MATERIAL CHARACTERISTICS AND THE PERFORMANCE OF ELECTROCHEMICAL CAPACITORS FOR ELECTRIC/HYBRID VEHICLE APPLICATIONS

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ABSTRACT

Electrochemical capacitors (ultracapacitors) are one approach to meeting the high power requirements for the energy storage system in an electric vehicle. Energy is stored in an electrochemical capacitor by charge separation in the double layer formed in the micropores of a very high surface area electrode material, which does not undergo chemical change as in a battery. Consequently, the material requirements for capacitors are very different from those of batteries. In the last several years, a number of promising material technologies have been identified for use in electrochemical capacitors. These include activated carbon fibers, foams, and composites, doped conducting polymers, and mixed metal oxides. The most important material property is its specific capacitance (F/gm or F/cm^3). Carbon materials with specific capacitances of 100 to 300 F/gm have been developed. Doped polymer materials having specific capacitances of 300 to 400 F/gm are also being studied. In addition to high specific capacitance, the electrode material must also have a low electronic resistivity (< 0.1 Ω-cm) in order that charge can be distributed with minimum voltage drop in the electrode. Electrochemical capacitor cells have been fabricated using the various material technologies with both aqueous and organic electrolytes. Tests of the cells have shown near ideal charge/discharge characteristics — that is, the voltage versus time curves are nearly linear for constant current tests. The energy densities of 1 V cells, using aqueous electrolytes, are 1 to 1.5 W·h/kg and those of 3 V cells, using organic electrolytes are 7 to 10 W·h/kg. Most of the cells have high power densities of 1 to 3 kW/kg. Numerous new materials for electrochemical capacitors have been identified, processed, and tested in electrodes and cells in recent years and progress is rapid in this relatively new field of research.

INTRODUCTION

As the power capability of electric vehicle drivelines (motors and electronics) has steadily increased in recent years, a major problem has been how to design batteries that can provide the peak power they require. Batteries are presently being developed with high peak power capability (peak power density as high as 500 to 700 W/kg), but it is not yet known what trade-offs in energy density, cycle life, and cost will result from the need to attain that high power density. Another approach to meeting the high power requirement of the energy storage system in electric and hybrid vehicle applications is to use a pulse power unit in conjunction with the battery (see Figure 1). The pulse power unit provides the peak power during accelerations and recovers energy during braking, and the battery provides the stored energy required to achieve the desired range of the vehicle. The pulse power unit is recharged from the battery during periods when the power demand is less than the average power required by the vehicle. Electrochemical capacitors (often referred to as ultracapacitors or supercapacitors) are promising candidates for the pulse

power unit. The United States Department of Energy (DOE) has had an ultracapacitor development program since 1992. This paper in large part is based on work done in the DOE program.

Before proceeding to a detailed consideration of electrochemical capacitors, it is of interest to compare the characteristics of batteries and capacitors to illustrate why the development of electrochemical capacitors was undertaken in the first place. The electrochemistry of electrochemical capacitors and batteries, and how they differ, are discussed in detail in References 1 and 2. The characteristics of electronic capacitors, electrochemical capacitors, and batteries are given in Table 1. Note that for almost every characteristic, the electrochemical capacitor is intermediate between the electronic capacitor and the battery. For example, in the case of charge/discharge time, the electrochemical capacitor has a time of 10 to 30 seconds compared with milliseconds and microseconds for the electronic capacitor and several hours for the battery. Similarly, the cycle life of the electrochemical capacitor is 100,00 to 200,000 cycles compared with the nearly infinite cycle life of the electronic capacitor and 500 to 2000 cycles for a mature battery technology. As will be discussed in later sections of the paper, the key parameter for electrochemical capacitors is energy density. As for the other characteristics, the electrochemical capacitor has an energy density intermediate between that of the electronic capacitor and the battery. The material requirements for designing and fabricating an energy storage device having the characteristics of the electrochemical capacitor are the subject of this paper.

