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Update of Ultracapacitor Technology and Hybrid Vehicle Applications: Passenger Cars and Transit Buses

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Abstract

Ultracapacitor technologies are reviewed with the emphasis on carbon-based devices using organic electrolytes. Recently available cells with capacitances up to 5000F have been tested at cell voltages of 2.5-2.7 V. These devices exhibited useable energy densities between 3.4-3.7 Wh/kg for constant power discharges at 500 W/kg. The calculated pulse power capability of the devices ranged between 1400-3900 W/kg for 95% efficient discharges. An 18-cell, 45V pack of 2600F ultracapacitors was assembled and tested to determine the effect of cell-to-cell variability and thermal effects on the operation of the pack for high power pulses over long periods. The pack was operated on the PSFUDS cycle for 36 hours with 10 minute rest periods between cycles without difficulty. The temperature and maximum differences between the cell voltages stabilized at acceptable levels indicating the pack could operate with minimal cooling and no voltage balancing circuitry.

The uses of ultracapacitors in engine-starting and hybrid-electric vehicle applications were studied to determine whether devices with presently available performance were suitable for those applications. Available devices with capacitances of 2500-5000F were determined to be well suited for vehicle applications with unit weights acceptable to vehicle designers of the various vehicle types. Ultracapacitors units for power-assisted hybrid passenger cars were heavier than the PNGV design targets, but such that they could be accommodated in the vehicles. Recent advances in ultracapacitor performance indicate that both the energy density and power capability of devices will continue to improve with the use of higher specific capacitance carbons and higher cell voltage resulting in energy densities approaching 6 Wh/kg in the next several years. The critical issue that will determine the evolution of markets for ultracapacitors will be device cost which has been decreasing rapidly in recent years and is projected to continue to decrease for the next several years. Unit costs will need to decrease to about $5/Wh for a rapid development of a mass market for ultracapacitors in vehicle applications. For this to occur, the price of the microporous carbons used in the devices needs to be $10-$20/kg and the devices must be produced on automated equipment.

Keywords: energy storage, supercapacitor, hybrid vehicle

Introduction

Electrical energy storage is an important element in the design and operation of hybrid electric vehicles. Presently batteries are used in most applications as the energy storage device. The batteries must be sized to meet both the energy storage (kWh) and power (kW) requirements of the vehicle system. In many hybrid vehicle designs, the power requirement is sufficiently high that the battery is sized by power and the result is that the energy storage unit stores significantly more energy than required by the system. The power requirements for both acceleration and regenerative braking of the vehicle must be meet at all states-of-charge of the battery encountered in its operation. This can result in restricting the battery state-of-charge to a relatively narrow range (40%<SOC<60%). Hence only a fraction of the energy stored in the battery is used in operating the vehicle resulting in added weight and cost that does not benefit the vehicle directly. In addition, the battery over its life experiences a large number (likely hundreds of thousand) of shallow cycles and seldom receives cell equalization charges. Some battery types seem to function well in this type of use and others, such as lead acid, do not. Hence battery cycle and calendar life issues are especially important and complex for hybrid vehicle applications.

The issues just discussed have lead to a resurgence of in the interest in electrochemical capacitors (often referred to as ultracapacitors) for vehicle applications. This is especially true in cases in which the power requirements are high and the need for energy storage is relatively small in order for the driveline system to function properly. The use of capacitors in place of batteries or in combination with batteries allows the energy storage unit to be optimized for both energy and power and for it to be used over a wide range of state-of-charge without concern for limiting its life. A number of auto companies and hybrid/electric powertrain developers are presently investigating the use of ultracapacitors for passenger car and transit bus applications. Fortunately in the last 1-2 years, several companies around the world have begun to produce relatively large quantities of large devices (>1000F) for use in vehicle demonstration programs and the cost of the devices has been reduced significantly. In addition, R&D efforts by several groups show promise of improving the energy density of ultracapacitors to 6-8 Wh/kg without sacrificing their inherent high power capacity and long life.

In this paper, the status of ultracapacitor technology is updated based on tests of recently developed single-cell devices and a 45 V pack consisting of 18 cells of the new devices. In addition, conceptual designs of energy storage units using state-of-the-art ultracapacitors for passenger car and transit bus applications are discussed in terms of both performance and cost. Projections are made of how the markets for ultracapacitors may develop in the near- and longer-terms.

