance

Constant Current (Average of 3 Cycles)								
I	C_ch	C_dis	R_ch	R_dis	t_dis	E (0 - V)	E / M	E / V
Amps	Farads		mOhms		s	W-h	W-h / kg (packaged)	W-h / l (packaged)
25	2821 +/- 9	2699 +/- 5	-	0.41 +/- 0.00	302	3.10	3.65	5.07
50	2809 +/- 10	2714 +/- 0	0.64	0.42 +/- 0.00	152	3.09	3.64	5.05
100	2633 +/- 32	2643 +/- 0	0.69	0.32 +/- 0.00	74	2.98	3.51	4.87
200	-	2648 +/- 0	-	0.23 +/- 0.00	37	2.89	3.40	4.72
300	-	2659 +/- 2	-	0.20 +/- 0.01	25	2.75	3.24	4.49
400	-	2660 +/- 2	-	0.19 +/- 0.00	19	2.59	3.05	4.23

Constant Power (V -> V/2, 3 Cycles)				
P (W)	P / M (W/kg) (packaged)	E (W-h)	W-h / kg (packaged)	W-h / l (packaged)
100	118	2.73 +/- 0.00	3.21	4.45
200	235	2.62 +/- 0.00	3.09	4.29
300	353	2.56 +/- 0.05	3.01	4.18
400	471	2.58 +/- 0.00	3.03	4.21
500	588	2.51 +/- 0.00	2.96	4.11
600	706	2.34 +/- 0.00	2.76	3.83

Table 2 (cont.)

AC Impedance			
Frequency (Hz)	C (Farads)	R (Ohms)	Phase Angle (Deg)

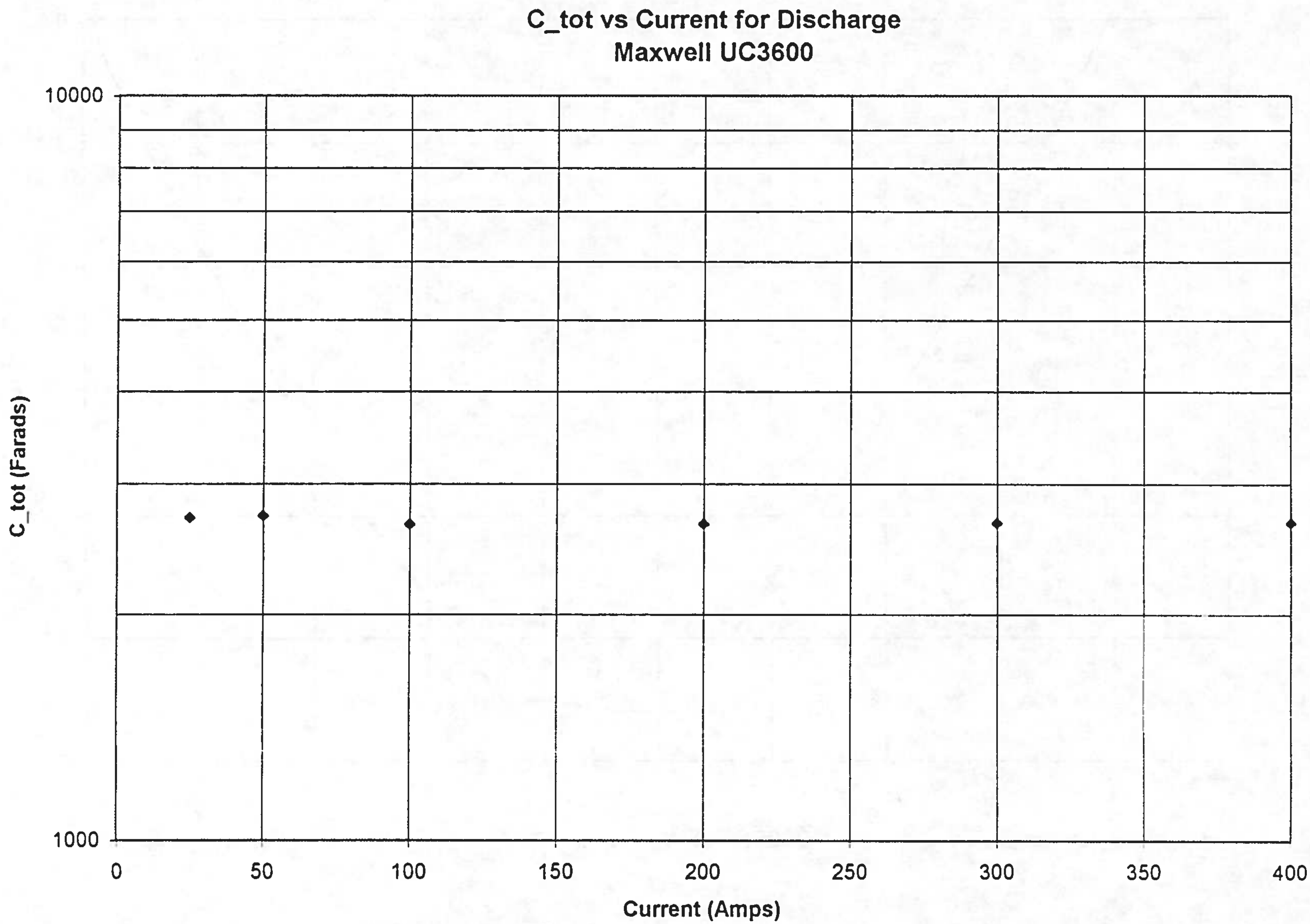
Generalized PSFUDS (P_{max} = 500 W/kg, packaged)

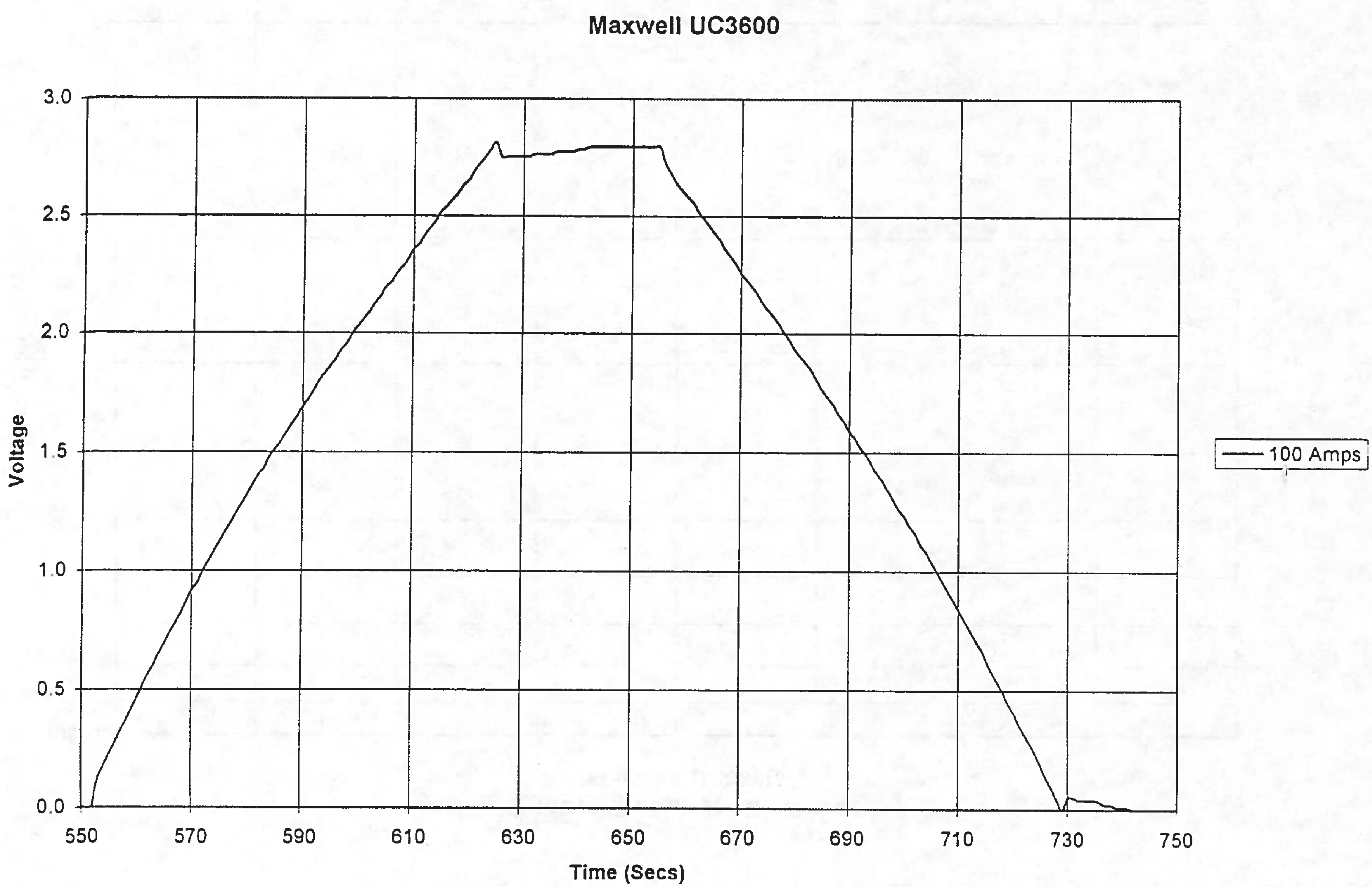
Charge Efficiency = 0.98 +/- 0.00
W-h Efficiency = 0.86 +/- 0.01