ENERGY STORAGE IN ELECTROCHEMICAL CAPACITORS

Energy is stored in an electrochemical capacitor (ultracapacitor) by charge separation within the micropores of a very high surface area electrode material (see Figure 2.) The charge separation is distributed throughout the volume of the electrode material in the double layer formed at the liquid – solid interface between the solid electrode material and the liquid electrolyte with which the electrode is impregnated. As shown in Figure 2, the internal construction of an electrochemical capacitor is much like that of a battery in that it has two electrodes, a separator, and an electrolyte for ion transfer within the cell. In most cases, the two electrodes in the electrochemical capacitor cell are identical (unlike in a battery where the electrodes are made of the different materials that form the electrochemical couple of the battery). A double layer forms at solid-liquid interfaces in all electrochemical systems and is discussed in all texts on electrochemistry and electrochemical engineering.[3,4] The current (electronic or ionic) at any electrode must be accounted for either by Faradaic reactions, surface charge-transfer, or charging of the double layer. In a battery, the faradaic reactions are dominant and the electrode material takes part in the reaction, with the effect of the double layer being minor. In the case of the simplest electrochemical capacitors, usually termed "double layer capacitors," all the current to or from the electrode is due to charging or discharging the double layer. In a double-layer capacitor, the ions from the electrolyte approach the electrode material, but do not react with it or are not absorbed into it. The faradaic current is zero in the case of the double-layer capacitor. A more complex situation arises in the double layer if some, or most, of the ions that enter the double layer are absorbed into the surface of the electrode (charge transfer) or are intercalated into the material matrix of the electrode. In this case, the double layer can store much more charge than in the simple case of double-layer capacitance, and the additional capacitance is referred to as pseudo capacitance. Even in this case, the electrode material, itself, does not take part in the

interface reactions, and all the ions being transferred are from the electrolyte. For vehicle applications, the simple double-layer devices are the most attractive as they are expected to have the highest power capability and the longest cycle life. However, it is expected that devices that utilize pseudo capacitance will have higher energy density.

The capacitance C of the double layer can be expressed as

$$C = \frac{dQ}{dV} \tag{1}$$

where Q is charge stored, and V is voltage across the double layer. The stored (E) is

$$E = \int C d\left(\frac{V^2}{2}\right) \tag{2}$$

In general, C is a function of the voltage. If C is a constant,

$$Q = CV \tag{3}$$

$$E = \frac{1}{2} CV^2 \tag{4}$$

These are the equations often used to describe the performance of simple double-layer capacitors.

C can be expressed in terms of the capacitance per unit area of the double layer, $\frac{farads}{cm^2}$, with the capacitance of an electrode given by:

$$\frac{C}{electrode}$$

$$= \left(\frac{F}{active\ cm_2}\right)\left(\frac{active\ area}{electrode}\right) \tag{5}$$

The active area per electrode can be expressed in terms of m^2/gm of electrode active material.

Hence:

$$\frac{C}{electrode} \qquad\qquad (6)$$

$$= \left(\frac{F}{active\ cm_2}\right)\left(\frac{m_2}{gm}\right)\left(\frac{gm}{electrode}\right)$$

It is convenient to introduce the parameter (f/gm), the specific capacitance of the electrode material. Now:

$$\frac{C}{electrode} = \left(\frac{F}{gm}\right) electrode\ material$$

$$\times \left(gm\ active\ material\right) \qquad\qquad (7)$$

The mass of the active material in the electrode is simply:

$$\frac{mass}{lectrode} = \left(density\ of\ the\ active\ materia\right.$$

$$\times \left(volume\ of\ the\ electrode\right) \qquad\qquad (8)$$

and the capacitance of the electrode can also be written as:

$$\frac{C}{electrode} = \left(\frac{F}{cm^3}\right) electrode\ material$$

$$\times \left(volume\ of\ the\ electrode\right) \qquad\qquad (9)$$

Either F/gm or F/cm^3 can be used to express the specific capacitance of an electrode material. A cell consists of two electrodes in series, so the capacitance of the cell is

$$\frac{C}{cell} = \frac{1}{2} \times \frac{C}{electrode} \qquad\qquad (10)$$

and the energy stored is

$$\frac{E}{cell} = \frac{1}{2} \times \frac{C}{cell} \times \left(\frac{V}{cell}\right)^2 \qquad (11)$$