Characteristics of Large Single Cell and Small Lab-Prototype Devices

Large Single Cell Devices

Large single cell, carbon-based devices are presently available from Maxwell in the United States, Epcos and Montena in Europe, Panasonic Industrial in Japan, and Ness in Korea. Maxwell and Epcos use carbon cloth for the electrodes and the other ultracapacitor developers use carbon particulate with a binder to form the electrodes. All the devices cited utilize an organic electrolyte, usually acetronitrile with salts added. In most cases, the cells are rated at 2.3-2.5V for continuous operation, but they can be utilized for pulsed vehicle applications at 2.5-3.0 V. In some cases, the device developers are now increasing their rated voltage to 2.5-2.7V with the target of increasing the rated voltage to 3V in the relatively near future. Since the energy stored and thus the energy density is proportional to the square of the voltage, increasing the safe operating voltage of the devices significantly increases the performance of the devices both respect to energy density and power capability and will reduce the cost per Wh of energy stored.

A number of the large ultracapacitor devices of recent development have been tested over the past year in the Hybrid Vehicle Propulsion Systems Laboratory at University of California-Davis (UC Davis). A photograph of several of the large devices tested is shown in Figure 1. The characteristics of the various devices tested are given in Table 1. A summary of the test data for devices tested as of December 2000 is given in Reference 1. A discussion of how the peak pulse power capability of the devices for a discharge efficiency EF can be calculated from the resistance of the device is given in Reference 2. In comparing the power capability of ultracapacitors and pulse power batteries, it is important to make the comparisons at the same discharge efficiency.

It is clear from Table 1 that devices are now available that store up to 4.75 Wh/cell (4700F, 2.7 V). The energy density of that device is 4.95 Wh/kg. It is usually assumed that 75% of that energy is available for use at system voltages between rated and one-half rated voltage. For system design purposes, it can now safely be assumed that devices with capacitances between 1000-5000F will be readily available as needed with safe operating voltages of 2.5-2.7 V/cell for pulsed vehicle applications. The Ragone curves (Wh/kg vs. W/kg) for a number of available devices are shown in Figure 2. The energy density values shown are for operation between 2.5V and 1.25V/cell and thus indicate the useable energy for each device. It is apparent from Figure 2 that presently available devices can have useable energy densities close to 4 Wh/kg for constant power discharges up to 500 W/kg. In addition, as indicated in Table 1, these devices can have peak pulse power densities greater than 1400 W/kg for a 95% efficient discharge and a matched impedance power, like that often quoted for batteries, of greater than 12 kW/kg. Rapid improvements in the performance of carbon-based large ultracapacitors have been made over the last several years and discussions with the developers of these devices indicate they expect significant further improvements in the next several years. These improvements include both increases in energy density and reductions in the device resistance, which will further increase the power capability of the devices.

Another family (Reference 3) of large capacitor-like devices has been developed by ESMA in Moscow, Russia. These devices utilize a carbon negative electrode, a nickel oxide positive electrode like that in nickel cadmium or nickel iron batteries, and an aqueous electrolyte (KOH) and have an operating voltage range of 1.4-.7 V. This type of device is often referred to as a hybrid ultracapacitor (Reference 2). An ESMA 13 V module consisting of 10 cells has been tested at UC Davis. As shown in Table 1 and Figure 2, the ESMA devices have significantly lower energy density and peak power capability than the carbon-based devices using an organic electrolyte. The 13-26 V modules from ESMA can be purchased at the present time for significantly less than comparable size carbon-based ultracapacitor units. Consequently the ESMA modules have been used in several vehicle demonstration projects (References 4,5) even though their performance for vehicle applications is less attractive than carbon based ultracapacitors.