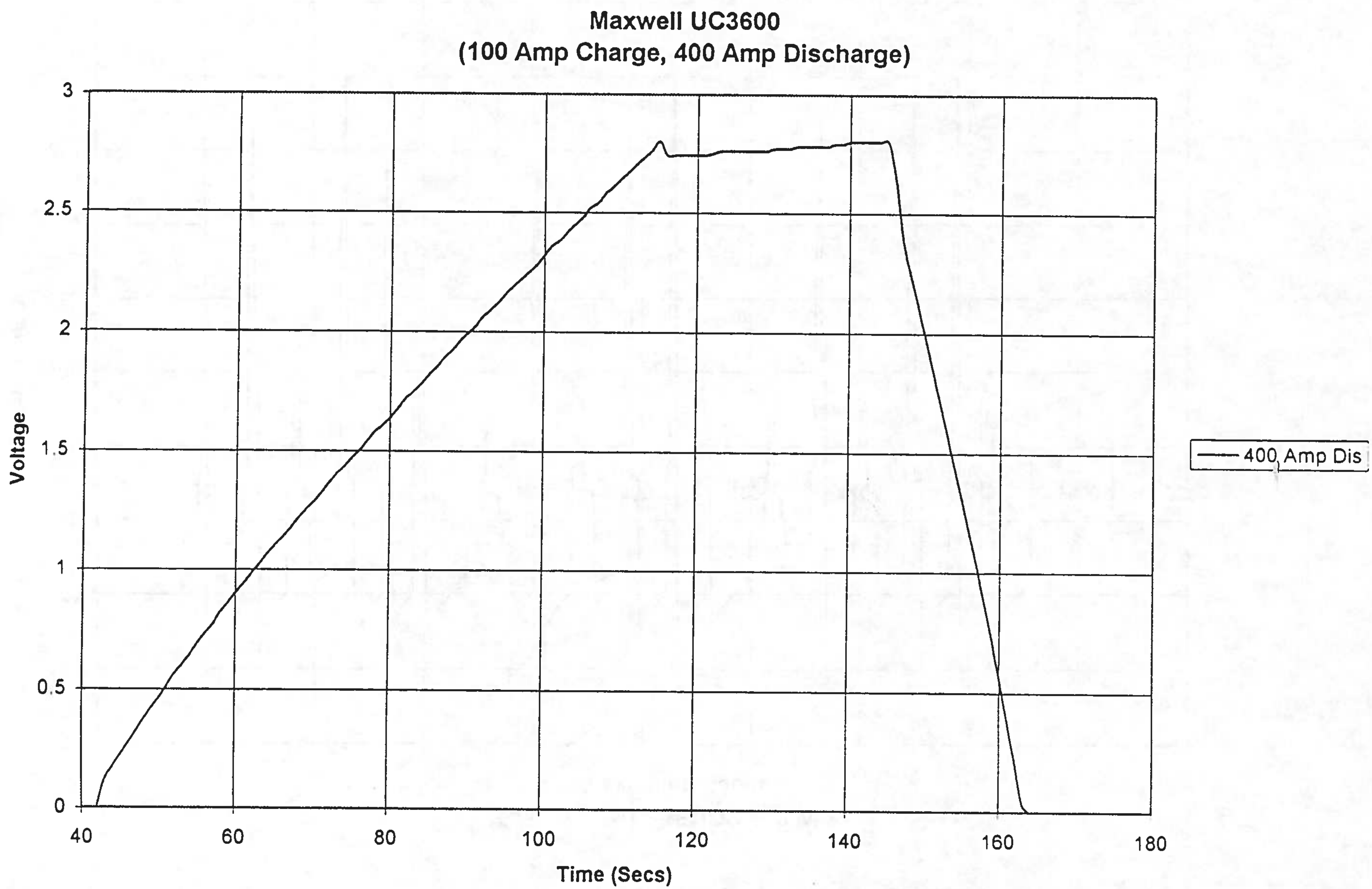
Leakage Current

$I_{leakage}$ = ≤ 6.0 mA (Measured after 8 hours)
$I_{leakage}$*A = NA
R_p = ≥ 380 Ω (V_w = 2.3 volts)

Self Discharge	
V (Volts)	Time (Hours)
3.00	0.0
2.90	0.3
2.80	1.0
2.75	1.8
2.70	3.0
2.65	5.0
2.60	8.2
2.55	13.3
2.50	20.6
2.45	28.7
2.40	40.5
2.35	53.6


C_tot vs Current for Discharge
Maxwell UC3600
10000
1000
C_tot (Farads)
0
50
100
150
200
250
300
350
400
Current (Amps)


Maxwell UC3600
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Voltage
550
570
590
610
630
650
670
690
710
730
750
Time (Secs)
100 Amps


Maxwell UC3600
(100 Amp Charge, 400 Amp Discharge)
Voltage
3
2.5
2
1.5
1
0.5
0
40
60
80
100
120
140
160
180
Time (Secs)
400 Amp Dis

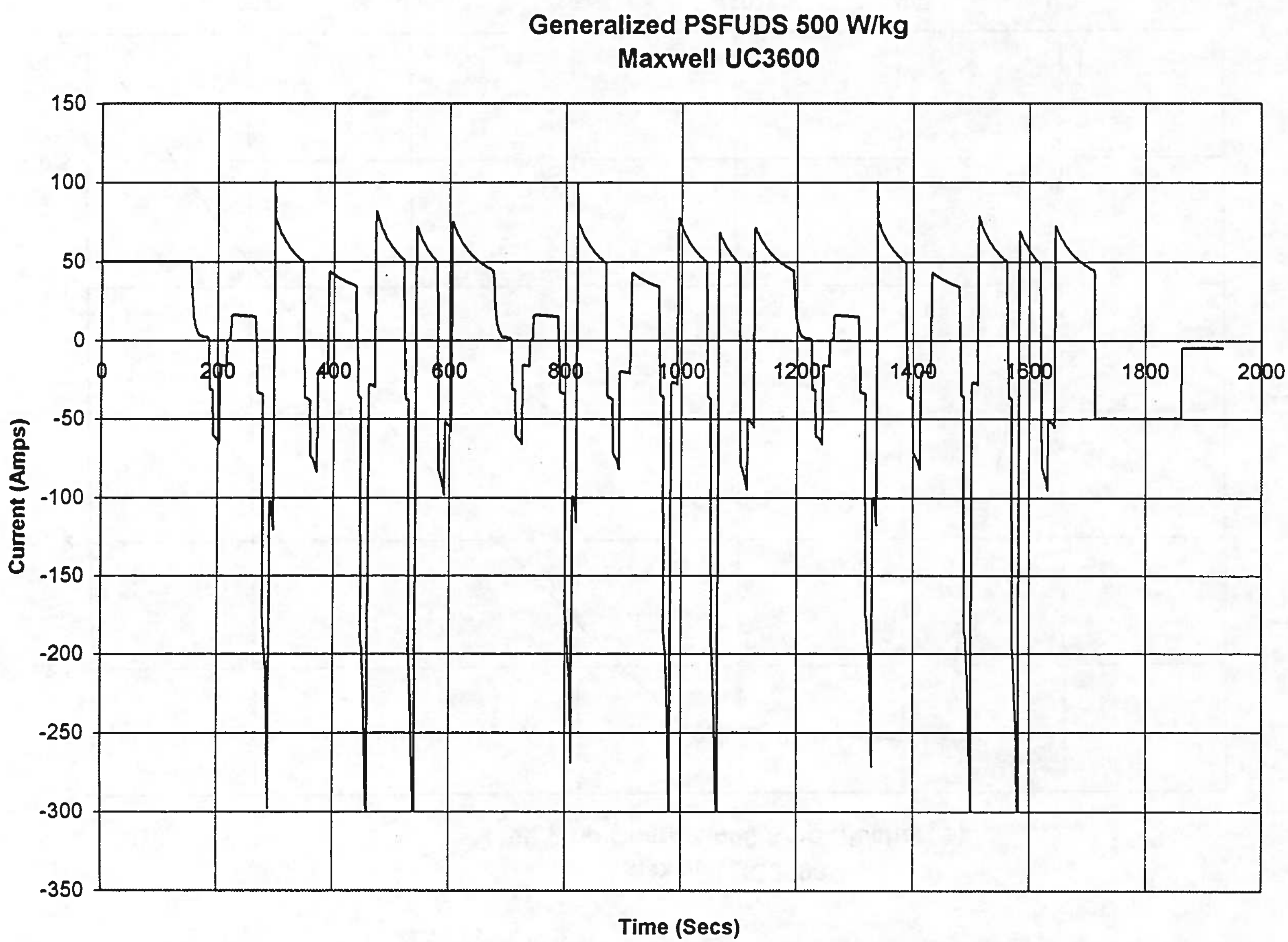

Generalized PSFUDS 500 W/kg
Maxwell UC3600
Current (Amps)
Time (Secs)
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Table 3: Summary of Test Data for the Maxwell-UC-1500 Device

Device Name:	UC 1500 (Model #: 34704; Serial #: 9713-12-05
Manufacturer	Maxwell
Electrolyte Type	Organic
Electrode	Carbon
Comments	Packaged Dimensions: Width X Height X Length = (7.5 X 2.4 X 16)cm^3
# Cells	1
Area / Cell	NA
Mass	390 grams (Packaged)
Volume	288 cm^3 (Packaged)
Voltage	Maximum => 3.0 volts; Working => 2.3 volts

Table 2. Device Performance

Constant Current (Average of 3 Cycles)								
I	C_ch	C_dis	R_ch	R_dis	t_dis	E (V - 0)	E / M	E / V
Amps	Farads		m-Ohms		s	W-h	W-h / kg (packaged)	W-h / l (packaged)
5 (1)	1015 +/- 4	1009 +/- 1	5.7 +/- 0.1	5.6 +/- 0.1	591	1.26	3.23	4.38
10 (1)	1012 +/- 6	1012 +/- 1	5.8 +/- 0.1	5.7 +/- 0.1	293	1.24	3.18	4.31
15 (1)	1004 +/- 3	1012 +/- 0	5.8 +/- 0.1	5.8 +/- 0.1	193	1.21	3.10	4.20
20 (1)	1000 +/- 2	1013 +/- 0	5.9 +/- 0.0	5.8 +/- 0.0	143	1.30	1.19	4.13
25 (1)	999 +/- 3	1016 +/- 0	4.8 +/- 0.2	4.6 +/- 0.0	115	1.19	3.05	4.13
25 (2)	1023 +/- 10	1043 +/- 0	1.8 +/- 0.2	1.0 +/- 0.0	119	1.32	3.38	4.58
50 (3)	1080 +/- 11	1099 +/- 4	1.6 +/- 0.0	0.7 +/- 0.0	62	1.35	3.46	4.69
100 (3)	1086 +/- 55	1104 +/- 4	0.7 +/- 0.1	0.6 +/- 0.1	31	1.29	3.31	4.48
200 (3)	-	1127 +/- 3	-	0.5 +/- 0.0	15	1.20	3.08	4.17
300 (3)	-	1096 +/- 0	-	0.4 +/- 0.0	10	1.06	2.72	3.68

(1) Tested 9/8/97 on Arbin (25 Amps - 9/2/97)
(2) Tested 9/2/97 on Bitrode
(3) Tested 8/11/97 on Bitrode

Table 3 (cont.)

Constant Power (V -> V/2, 3 Cycles)				
P (mW)	P / M (W/kg) (packaged)	E (W-s)	W-h / kg (packaged)	W-h / l (packaged)
50	130	1.03	2.64	3.58
100	260	1.01	2.59	3.51
150	390	0.96	2.46	3.33
200	510	0.95	2.44	3.30
300	770	0.83	2.13	2.88
500	1280	0.83	2.13	2.88

<u>Generalized PSFUDS</u> (P_{max} = 500 W/kg, packaged, averaged over 3 cycles)

Charge Efficiency = 0.99 ± 0.01
W-h Efficiency = 0.92 ± 0.01

<u>Leakage Current</u> (Current was dropping after 8 hours of testing)

$I_{leakage}$ = 11.3 ± 6.9 mA (Average and standard deviation taken between 4.0 - 8.0 hours)
$I_{leakage}$ *A = NA
R_p = 126 - 523 Ω (V_w = 2.3 volts)

Self Discharge	
V (Volts)	Time (Hours)
3..0	0.0
2.9	0.2
2.8	0.9
2.7	2.6
2.6	5.6
2.5	9.3
2.4	12.8
2.3	17.1
2.2	21.5
2.1	26.0
2.0	30.8
1.9	36.3
1.8	42.6
1.7	49.1
1.6	55.9
1.52	61.5

Table 4: Summary of Test Data for the Superfarad Device

Device Name:	SuperFarad 48 Volt Super Capacitor from Kiev
Manufacturer	SuperFarad
Electrolyte Type	Organic
Electrode	Carbon
Comments	Packaged Dimensions: L X W X H = (27 X 35.5 X 18)cm^3
# Cells	16
Area / Cell	NA
Mass	17 kg (Packaged)
Volume	17 Litres (Packaged)
Voltage	Working => 44 Volts; Maximum => < 48 Volts