For the case where the two electrodes are identical, the voltage is split about equally between the two electrodes. If the electrodes are different, the charge stored on the two electrodes is the same, and the voltage will split as the ratio of the capacitances of the electrodes. The maximum achievable voltage per cell depends on the electrolyte used in the capacitor. For aqueous electrolytes, the maximum is $\approx$ 1.2 V due to electrolysis of water at higher voltages. The maximum using organic electrolytes is 3 to 4 V.

MATERIAL TECHNOLOGIES

In the last several years, a number of promising material technologies have been identified for use in the development of high energy density, electrochemical capacitors for electric/hybrid vehicle applications. These technologies are:

- Carbon/metal composites
- Foamed (aerogel) carbons
- Monolithic cellulose - derived carbon foams
- Doped conducting polymers
- Mixed metal oxides

Carbons

More work[5,12] has been done using carbons for electrochemical capacitors than with any other material. Carbon has been used in a number of forms (i.e., particles, fibers, cloth, foams, and carbon/metal composites). In all cases, the carbon has been activated to attain high surface area with a well-developed micropore structure. The carbon has been formed into thin electrodes by a number of processes (i.e., pressing with and without heat treatment, mixing with a resin, and spreading into a thin layer, paper making, sintering with metal fibers, sol gel; weaving, and extruding). In some cases, the activation step was done in-situ with the electrode forming, and in other cases the activation and electrode formation steps were done separately. In general, the intent was to attain a thin electrode (much less than a mm) with a high carbon density (up to 1 gm/cm^3) and low electronic resistivity (< 0.01 Ω-cm). As will be discussed in the next section of the paper, the key material property is the specific capacitance of the carbon. Unless the specific capacitance of the carbon is high (> 100 F/gm), it is not possible to fabricate high-energy density capacitors from it. For the most part, the carbon-based ultracapacitor devices function as simple double-layer devices with near ideal charge/discharge characteristics (linear voltage versus time at constant current indicating the capacitance is a constant independent of voltage). Some work has been done to enhance the specific capacitance of the carbon by absorbing selected species (surface functional groups) on the carbon surface during the activation step to facilitate surface change transfer reaction.[9,11] This approach can lead to specific capacitance values, for the carbon, of 200 to 300 F/gm.

Doped Conducting Polymers

Research on utilizing doped polymers as the active electrode material for electrochemical capacitors has been in progress at the Los Alamos National Laboratory since 1992.[13-16] A thin (<100 micron), high surface area layer of a conducting polymer, such as polyaniline, is electrochemically grown on carbon cloth, or a metallic foil current collector, to form the electrode. During the electrochemical formation process, the electrode material can be p-doped or n-doped. When the electrode is charged or discharged, the dopant ions move in from or out of the polymer into the double layer formed in the micropores of the electrode. In a capacitor cell, the dopant ions move between electrodes as an ionic current in the electrolyte. These devices utilize pseudo capacitance rather than simple double-layer charge separation for energy storage. As a result, the specific capacitance of these electrodes is very high, (400 to 500 F/gm of active material). The charge/discharge characteristics of these devices are not as ideal as those of most carbon-based devices, but they are capacitor-like (Q is a strong function of V) in character. The electronic resistivity of the polymer is sufficiently low (0.01 to 0.1 Ω-cm) that the resistance of the electrode is relatively low, and devices fabricated from the polymers can have high-power densities.