A Prototype Laboratory Device

Prototype, carbon-based ultracapacitor devices from Skeleton Technologies in Sweden have also been tested in the laboratory at UC Davis. An initial device was clamped with bolts between two metal plates. A later version of basically the same technology was more efficiently packaged , but still not up to the packaging standards of a commercial device. The device characteristics given in Table 1 are based on the weight of the active materials (electrode, current collector, separator, and electrolyte) and not the weight of the packaging. The devices were fabricated in Kiev, Ukraine and Tartu, Estonia from carbon developed in Russia/Sweden by Skeleton Technologies (see References 6,7). The capacitances of the two devices are 47F and 6151F, respectively. As indicated in Table 1, both devices have a very low resistance and consequently very high power capability. As indicated in Table 1 and Figure 2, the prototype devices have higher energy density and power capability than commercially available devices. This indicates that both higher energy and power densities can be expected in the future from commercial, carbon- based devices. Work is in process at Skeleton Technologies to convert the prototype, small cell technology to larger devices with efficient packaging.

Tests of an Eighteen (18) Cell, 50V Unit

An ultracapacitor energy storage unit for a vehicle will necessarily consist of many cells in series to attain the required system voltage. Two issues of importance in assessing the feasibility of such a unit are cell-to-cell voltage variability and temperature rise after many hours of cycling at high power. In order to study these potential problems, an eighteen (18) cell unit of Ness 2500F capacitors was assembled as shown in Figure 3. The 18-cell pack was instrumented such that the voltage of six (6), three cell groups could be monitored during the testing. No provision was made for voltage balancing circuits between the cells. In fact, one of the objectives of the tests was to determine whether such circuits appeared to be necessary. A thermocouple was placed on a cell in the center of the pack to track the temperature. Minimal cooling was provided by a fan blowing air across the top of the pack. Testing of the pack was then initiated to determine if the performance of the multi-cell pack during cycling for long periods was as would be expected based on the characteristics of the individual cells.

The first test of the pack was done using fifty (50) charge/discharge cycles at 100A between 45 and 22V. As shown in Figure 4, the V vs. time plots for the pack at cycles 5 and 50 were nearly identical. The pack capacitance of 2511F and resistance of .0059 Ohm were consistent with the average values of 2550F and .27 mOhms measured previously for one-hundred (100) individual cells. Constant power test data for the pack are summarized in Table 2. The data shown are consistent with similar data taken previously on a single cell (Reference 1). Hence as expected, the performance of a pack can be predicted based on tests of typical, individual cells.

The next set of tests involved cycling the pack on the PSFUDS cycle (Reference 8) using a maximum power step of 500W/kg. Each of the PSFUDS cycles was followed with a 10 minute rest period to observe its effect on the cell-to-cell variability. The pack was cycled through 120 of these cycles for a total test time of about 36 hours. During this period, the room temperature in the lab exhibited a significant diurnal cycle of first heating and then cooling. The change in the voltage variability and temperature with cycling are shown in Figures 5and 6. Figure 5 seems to indicate that the cell voltage variability first increases with cycling and then levels off or increases very slowly. The behavior of the pack temperature also shows an initial increase and then tends to level off for long period cycling. This testing is preliminary in nature, but would seem to indicate that for state-of-the art carbon-based capacitors, large increases in cell-to-cell variability with PSFUDS type cycling (that is sequential charging and discharging) should not be a problem even without balancing circuits and that air cooling the ultracapacitors even with high power discharges should be possible with small CFM size fans.

The last set of tests was intended to determine the self-discharge characteristics of the pack. The pack was charged to 45V and held at that voltage for 120 seconds. The pack was then disconnected from any load and the voltage measured for three days (72 hours). The test data are presented in Figure 7. Also shown in the figure are similar results for a single cell. The pack and the single cell self-discharge at essentially the same rate with the rate of discharge approaching a near constant value after xxx hours Previous tests of a single Maxwell U-3600 capacitor (Reference 9) indicate a self-discharge rate nearly the same as the 18 cell pack.

Vehicle Applications

The following automotive-transportation applications will be discussed in this section:

- Engine starting – 12V and 36-42 V systems
- Hybrid-electric vehicles-passenger cars and transit buses

More detailed reviews of ultracapacitors in vehicle applications are given in References 10 and 11.