Table 2. Device Performance

Constant Current								
I	C_ch	C_dis	R_ch	R_dis	t_dis	E (V - 0)	E / M	E / V
Amps	Farads		m-Ohms		s	W-h	W-h / kg (packaged)	W-h / l (packaged)
20 (1)	221 +/- 3	218 +/- 0	44.0 +/- 0.6	35.0 +/- 0.4	209 +/- 0	-	-	-
50 (2)	265 +/- 1	261 +/- 1	39.3 +/- 0.5	21.5 +/- 0.1	217 +/- 2	65.5 +/- 0.7	3.85	3.85
100 (2)	260 +/- 0	259 +/- 0	44.2 +/- 1.2	23.4 +/- 0.4	104 +/- 0	61.3 +/- 0.1	3.61	3.61
200 (2)	-	243 +/- 2	-	20.8 +/- 0.0	47 +/- 1	52.3 +/- 0.4	3.08	3.08
300 (2)	252 +/- 1	255 +/- 6	40.2 +/- 1.0	21.7 +/- 0.6	28 +/- 1	43.6 +/- 0.6	2.56	2.56
400 (2)	-	216 +/- 1	-	20.7 +/- 0.2	20	38.9	2.29	2.29
50 (3)	269 +/- 1	267 +/- 1	42.8 +/- 0.4	22.7 +/- 0.4	242 +/- 1	82.1 +/- 0.1	4.82	4.82
100 (3)	259 +/- 3	260 +/- 1	40.6 +/- 1.1	20.3 +/- 0.2	114 +/- 0	75.3 +/- 0.5	4.43	4.43
200 (3)	265 +/- 3	261 +/- 3	40.6 +/- 1.0	22.2 +/- 0.6	54 +/- 1	65.8 +/- 1.0	3.87	3.87
100 (4)	236 +/- 3	236 +/- 0	40.9 +/- 0.7	22.9 +/- 0.3	84 +/- 0	44.8 +/- 0.3	2.64	2.64
300 (4)	250	247	41.2	22.8	24	32.4	1.91	1.91

(1) - 0 - 20 Volts tested on Arbin, average of 3 cycles.
(2) - 0 - 44 Volts tested on Bitrode, average of 3 cycles. (400 Amps - average of 2 cycles)
(3) - 0 - 48 Volts tested on Bitrode, average of 3 cycles.
(4) - 0 - 40 Volts tested on Bitrode, average of 3 cycles. (300 Amps - 1 cycle)

Table 4 (cont.)

Constant Power				
P (kW)	P / M (W/kg) (packaged)	E (W-h)	W-h / kg (packaged)	W-h / l (packaged)
1.5 (1)	88	37.6 +/- 0.2	2.21	2.21
1.5 (2)	88	48.5 +/- 0.3	2.85	2.85
3.0 (2)	176	42.0 +/- 0.5	2.47	2.47
5.0 (2)	294	34.6 +/- 0.0	2.04	2.04
7.5 (2)	441	26.9 +/- 0.0	1.58	1.58
10.0 (2)	588	21.6 +/- 0.0	1.27	1.27

(1) - 1 cycle, 40 - 20 Volts.
(2) - Average of 2 cycles, 44 - 22 Volts

<u>Generalized PSFUDS</u> (P_{max} = 420 W/kg, Average of 2 cycles)

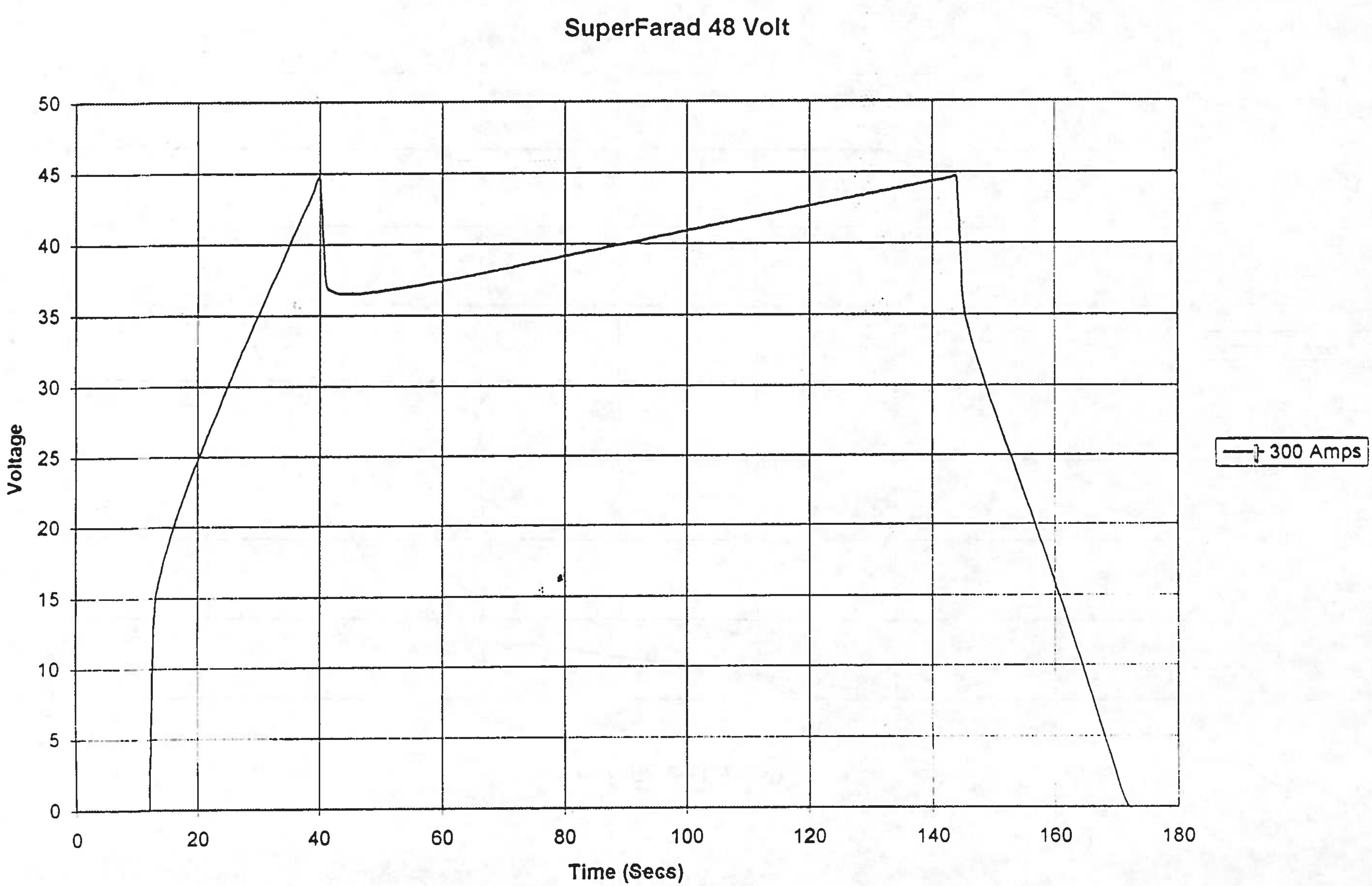
Charge Efficiency = (98.4 +/- 0.8) %
W-h Efficiency = (75.5 +/- 0.8) %

<u>Leakage Current</u>

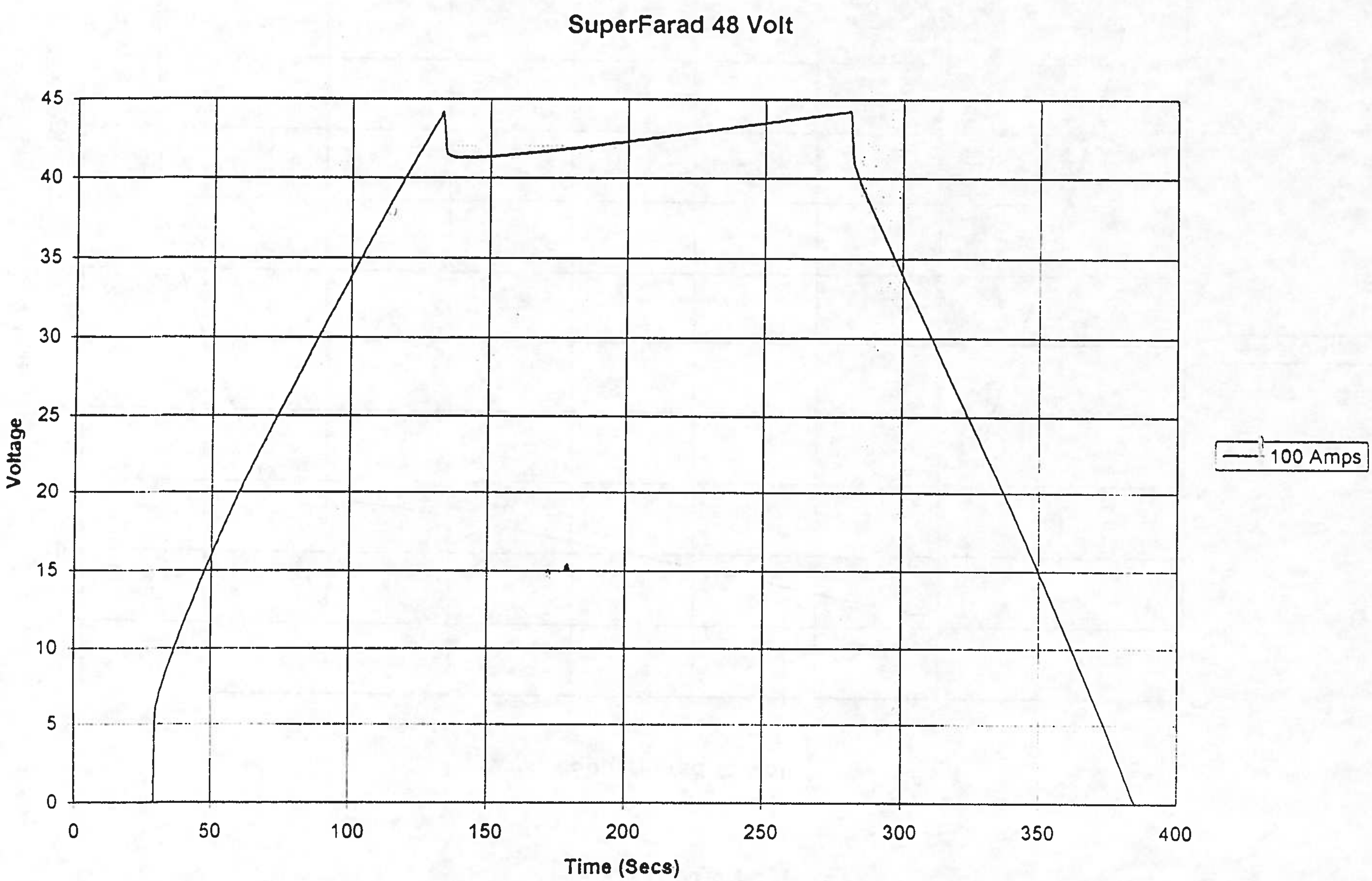
$I_{leakage}$ =
$I_{leakage}$ *A =
R_p =