Mixed Metal Oxides

Electrochemical capacitors using metal oxide materials for the electrodes have been under development for nearly ten years. Most of the work has been done using ruthenium and tantalum oxides. Thin layers (10 to 50 microns) of the oxides can be formed on metallic substrates by applying ruthenium chloride to the substrate followed by oxidation in air at 300 to 500°C. The electrode layers are porous, having a surface area of 100 to 200 m^2/gm. This is a relatively low surface area for capacitor electrode material. It is generally accepted that the dominant energy storage mechanisms in the double layer formed on the metal oxide are redox, charge transfer reactions, resulting in a specific capacitance of 150 to 200 microF/cm^2 of active surface area compared to 20 to 30 microF/cm^2 of active surface area for simple charge separation in the double layer. Based on mass, the corresponding specific capacitance for the metal oxides can be 150 to 350 F/gm, which led to considerable optimism a number of years ago that high energy density capacitors could be developed using ruthenium oxide electrodes. As indicated in References 19 and 20, progress has been slower than anticipated due primarily to problems in attaining surface areas much greater than 100 m^2/gm and specific capacitances greater than about 150 F/gm for large electrode areas (> 50 cm^2).

The devices discussed above utilized anhydrous, crystalline ruthenium oxide as the electrode material. In a recent paper,[21] the use of hydrous ruthenium oxide (RuO_2 x H_2O) as an electrode material in an electrochemical capacitor is investigated. It was found that the specific capacitance of the hydrous RuO_2 with an aqueous electrolyte (sulfuric acid) was 750 F/gm which is much higher than ever measured for anhydrous ruthenium oxide. The hydrous oxide material was amorphous compared to the crystalline form of the anhydrous oxide. The high specific capacitance is thought to be due to intercalation of H+ions into the bulk of the hydrous oxide making the specific capacitance much less sensitive to surface area than was the case for the anhydrous oxide. Cyclic voltammetry measurements with the hydrous oxide indicate the capacitance of the material is nearly independent of voltage except at near 0 V where it is lower. The electronic resistivity of pellets made from the hydrous oxide power is low, ≈0.001 Ω-cm. Hence, the hydrous ruthenium oxide appears to be an excellent material for electrochemical

capacitors. However, as was the case for the doped polymer electrode materials, only small devices have been fabricated to date, and much work remains to be done to more completely understand the characteristics of the hydrous oxide material for electrochemical capacitors. In addition, the ruthenium materials are very expensive and probably not suitable for capacitors for consumer markets, such as, automobiles and electric hand-tools.

ELECTRODE MATERIAL CHARACTERISTICS

The various material technologies currently being investigated for use in the electrodes of electrochemical capacitors were identified in the previous section, and the material characteristics of interest discussed. These characteristics, including those of the electrolytes to be used in the devices, are summarized in Table 2.

The relationships between the electrode material characteristics and the capacitance of a device were discussed in a previous section of the paper. In this section, the relationships between the resistance of a device, the material characteristics, and the dimensions of the device are considered. There are several contributors to the resistance:

1. The electrode electronic resistance
2. The ionic resistance in the micropores of the electrode
3. The ionic resistance of the electrolyte in the macropores of the electrode
4. The interfacial resistance between the electrode and the current collector
5. The ionic resistance of the separator.

The most complex and uncertain of these resistances is the ionic resistance in the micropores of the electrode material. The micropore resistance has been analyzed in terms of a simple transmission line model in Reference 22, and measured using AC impedance methods in References 9 and 23. It is shown in Reference 9 that the DC (low frequency) resistance of the micropores can be expressed as:

$$R_{pores} = \frac{L_{pore} \times k_{electrol}}{\left(2 \pi \times r^2 \times n\right)} \tag{12}$$

where:

$$L_{pore} = \text{effective pore length}$$

$$r = \text{average pore radius}$$

$$n = \text{number of pores in the electrode}$$

$$k_{electrol} = \text{specific ionic resistance of the electrolyte } (\Omega\text{-cm})$$

The number of pores in the electrode is given by:

$$n = n' \times (A_x \times L) \tag{13}$$

where:

$$n' = \text{number of pores per unit volume}$$

$$A_x = \text{cross-sectional area of the electrode}$$

$$L = \text{thickness of the electrode}$$

Hence the pore resistance is given by:

$$R_{pores} = \frac{L_{pore} \times k_{electrol}}{(2\pi \times r^2 \times n \times A_x \times L)} \qquad (14)$$

$$_{pores} = \frac{C_1 \times k_{electrol}}{(A_x \times L)}; \quad C_1 = \frac{L_{pore}}{(2\pi \times r^2 \times n} \qquad (15)$$