Engine starting (12V and 36-42V systems)

Ultracapacitors can be used to augment the power from batteries for starting engines for passenger cars, trucks, and buses. The two cases considered here are a mid-size passenger car and a large class 8 truck. In the case of the passenger car, ultracapacitor modules that can be used with both the standard 12V and the future 36-42V systems will be discussed. In the case of the trucks, multiple capacitor modules are used in combination with the several batteries needed to get adequate power at low, sub-zero ambient temperatures. The ultracapacitor characteristics assumed in defining the modules are 4.5 Wh/kg for the total energy stored, 3.375 Wh/kg for the useable energy, and peak power of greater than 2 kW/kg (90% efficiency). There are a number of devices presently available that meet these performance specifications (see Table 1)

In sizing the ultracapacitors for engine starting applications, it is necessary to know the useable energy required (Wh) and the maximum power requirement (kW). In the case of the passenger car, for normal starting of the engine, the maximum power is sustained for one second or less. For cold starting or repeated attempts for starting the engine, more energy is required. In this study, the energy requirement was calculated on a maximum power of 6.5 kW for 5 seconds or 9 Wh. Assuming that 75% of the energy stored in the capacitor is useable, this results in a total energy storage requirement of 12 Wh for passenger cars. After a discussion with a manufacturer of large trucks, the corresponding requirements for the truck were taken to be 10kW for 10 seconds, which results in a useable energy of 28Wh and a total energy stored of 37 Wh.

For the12V systems, the passenger car requirements can be met with a single module. For the large truck, it seems appropriate to use three modules of the same design as used in the passenger car system. The ultracapacitor module would consist of five cells connected in series. Each cell would have a capacitance of 2600F and be rated at 2.6V. In operation the voltage of some cells could be slightly higher or lower than 2.6V due to cell-to-cell variability. The weight and volume of the cells in the 12V module would be 2.67 kg and 2.25 liters, respectively. The pulse power of the module calculated using the equation cited in Reference (2) is in excess of 15kW for an efficiency of greater than 80%. It would be expected that the power capability of the module is less at sub-zero temperatures than at normal ambient temperature conditions especially for devices using an organic electrolyte. However, tests (References 12, 13) of devices from Panasonic and Ness indicate that this reduction in power is relatively small being less than 10% at a temperature of –30 deg C.

In the truck application using three of the 12V ultracapacitor modules connected in parallel, the weight of the capacitors is 8 kg and the volume is 6.75 liters. At the present time as many as four 100Ah batteries are used in Class 8 trucks to achieve reliable starting at low temperatures. This results in a battery weight of greater than 100 kg, which is large compared to the weight of the capacitor unit. The peak power of the capacitor unit used in the truck application would be greater than 45 kW, which would be more than enough power to start the truck without assistance from the battery (References 14-15) even at low temperatures.

Consideration is presently being given to the use of 36-42 volt systems in passenger car applications for both conventional ICE and hybrid driveline designs. Hence it is of interest to conceptually design a capacitor module for use in 36-42V electrical systems. The building block for a 21V module could be a 1500F cell similar to the 2600F cell used in the modules for the 12V module discussed previously. Each of the 1500F cells would store 1.4 Wh, weigh .31 kg, and have a resistance of .2 mOhm at 25 deg C. The 21V module would consist of eight cells, weigh 2.5 kg, and store 11 Wh of energy (8.4 Wh useable). The resistance of the module would be 1.6 mOhm with a resultant calculated peak power capability of about 15 kW. Two of the 21 V modules would have a power capability of 30 kW, which is much more than required by the 36-42 volt system. The capacitor unit could be used to power an electric motor to both accelerate the vehicle and to recover energy during regenerative braking if the vehicle is so equipped.

The results of the considerations of the use of ultracapacitors for engine starting systems are summarized in Table 3. In all cases, the capacitors can provide the required energy storage with a peak power capability much in excess of the power requirements for the systems.

Hybrid vehicle applications

Ultracapacitors can also have applications in hybrid-electric drivelines using either an engine-generator or a fuel cell to generate on-board electricity. It is most likely that ultracapacitors would be considered for hybrid vehicles that utilize a power assist control strategy. In those cases, the engine, engine-generator, or fuel cell would load follow except for very rapid approaches to near peak demand at which times the capacitors would provide assistance. In addition, the capacitors would be utilized to recover energy during regenerative braking. In these applications, the high power capability of the ultracapacitors are of special importance.