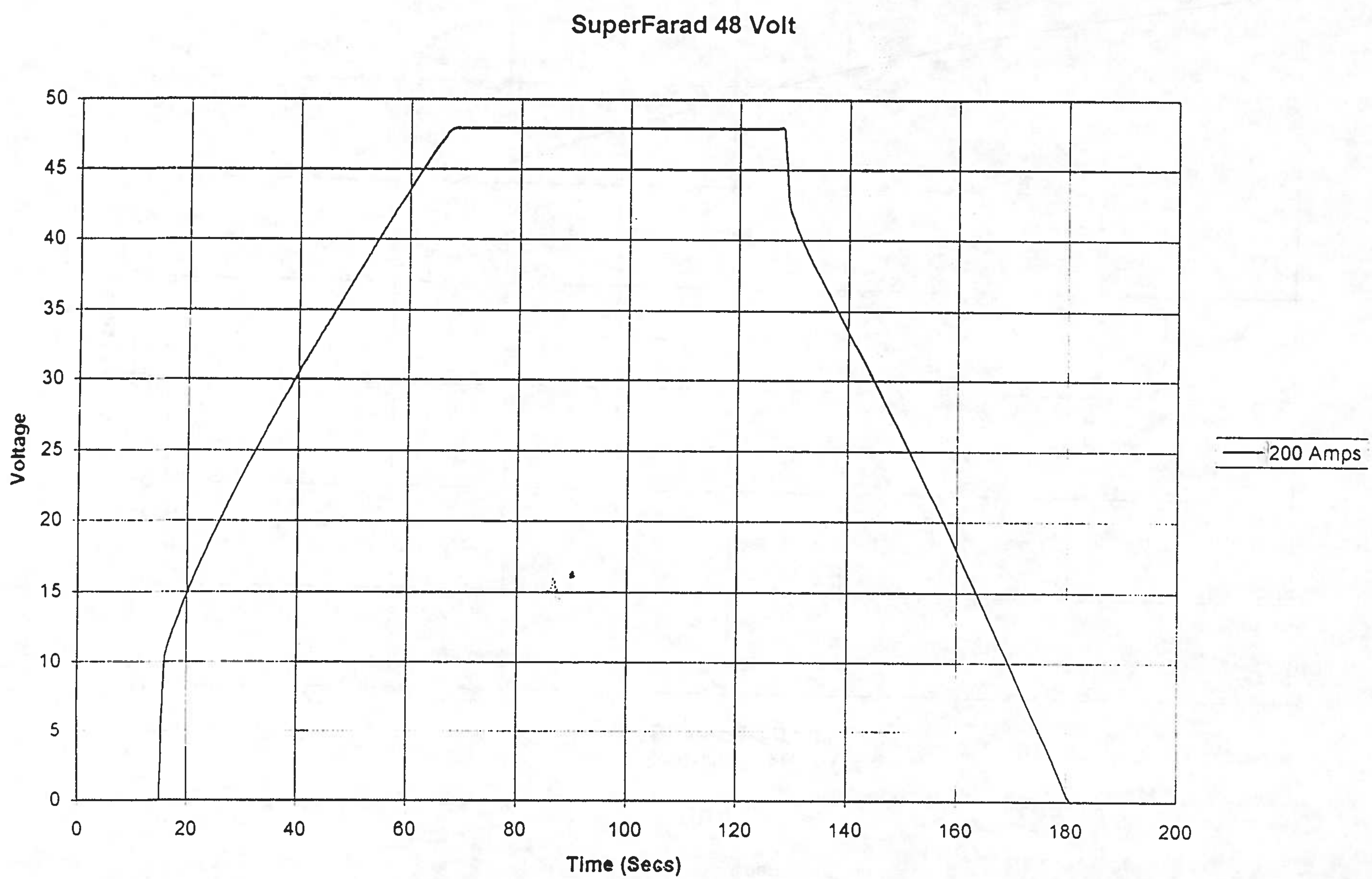
Self Discharge	
V (Volts)	Time (Hours)
44	0.0
41	0.4
40	0.7
39	1.1
38	1.9
37	3.2
36	5.2
35	8.3
34	12.7
33	19.0
32	26.8
31	35.8
30	48.0

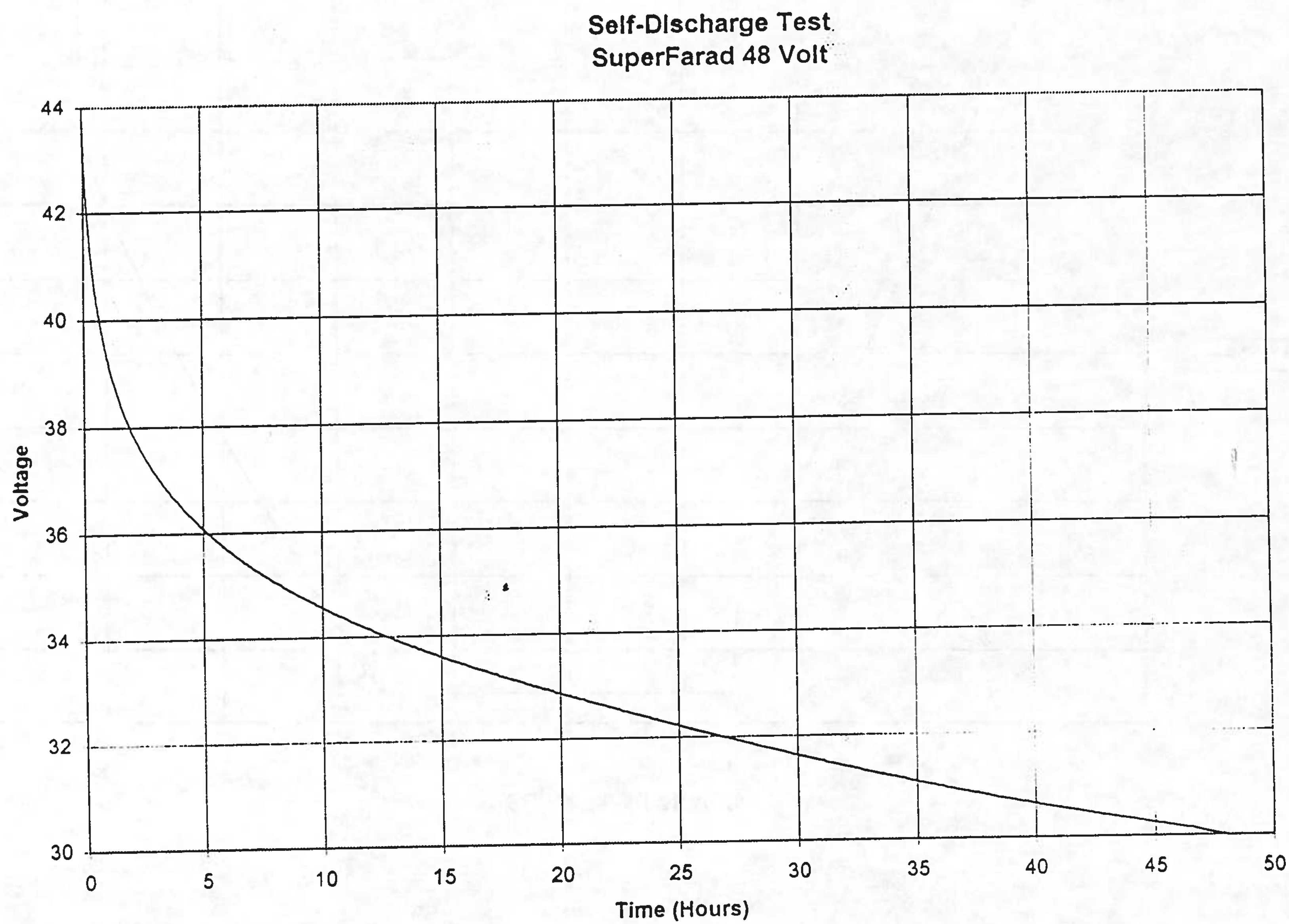
V vs t (300 Amps)



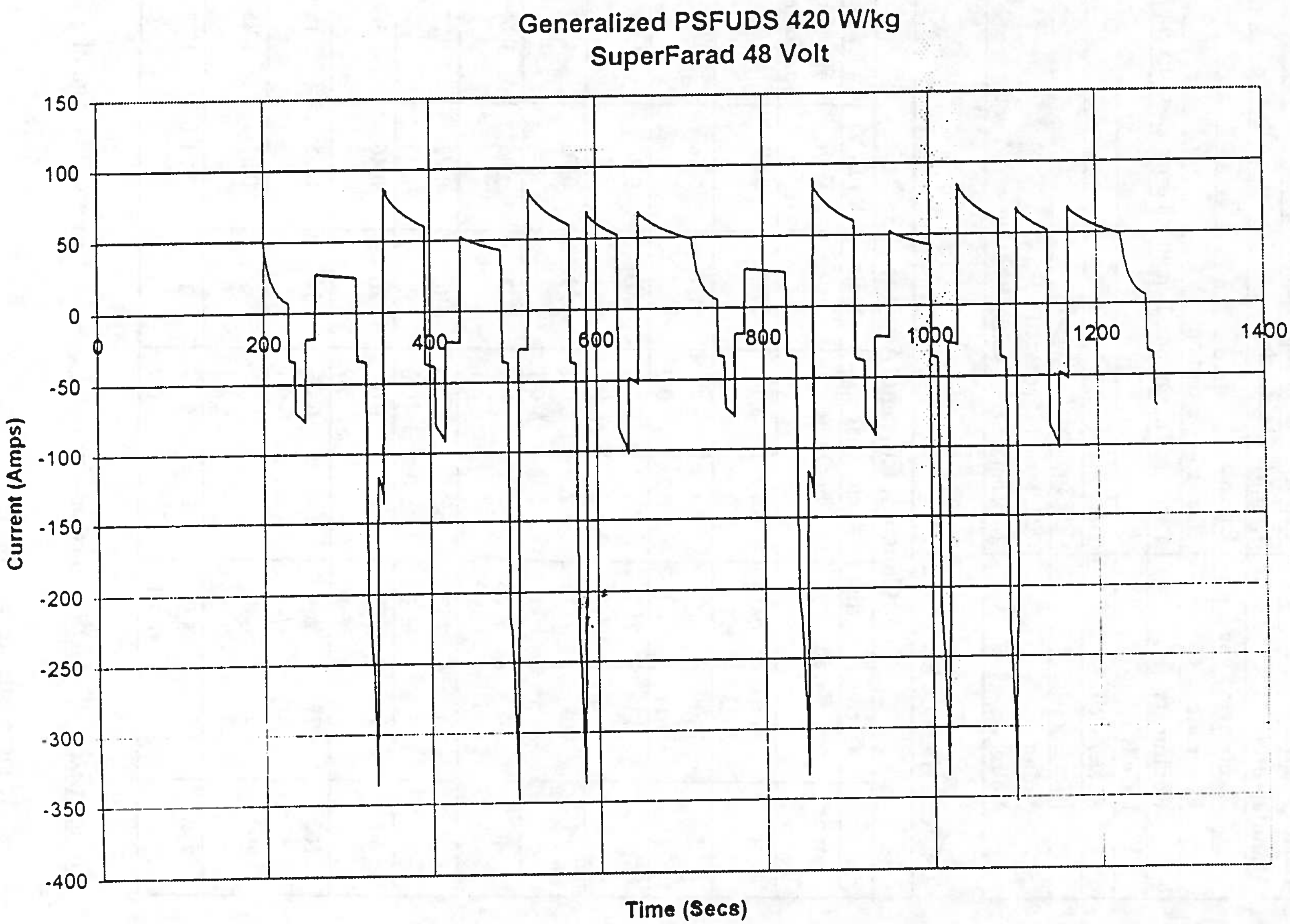
V vs t (100 Amps)




SuperFarad 48 Volt
50
45
40
35
30
25
20
15
10
5
0
Voltage
0
20
40
60
80
100
120
140
160
180
200
Time (Secs)
200 Amps