C_1 can be determined from AC impedance measurements for a sample electrode. Note that the pore resistance is small for thicker electrodes for a given pore geometry (n', r, L_{pore}), because the pores carry the current in parallel. The total electrode resistance (Ω-cm^2) for a bipolar cell can be written as:

$$R_{electrode} = R_{intf} + R_{etd} + R_{pores} + R_{sep} \qquad (16)$$

where:

$$R_{intf} = k_{intf} \qquad (17)$$

$$R_{etd} = \left(\frac{L}{2}\right) \times k_{etd} \qquad (18)$$

$$R_{electrol} = \left(\frac{L}{2}\right) \times k_{electrol} \qquad (19)$$

$$R_{sep} = \left(\frac{L_{sep}}{2}\right) \times k_{sep} \tag{20}$$

It has been assumed that the mean diffusion distance is one-half the element thickness for all the layers. The contribution of the terms that vary with electrode thickness L can be expressed as:

$$R_{electrode}L = \frac{L}{2} \times k_{eld} + \frac{L}{2} \times k_{electrol}$$

$$+ \frac{L_{pore} \times k_{electrol}}{\left(2 \pi r^2 n' A_x L\right)} \tag{21}$$

For the case in which $k_{eld} << k_{electrol}$, the minimum value of $R_{electrol}$ occurs for

$$L_{min} = \sqrt{2 C_1} \tag{22}$$

and

$$R_{electrode} \, min = \sqrt{2 C_1} \, k_{electrol} \tag{23}$$

Hence, making the electrode thicker for a fixed cross-sectional area, increases its resistance only after the thickness has exceeded L_{min}. The AC impedance data for most electrochemical capacitor materials show that the specific capacitance and the micropore resistance are frequency-dependent. This means that the charge/discharge characteristics of cells fabricated from particular materials will be rate-dependent, and the optimum designs with those materials will be application-specific.

One of the most persistent problems faced by electrochemical capacitor developers has been attaching the electrodes to the current collector without suffering a high contact resistance at the interface. This has been a particularly serious problem when the formation of the electrode layer and its attachment to the current collector are two separate steps in the fabrication of the electrode. In this case, a metallic collector is often pressed against the electrode layer during the assembly of the capacitor cell, and the pressure is maintained mechanically. This usually results in an uncertain contact resistance, and in addition , this approach is clearly not suitable for assembling bipolar stacks of cells having a large cross-sectional area (>200 cm²). Methods of bonding the porous, high-surface area electrodes to highly conductive current collectors must be developed that

are suitable for high-volume manufacturing. If the electrode layer is formed on the current collector as part of the electrode fabrication process such as in the case for the carbon/metal electrodes being developed by Maxwell Laboratories.[5-7] and the mixed metal oxide electrodes being developed by Pinnacle Research Institute (PRI),[24] the contact resistance at the electrode-current collector interface has been minimal and has not caused any difficulty.

A summary of material characteristics for electrochemical capacitors using the various electrode material technologies as given in Table 3. Values are given for each of the material properties listed in Table 2. In most cases, a range of values is given both because of the present uncertainty in knowledge of the property and differences in the property that are obtained using different processing techniques. The values of the properties shown in Table 3 can be used in the formulas previously given in the paper to estimate the characteristics of electrodes for electrochemical capacitors fabricated using the various materials. Characteristics of cells assembled using the various materials are discussed in the next section, based primarily on test data taken at the Idaho National Engineering Laboratory (INEL) as part of the DOE Ultracapacitor Development Program.