Energy storage units for use in hybrid vehicles must accommodate high voltage. For passenger cars, the voltage is likely to be about 300V and for trucks and transit buses about 600V. This would require about 125 cells in series for a car and 250 cells in series for a truck or bus. If one used the same cells and modules as discussed previously for the 12V engine-starting application, the hybrid-electric car would require 25 12V modules and the truck/bus would require 50 modules. Modules having more than five 2.6V, 2600F cells could be assembled to reduce the number of modules, but the performance of the high voltage units would be essentially the same. The energy stored per cell is 2.44 Wh at a rated voltage of 2.6V resulting in a total energy per string in the high voltage unit of 305 Wh for the passenger car and 610 Wh for the truck/bus.

In the case of the passenger car, the useable energy stored per string is about 30% less than the 300 Wh specified in the PNGV design targets for a power assisted hybrid (Reference 16). This shortfall in energy stored could be made up by either increasing the rated voltage to 3V or the capacitance of the cells to 3500F. The latter approach, which is more compatible with present technology, would increase the weight of the ultracapacitor unit for the passenger car from 68 kg to 89 kg. The weight (68 kg) and volume (56 liters) of the cells in the ultracapacitor unit are about 70% greater than the weight (40 kg) and volume (32 liters) given in the PNGV specifications. Ultracapacitors with an energy density of about 8 Wh/kg would be required to meet the PNGV size targets. The energy density of the presently available devices is 4.5 Wh/kg.

Each high voltage string of capacitors for the hybrid-electric truck/bus application would store 610 Wh of electrical energy. Simulation results for buses using ultracapacitors are given in Reference 17. The results indicate that for a bus utilizing a series hybrid driveline, the energy storage requirement is 1500-2000 Wh to load level the engine-generator on the New York City driving cycles. Hence at least two 600V strings of the capacitors would be needed to store sufficient energy for the bus application. For example, two strings of 5000F cells would store 2350 Wh and weigh 520 kg. Such a unit would provide 250 kW of power in both motoring and regenerative braking at a relatively low power density of slightly less than 500 W/kg. The ultracapacitor unit would be much lighter than the lead-acid or nickel-cadmium battery packs currently used in hybrid electric transit buses (References 18,19). The low resistance of the capacitor units would also result in lower losses in storing the energy and as a result higher fuel economy than would be the case using batteries (References 17,20).

The analyses of passenger car and bus hybrid-electric vehicle applications in this section indicate that ultracapacitors can be used effectively in such applications. The results of the analyses are summarized in Table 4. The key issues concerning whether ultracapacitors can be used in hybrid vehicles are no longer concerned with device performance, but rather cost and availability of devices. Cost issues will be addressed in a later section of the paper.

Evolution of the Ultracapacitor Markets for Vehicle Applications

Projections of large markets for ultracapacitors in vehicle applications have been made in the past (References 21,22) and continue to be made at the present time. No attempt will be made in this paper to predict the sales volume of the market as that is very highly dependent on the price of the devices available at any period of time and the value of the devices perceived by the vehicle developers. Before markets can be developed, it is necessary that successful on-road demonstrations of ultracapacitors in vehicles be made. With the present availability of large numbers of appropriate ultracapacitor devices, such demonstrations are now in the planning stages and should be undertaken in the relatively near futures for passenger cars, truck/buses, and fuel cell powered vehicles. It can be expected that these demonstrations will lead to the evolution of markets as the value of the ultracapacitors in the various applications is experienced. It seems likely that markets for ultracapacitors will evolve in the following order: (1) hybrid-electric transit buses alone or with batteries, (2) 42 volt systems in combination with lead-acid batteries, (3) small hybrid-electric passenger cars, (4) hybrid-electric sport utility vehicles (SUVs), and (5) direct hydrogen, fuel cell powered vehicles. All of these applications require relatively small energy storage for the size of the vehicle and high power, high efficiency (>90%), and long life from the energy storage unit. Such applications are ideal for ultracapacitors.