Self-Discharge Test
SuperFarad 48 Volt
Voltage
44
42
40
38
36
34
32
30
0
5
10
15
20
25
30
35
40
45
50
Time (Hours)

I vs t



Generalized PSFUDS 420 W/kg
SuperFarad 48 Volt
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
Current (Amps)
0
200
400
600
800
1000
1200
1400
Time (Secs)

Table 5: Summary of Test Data for the Cap-XX Device

Device Name:	Cap-XX, Model SuperCap 800-2.7
Manufacturer	**Cap-XX (Australia)**
Electrolyte Type	Organic
Electrode	Double Layer Carbon
Comments	Packaged Dimensions: Length X Diameter = 10.5 cm X 4.0 cm
# Cells	1
Area / Cell	NA
Mass	172.8 grams (Packaged)
Volume	131.9 cm^3 (Packaged)
Voltage	Maximum => 3.0 volts; Working => 2.7 volts

Table 2. Device Performance

Constant Current (Average of 3 Cycles)								
I	**C_ch**	**C_dis**	**R_ch**	**R_dis**	**t_dis**	**E (0 - V)**	**E / M**	**E / V**
Amps	**Farads**		**m-Ohms**		**s**	**W-h**	**W-h / kg (packaged)**	**W-h / l (packaged)**
1	775 +/- 23	745 +/- 5	6.4 +/- 0.3	8.3 +/- 0.6	2204	0.87	5.03	6.60
5	730 +/- 11	719 +/- 1	7.4 +/- 0.2	8.4 +/- 0.0	418	0.83	4.80	6.29
10	713 +/- 6	712 +/- 0	7.4 +/- 0.1	8.3 +/- 0.0	203	0.80	4.63	6.07
20	705 +/- 3	712 +/- 0	7.2 +/- 0.0	8.0 +/- 0.1	99	0.76	4.40	5.76
40	-	542 +/- 0	-	9.4 +/- 0.1	43	0.56	3.24	4.25
50	702	757 +/- 3	6.3 +/- 0.0	6.0 +/- 0.0	38	0.72	4.17	5.46
60	-	673 +/- 0	-	9.6 +/- 0.2	26	0.46	2.66	3.49
100	677 +/- 2	764 +/- 8	6.4 +/- 0.1	6.0 +/- 0.1	16	0.55	3.18	4.17
200	-	640 +/- 20	-	5.7 +/- 0.1	6	0.32	1.85	2.43
250	-	523 +/- 61	-	5.9 +/- 0.2	3	0.23	1.33	1.74

<u>Generalized PSFUDS</u> (Constant Current, I_{max} = 38.7 Amps, Average of 3 Cycles)

Charge Efficiency = 0.99 +/- 0.02
W-h Efficiency = 0.83 +/- 0.02

Table 5 (cont.)

Constant Power (V -> V/2, 3 Cycles)				
P (mW)	P / M (W/kg) (packaged)	E (W-h)	W-h / kg (packaged)	W-h / l (packaged)
20	115.7	0.596 +/- 0.004	3.45	4.52
30	173.6	0.565 +/- 0.000	3.27	4.28
50	289.4	0.503 +/- 0.000	2.91	3.81
100	578.7	0.372 +/- 0.016	2.15	2.82
150	868.1	0.250 +/- 0.001	1.45	1.90
200	1157	0.163 +/- 0.001	0.94	1.24
300	1736	0.071 +/- 0.007	0.41	0.54

AC Impedance			
Frequency (Hz)	C (Farads)	R (Ohms)	Phase Angle (Deg)

Leakage Current

$I_{leakage}$ = (5.3 +/- 0.6) mA *

$I_{leakage}$ *A = NA

R_p = 458 - 574 Ohms (V_w = 2.7 volts)

* - Average and standard deviation taken between - 5.5 hrs $\leq t \leq$ 8 hrs

Self Discharge	
V (Volts)	Time (Hours)
3.0	0.0
2.8	0.1
2.7	0.3
2.6	0.9
2.5	2.0
2.4	4.9
2.3	13.8
2.2	35.6
2.1	60.0

Table 6: Summary of Test Data for the Panasonic Device

Device Name:	Power Cap Sample, 2.3 V, 800 F, No. 848
Manufacturer	Panasonic
Electrolyte Type	Organic
Electrode	Carbon
Comments	Packaged Dimensions: Length X Diameter = 12.0 cm X 5.0 cm
Number of Cells	1
Area / Cell	NA
Mass	321.1 grams (Packaged)
Volume	235.6 cm^3 (Packaged)
Voltage	Maximum => 3.0 volts; Working => 2.3 volts

Table 2. Device Performance (Calculations based on packaged mass and dimensions)

Constant Current (Average of 3 Cycles)								
I	**C_ch**	**C_dis**	**R_ch**	**R_dis**	**t_dis**	**E (0 - V)**	**E / M**	**E / V**
mA	**Farads**		**mOhms**		**s**	**W-h**	**W-h / kg**	**W-h / l**
5 (1)	839 +/- 23	820 +/- 0	19.2 +/- 1.4	19.1 +/- 0.4	466	0.91	2.83	3.86
10 (1)	821 +/- 17	811 +/- 2	20.0 +/- 2.7	18.7 +/- 1.0	221	0.84	2.62	3.57
15 (1)	813 +/- 12	808 +/- 2	13.0 +/- 1.8	13.0 +/- 0.6	147	0.84	2.62	2.62
20 (1)	816 +/- 10	814 +/- 7	14.5 +/- 1.3	15.0 +/- 1.1	106	0.79	2.46	3.35
25 (2)	800 +/- 16	797 +/- 1	4.6 +/- 0.1	5.1 +/- 0.0	91	0.88	2.74	3.74
25 (3)	793 +/- 21	809 +/- 0	2.9 +/- 0.1	2.8 +/- 0.2	93	0.96	2.99	4.07
50 (4)	892 +/- 12	916 +/- 1	2.4 +/- 0.0	2.3 +/- 0.1	50	1.05	3.27	4.46
100 (4)	891 +/- 2	937 +/- 1	2.3 +/- 0.1	2.0 +/- 0.1	25	0.99	3.08	4.20
200 (4)	-	958 +/- 0	-	1.8 +/- 0.0	12	0.90	2.80	3.82
300 (4)	-	916 +/- 30	-	1.6 +/- 0.0	8	0.78	2.43	3.31

1 - Tested 9/4/97 on Arbin
2 - Tested 9/2/97 on Arbin
3 - Tested 9/2/97 on Bitrode
4 - Tested 8/11/97 on Bitrode

<u>**PSFUDS**</u> (Constant Current, I_{peak} = 51 Amps, Average of 3 Cycles)

Charge Efficiency = 0.99 +/- 0.03
W-h Efficiency = 0.91 +/- 0.03

Table 6 (cont.)

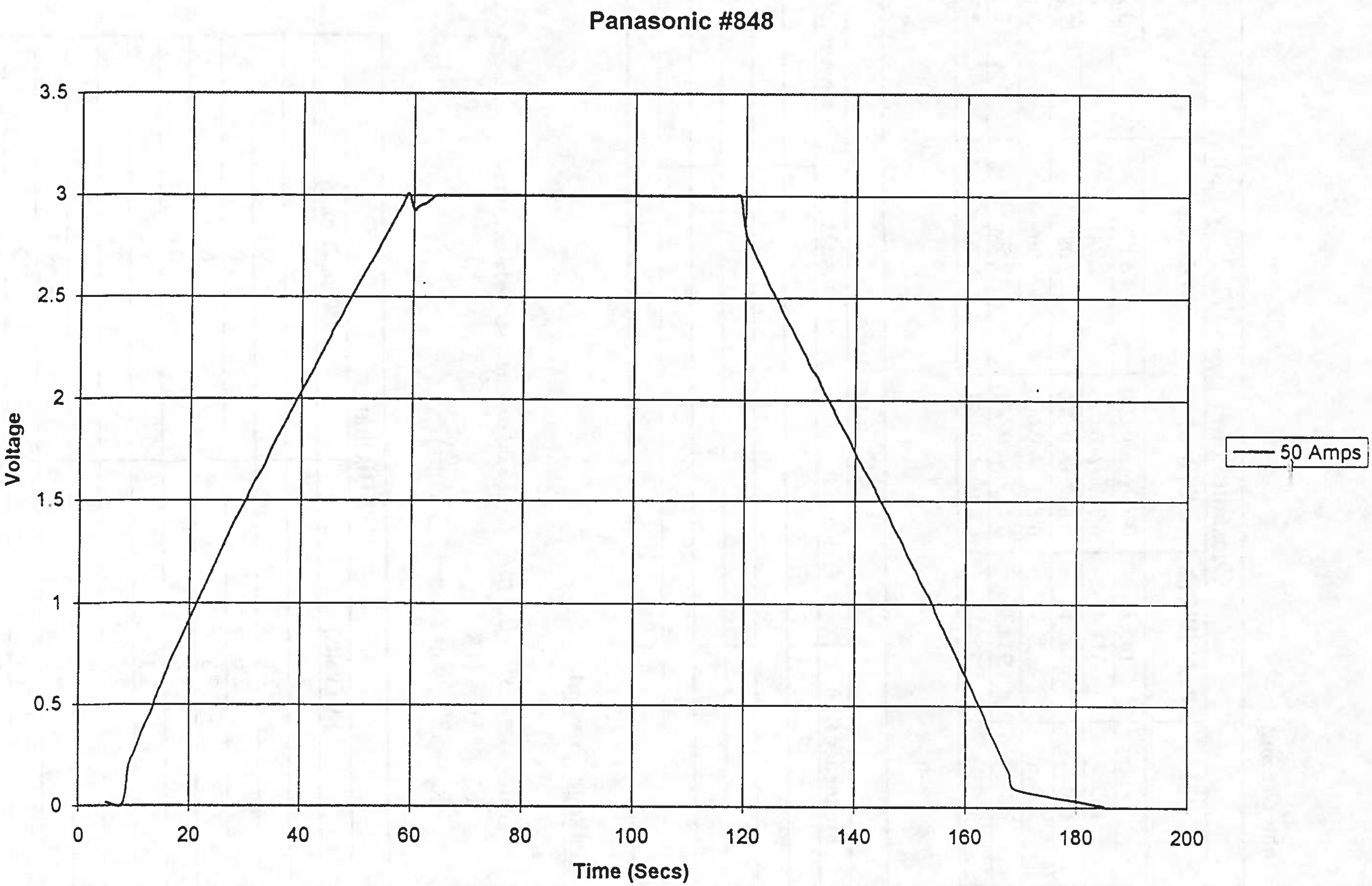
Constant Power (V -> V/2, 3 Cycles)				
P (W)	P / M (W/kg)	E (W-h)	W-h / kg	W-h / l
50	155.7	0.766 +/- 0.000	2.39	3.25
100	311.4	0.719 +/- 0.016	2.24	3.05
150	467.1	0.667 +/- 0.000	2.08	2.83
200	622.9	0.611 +/- 0.000	1.90	2.59
300	934.3	0.495 +/- 0.001	1.54	2.10
500	1557	0.404 +/- 0.001	1.26	1.71

AC Impedance			
Frequency (Hz)	C (Farads)	R (Ohms)	Phase Angle (Deg)

Leakage Current

$I_{leakage}$ = 4.3 +/- 0.9 mA (Average and standard deviation taken between 5.5 - 8.0 hours)
$I_{leakage}$ *A = NA
R_p = 530 Ohms (Vw = 2.3 Volts)