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Table 1: Summary of the characteristics of advanced prototype and commercially available carbon-based ultracapacitors

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Skeltech*	2.3	47	5.2	.24	5.2	5722	51000	.005	.0038
Skeltech*	2.3	615	.50	.30	3.9	7001	62000	.055	.066
Maxwell	2.5	2700	.23	1.35	2.55	1004	8929	.70	.62
Ness	2.5	2550	.33	.84	2.31	819	7284	.65	.534
Ness	2.7	3870	.175	.68	3.43	1401	12457	.836	.731
Ness	2.7	4615	.225	1.08	3.70	1053	9688	.865	.731
Panasonic	2.5	1200	1.0	1.2	1.3	744	4596	.34	.245
Panasonic	2.5	1791	.45	.80	3.44	1260	11200	.310	.245
Montena	2.5	1800	.50	1.8	2.49	879	7612	.40	.30
Montena	2.5	2800	.25	.70	3.33	1339	11905	.525	.393
ESMA	14	940	2.7	2.5	1.0	151	1344	13.5	7.46

*unpackaged

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated

(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge,

Table 2: Energy Density at Constant Power for the 18-cell Ultracapacitor Pack

Constant Power W/kg	Wh/kg 18 cell pack	Wh/kg Average cell
100	2.36	2.4
200	2.31	2.36
300	2.25	2.35
500	2.2	2.3
700	1.94	—

44-22V, 139 F, 5.7 mOhm

Weight: 11.7 kg (.65 kg/cell)

Table 3: Capacitor Module/System Characteristics for Engine Starting Applications

		Batteries			Capacitor Modules				
Application	System Voltage	No.	Ah	Wgt. (kg)	No.	V	Wh Total (1)	Pulse Power (kW) (2)	Wgt. (kg)
Passenger car	12V	1	48	24	1	12	12	12	2.67
Passenger car	36-42V	(3)	28	30	2	21	22	24	4.93
Class 8 Truck	12V	4	75	140	3	12	37	37	8.0

(1) Total energy stored in the capacitor unit (useable energy 75% of total), energy density 4.5 Wh/kg

(2) Pulse power at EF= 80%, 25 deg C, 4600 W/kg

(3) Battery for the 36-42V system assumed to provide twice the energy storage and pulse power of the standard 12V battery and have an energy density of 40 Wh/kg

Table 4: Capacitor Cell/Unit Characteristics for Hybrid-electric Passenger Car and Transit Bus Applications

		Capacitor cell			Capacitor unit				
Application	System Voltage	V	F	Wh	Cells Per String	No. Of Strings	Wh Total (1)	Wgt. (kg)	Max. Steady Power (2)
Passenger Car	300	3	2600	3.25	125	1	400	67	60
Transit Bus	600	3	3500	4.4	250	2	2200	362	300

(1) Total energy stored in the unit (useable energy is 75% of total), energy density 4.5 Wh/kg