Self Discharge	
V (Volts)	Time (Hours)
3.0	0.0
2.8	0.1
2.6	0.3
2.5	0.5
2.4	0.8
2.3	1.4
2.2	2.4
2.1	4.5
2.0	9.5
1.9	22.1
1.8	45.3



Panasonic #848
Voltage
3.5
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
120
140
160
180
200
Time (Secs)
50 Amps

V vs T (100 Amps)

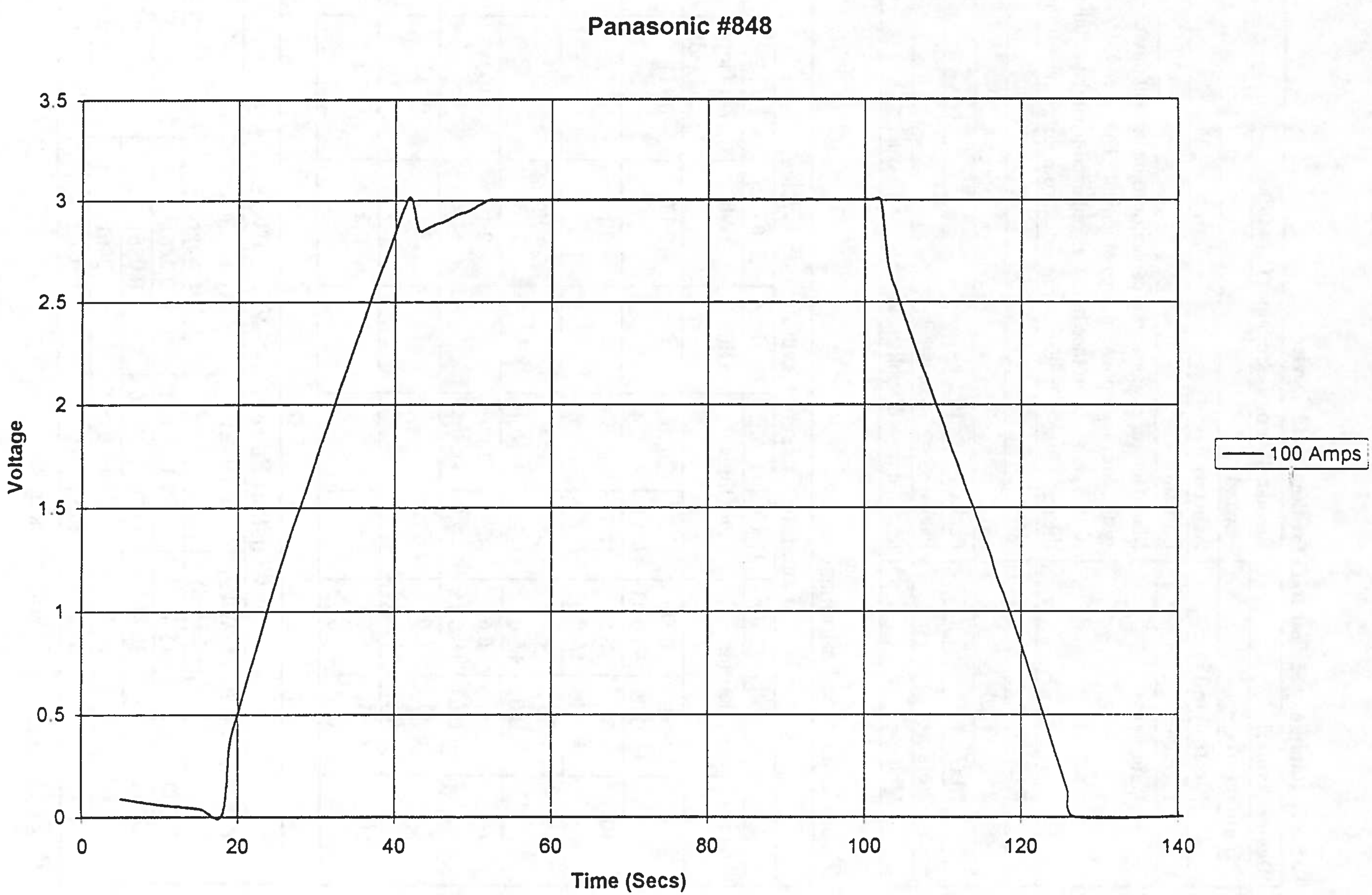


Table 7: Summary of Test Data for the Econd Device

Device Name:	Russian 48 Volt Pulse Super Capacitor
Manufacturer	**Econd**
Electrolyte Type	Aqueous
Electrode	Carbon
Comments	Manufacturer suggests this capacitor to be used in power supplying systems for high power pulse equipment. Diameter X Height = (22.6 X 19.5) cm. Resistance data was obtained from the Arbin tester, while the rest of the data was extrapolated from tests done on the Bitrode.
# Cells	NA
Area / Cell	NA
Mass	Packaged => 19.5 kg
Volume	Packaged => 7820 cm^3
Voltage	Maximum => 60 volts; Working => 48 volts

Table 2. Device Performance

Constant Current (Average of 3 Cycles)								
I	C ch	C dis	R ch	R dis	R dis*A	E (0 - V)	E / M	E / V
Amps	Farads		mOhms		Ohm-cm^2	W-h	W-h / kg (packaged)	W-h / l (packaged)
5	6.51 +/- 0.09	6.58 +/- 0.02	22.2 +/- 4.6	20.6 +/- 0.4	-	2.17	0.111	0.277
10	6.38 +/- 0.13	6.61 +/- 0.03	18.7 +/- 2.4	19.6 +/- 0.6	-	2.17	0.111	0.277
15	6.36 +/- 0.01	6.67 +/- 0.03	19.2 +/- 2.1	19.9 +/- 0.1	-	2.08	0.109	0.266
20	6.46 +/- 0.01	6.63 +/- 0.15	18.7 +/- 2.7	20.0 +/- 0.1	-	2.10	0.108	0.269
30	6.50 +/- 0.02	6.69 +/- 0.19	-	-	-	2.16	0.111	0.276
50	6.54 +/- 0.01	6.80 +/- 0.30	-	-	-	2.21	0.113	0.283

Constant Power (V -> V/2, 3 Cycles)				
P (`W)	P / M (W/kg) (packaged)	E (W-h)	W-h / kg (packaged)	W-h / l (packaged)
300	15.4	1.679 +/- 0.001	0.0861	0.215
600	30.8	1.679 +/- 0.000	0.0861	0.215
1000	51.3	1.679 +/- 0.001	0.0861	0.215
1200	61.5	1.681 +/- 0.001	0.0862	0.215

PSFUDS (P_{max} = 55 W/kg, packaged)

Charge Efficiency = 0.99 ± 0.00

Table 7 (cont.)

AC Impedance			
Frequency (Hz)	C (Farads)	R (Ohms)	Phase Angle (Deg)

Leakage Current

$I_{leakage}$ = 5.8 +/- 0.3 (Average and Standard Deviation taken between 3-8 hours)
$I_{leakage}$ *A = NA
R_p = 3.5 k-Ohms (V_w = 20 volts)

Self Discharge	
V (Volts)	Time (Hours)
20.0	0.0
18.0	0.3
16.0	0.9
14.0	2.2
12.0	2.7
10.0	3.9
8.0	5.5
6.0	7.8
5.0	9.3
4.0	11.3
3.0	14.1
2.0	18.8
1.0	31.9
0.55	60.9

Table 8: Generalized PSFUDS (W·h/kg ≥5).

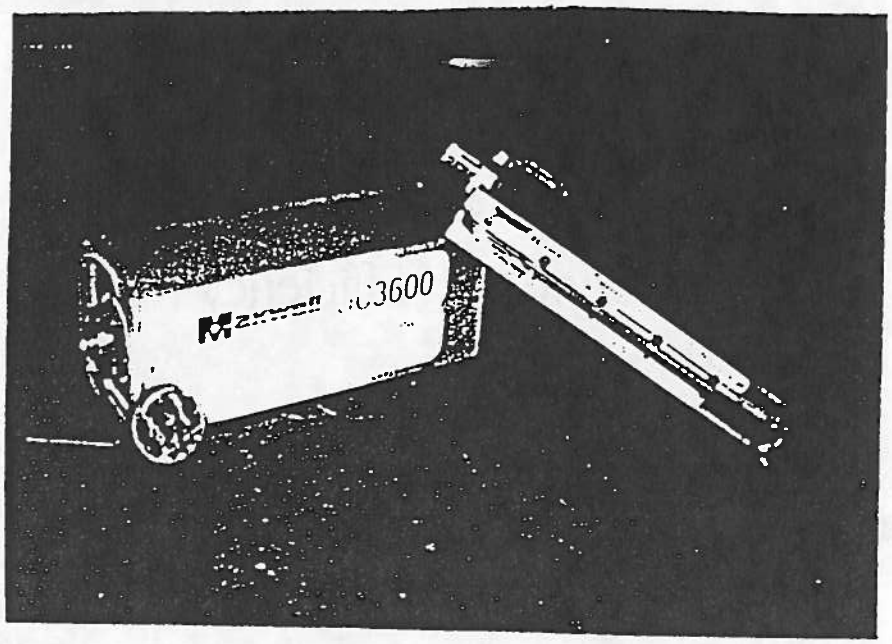
Time Step (s)	P/P_{max}	Charge (C) or Discharge (D)
8	0.2	D
12	0.4	D
12	0.1	D
50	0.1	C
12	0.2	D
12	1.0	D
8	0.4	D
50	.3	C
12	0.2	D
12	0.4	D
18	0.1	D
50	.2	C
8	0.2	D
12	1.0	D
12	0.1	D
50	.3	C
8	0.20	D
12	1.0	D
38	.25	C
12	0.4	D
12	0.2	D
≥50	.3	C to V_w
Total 470 s		

Pmax = 500 W/kg * Weight of device (kg)

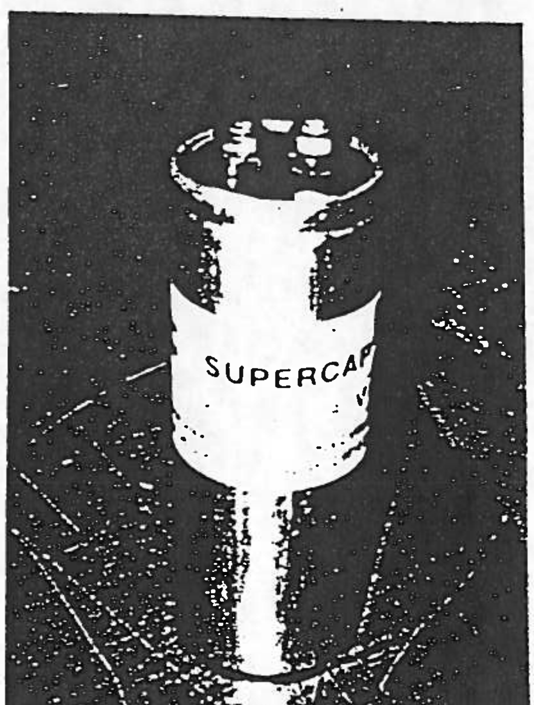
Table 9:
Summary of the PSFUDS Round-trip Efficiency Results

Device	RC (Sec)	Round-trip Efficiency (%)
Maxwell		
UC-1500*	.56	92
UC-3600*	.61	86
Superfarad*	5.7	76
Panasonic	1.7	91
Cap-XX	3.8	83
Econd	.13	97

* PSFUDS cycles with maximum Power Step of 500 W/kg for 8 seconds.

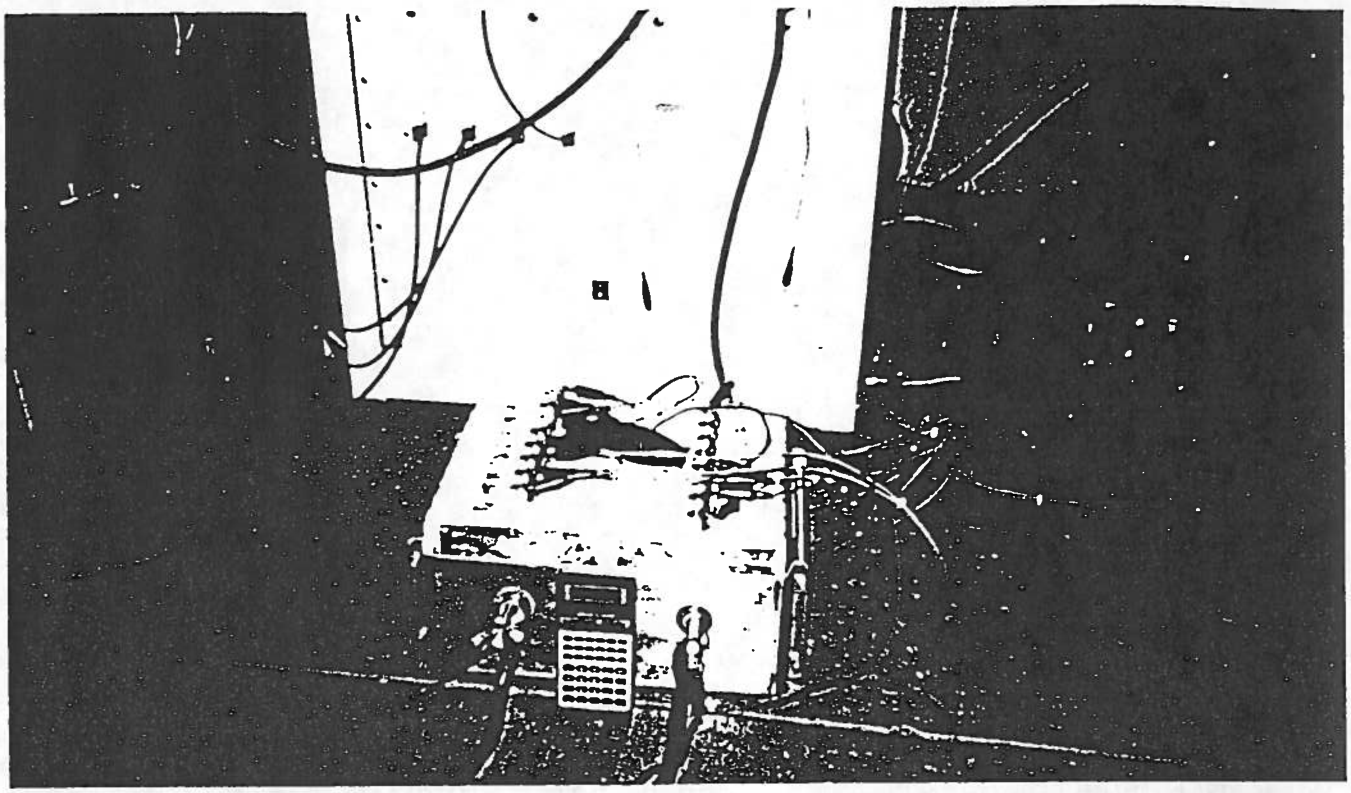


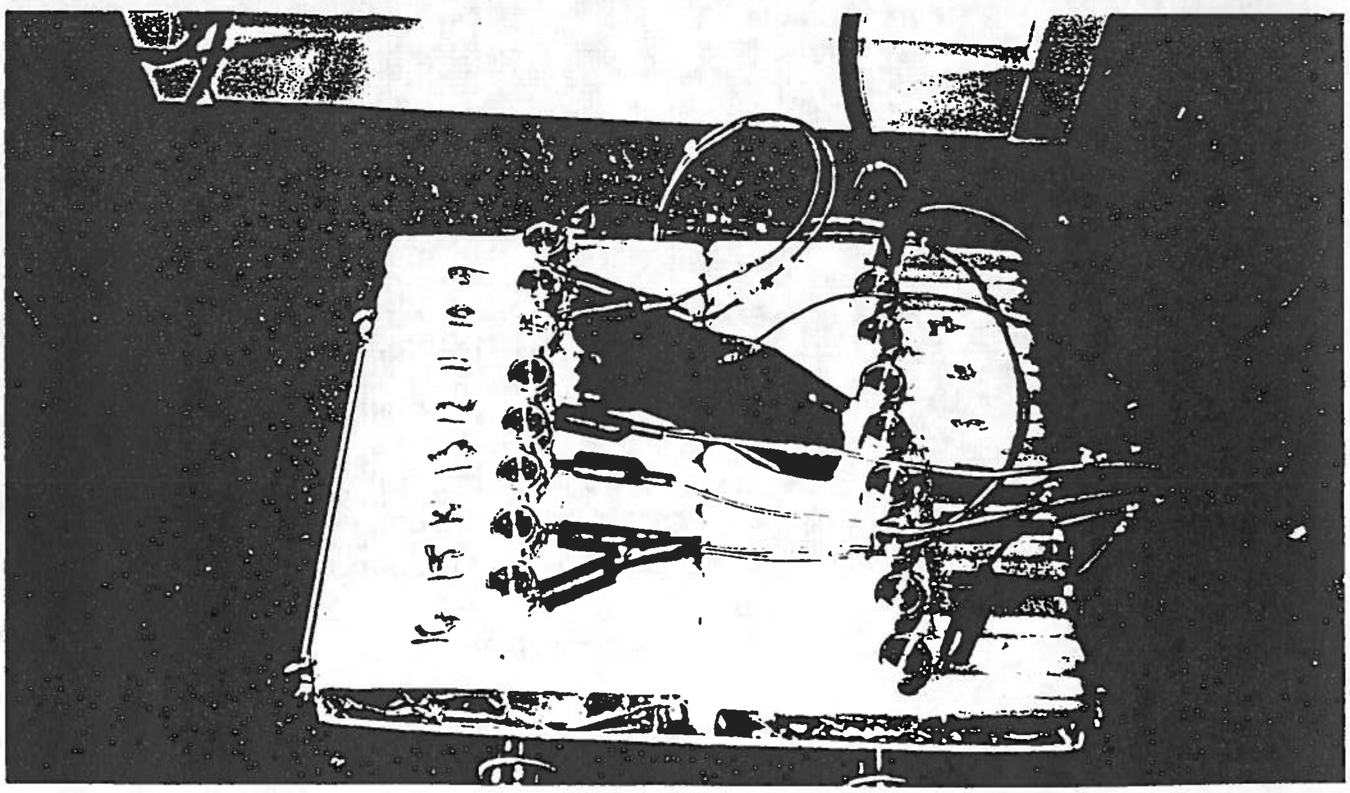
Maxwell Ultracapacitor Devices



The Cap-XX Ultracapacitor

Figure 1





Superfarad 50V, 250F, 16Kg

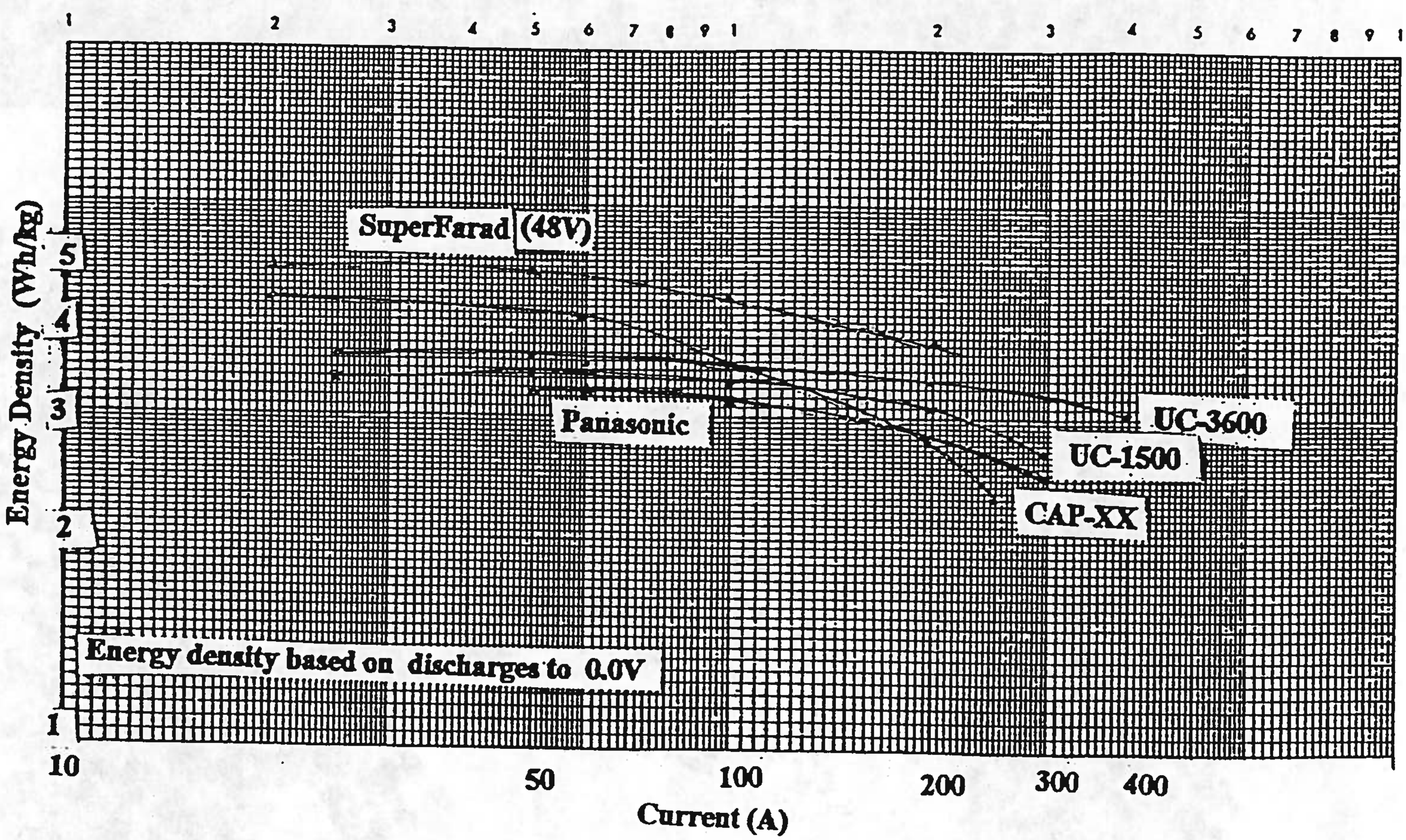


Figure 3 : Energy Density of Packaged Electrochemical Capacitors using Organic Electrolytes for Constant Current Discharges