(2) Maximum steady power at 800W/kg, pulse power 2000 W/kg

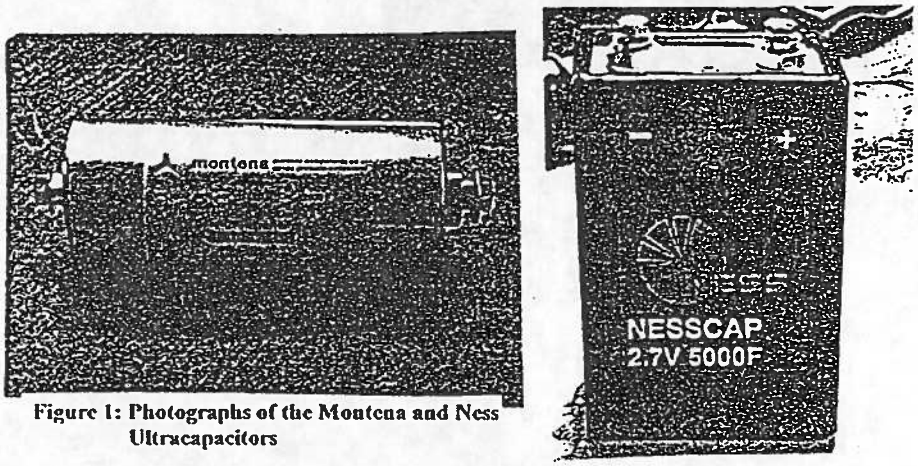


Figure 1: Photographs of the Montena and Ness Ultracapacitors

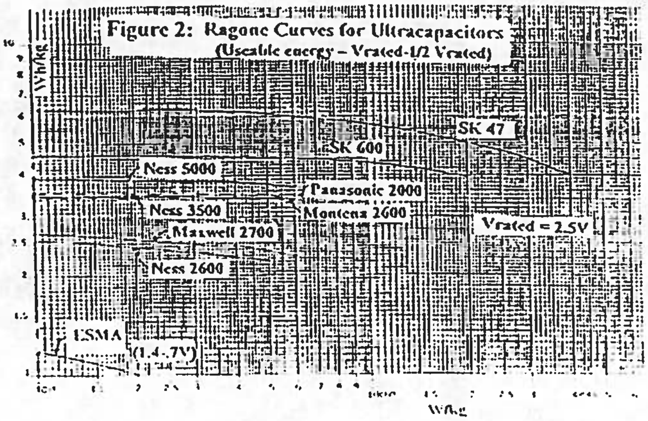


Figure 2: Ragone Curves for Ultracapacitors
(Useable energy – Vrated-1/2 Vrated)

Figure 3: The 18-cell, 45V Pack of Ness 2600F Ultracapacitors

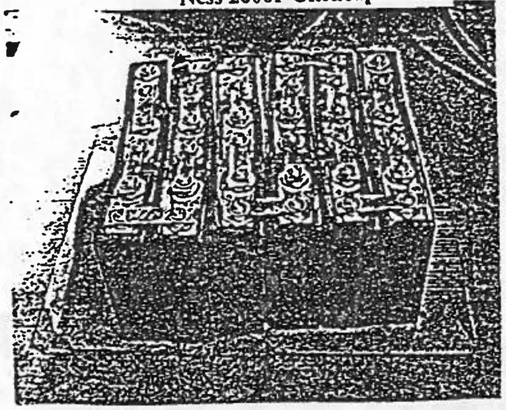


Figure 4: Pack Voltage vs. time for 100A charge/discharge

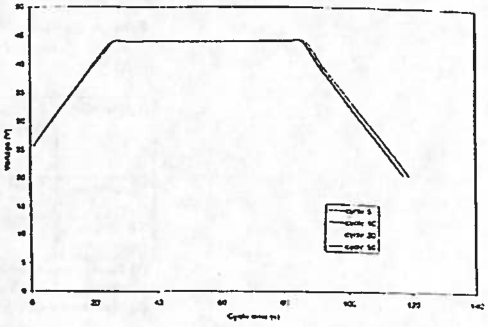


Figure 5: Max-Min cell variability for PSFUDS cycling

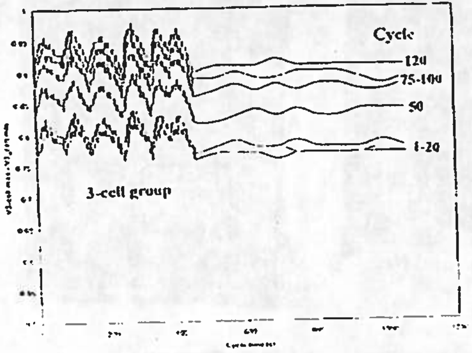
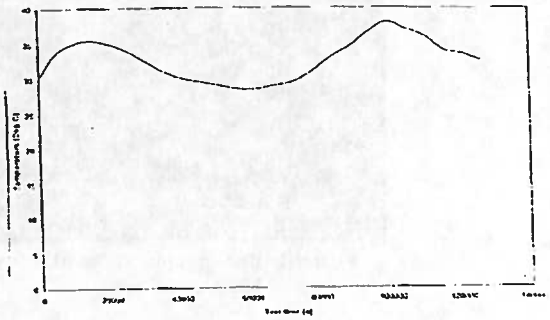


Figure 6: Temperature vs. time for the PSFUDS, 120 cycles



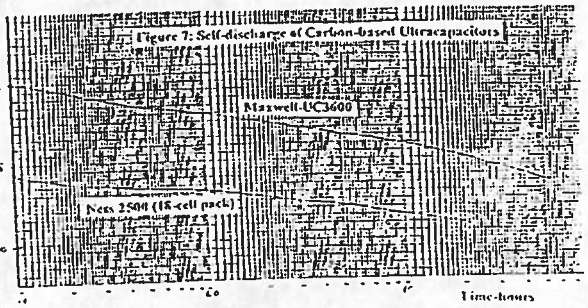


Figure 7: Self-discharge of Carbon-based Ultracapacitors