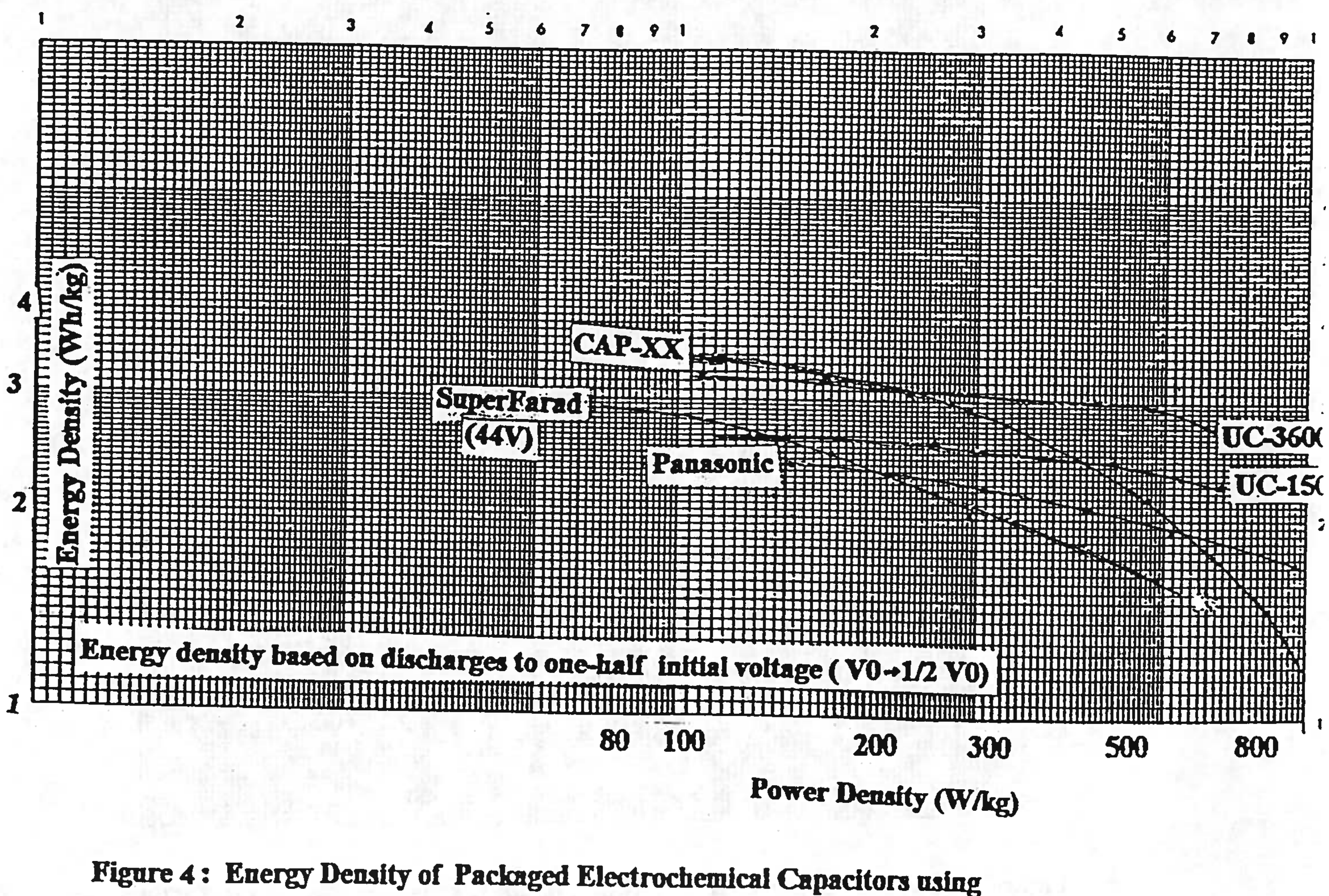


Figure 4 : Energy Density of Packaged Electrochemical Capacitors using Organic Electrolytes for Constant Power Discharges

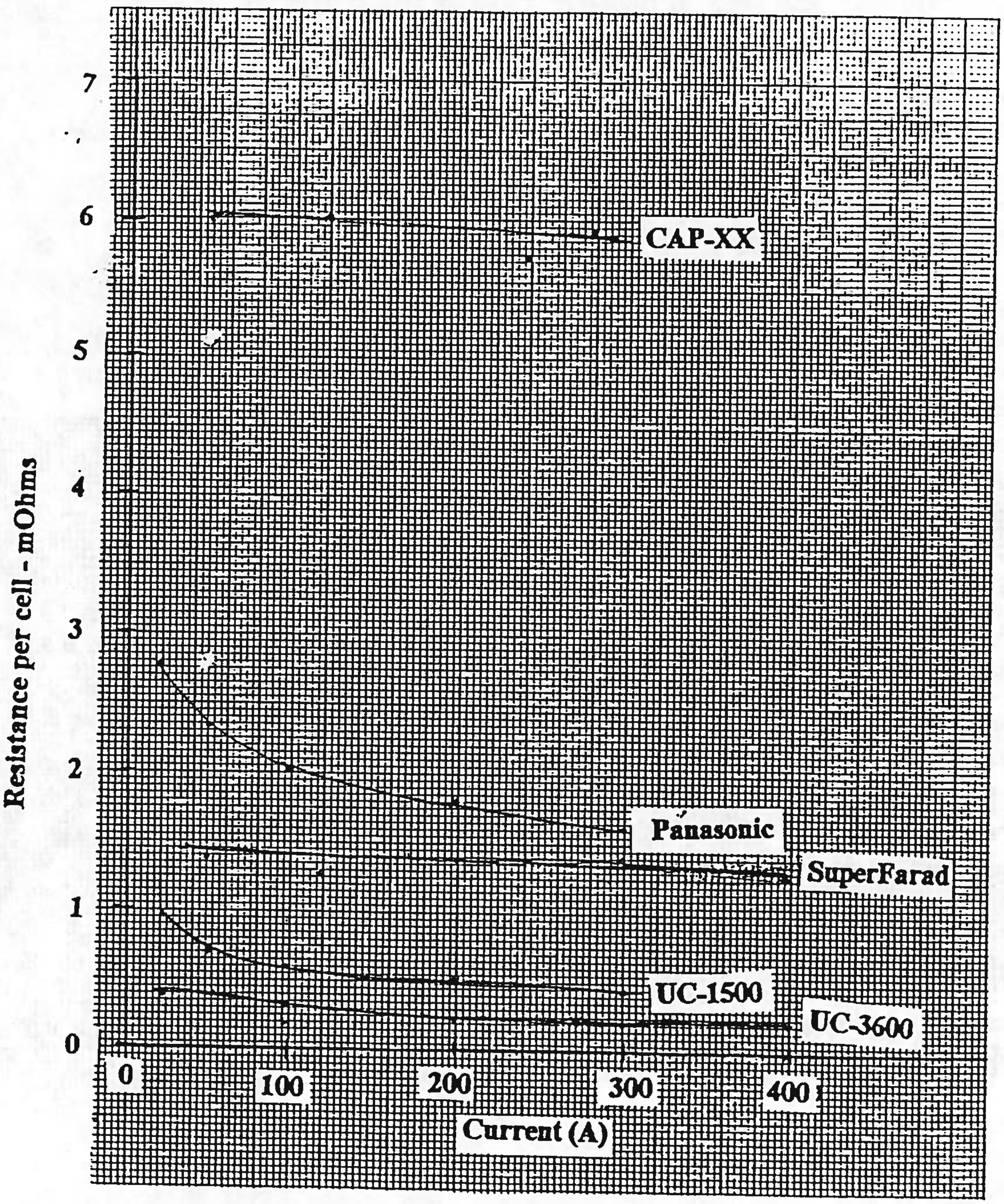


Figure 5: Resistance per Cell as a Function of Discharge Current for Various Electrochemical Capacitors using Organic Electrolytes

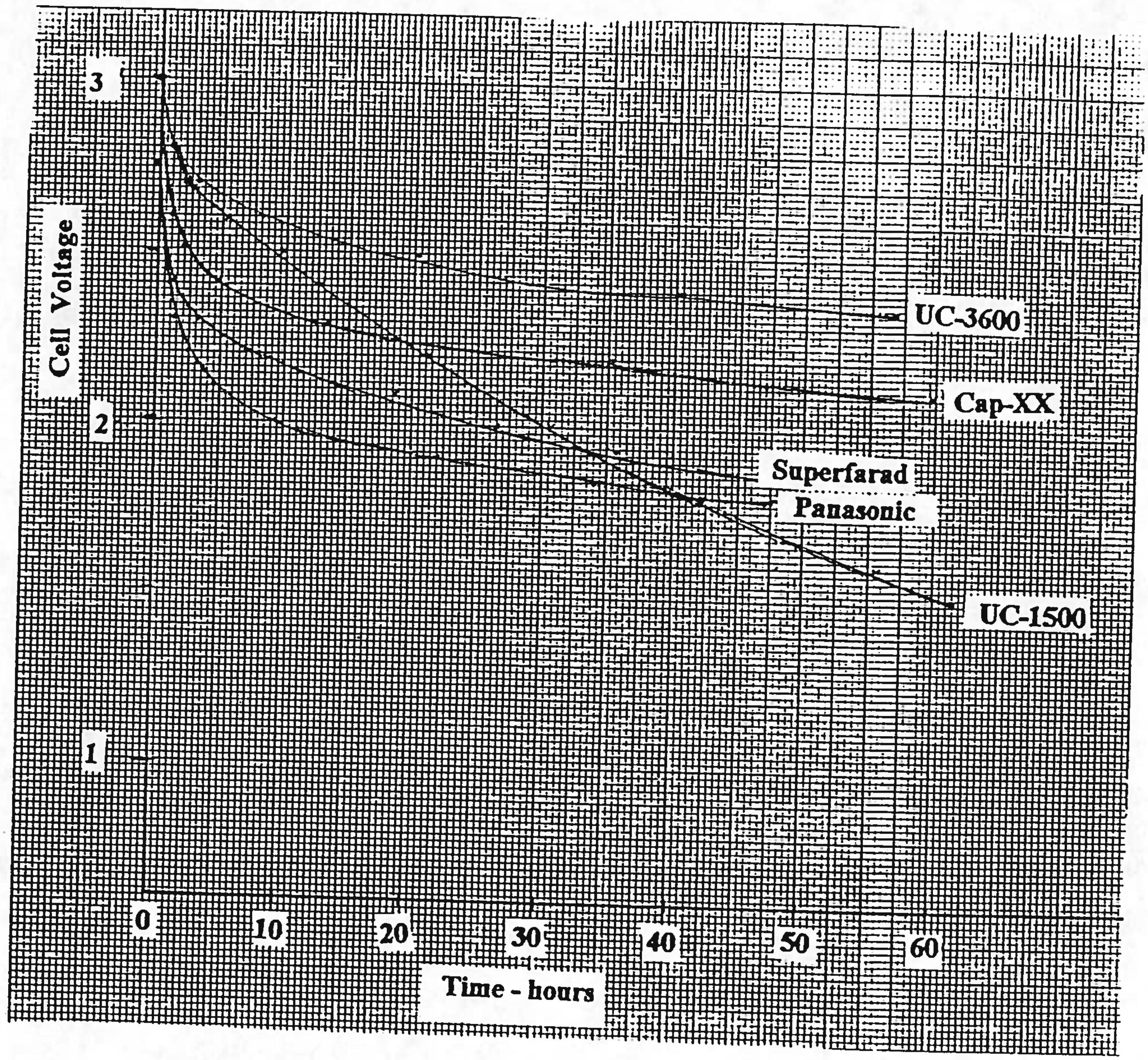


Figure 6: Self-Discharge (Cell Voltage vs. time) of the Ultracapacitors