ELECTROCHEMICAL CAPACITOR CELL CHARACTERISTICS

The INEL has been testing electrochemical capacitors (ultracapacitors) for electric vehicle applications since 1991.[25] The first capacitors tested were carbon-based, spiral wound, single cell, 3 V power capacitors from Panasonic, and ruthenium-based, 20 V bipolar stacks from PRI. Procedures for testing electrochemical capacitors for electric vehicles have evolved over the last four years, and are now reasonably well documented.[26] Data are now available for capacitors fabricated from all of the electrode material technologies previously discussed. Most of the testing has been done using direct current (DC) methods, much like that done for batteries. The DC tests include constant-current and constant-power charging and discharging tests, from which the energy density and resistance of the devices can be determined. Transient cycle tests, which are intended to simulate the repeated charging and discharging of the capacitors as they load level a battery in an electric vehicle, are also performed to determine the round-trip efficiency of the devices when part of the cycle is done at high power. The AC impedance testing has also been done on some of the Maxwell Laboratory deliverables.

As shown in Figure 3, the charge/discharge curves (voltage vs. time) of the electrochemical capacitors appear to be surprisingly ideal in that the curves are linear with time for constant-current tests indicating that the capacitance and resistance are constant essentially independent of voltage. Traces such as those shown in Figure 3 are typical for carbon-based devices using both aqueous and organic electrolytes over a wide range of charge/discharge times (see Figure 4). Constant power discharge curves are not linear as the current changes during the discharge due to the decreasing voltage (see Figure 5). The data indicate that devices that store energy in the double-layer by simple charge separation behave in a nearly ideal manner (that is $Q = CV$ and $E = \frac{1}{2} CV^2$) for discharge times appropriate for electric vehicle applications,. Devices that utilize pseudo-capacitance for energy storage indicate a higher degree of non-ideal behavior (see Figures 6 and 7), but even in those cases, there is a clear capacitor-like character to the charge/discharge curves, much different than that characteristic of batteries. Extensive DC testing[27] of electrochemical capacitors indicates that, to a first approximation, they behave as a simple RC circuit, where C is the capacitance obtained from the slope of the charge/discharge curve and R is the equivalent series resistance (ESR) of the device calculated from the IR step at the beginning or end of the constant current portion of the test.[26] Tests at high discharge rates

show that C is rate-dependent, decreasing significantly at very high rates (discharges in < 5 s). The resistance R is much less rate dependent in the DC tests. The AC impedance test data (see Figure 8) clearly show that the capacitance and resistance of the devices are frequency-dependent when frequency is varied over several orders of magnitude, but the detailed relationship between the DC test results and the frequency-dependent characteristics of C and R is not yet well understood.

A summary of the cell characteristics of electrochemical capacitors as of early 1995, are given in Table 4. More complete, recent summaries of electrochemical capacitor technology for electric vehicle applications are given in References 20, and 27 through 29. The results indicate that for carbon-based devices using aqueous electrolytes, energy densities of 1 to 1.5 W·h/kg have been attained with peak energy densities of $\approx$ 1 kW/kg. Energy densities of 7 to 10 W·h/kg have been attained in carbon-based devices using organic electrolytes, which permit a cell voltage of 3 V. As would be expected, the resistance (1 to 1.2 Ω-cm^2) of a cell using an organic electrolyte is higher than the resistance (0.2 to 0.3 Ω-cm^2) of the 1 V cell using the higher conductivity, aqueous electrolytes. Nevertheless, the cells using the organic electrolytes have been tested at power densities up to 3 kW/kg (see Table 5). Work is continuing on the fabrication of bipolar stacks of 3 V carbon-based capacitor cells. Initial tests of a completely sealed, 24 V stack at Maxwell Laboratory indicate that an energy density of 10 W·h/kg has been achieved. Work on carbon-based devices, underway at other DOE contractors, shows promise of achieving 5 W·h/kg with aqueous electrolytes and 15 to 20 W·h/kg with organic electrolytes.

The progress on developing high energy density, electrochemical capacitors using mixed oxide (anhydrous ruthenium oxide) electrodes has been slower than anticipated based on early published information.[18,25] Completely sealed, bipolar devices (up to 100 V) have been fabricated by PRI, but those devices have an energy density of < 1 W·h/kg.[20] They have a relatively low resistance (0.2 Ω-cm^2) and can be charged and discharged at high-power densities (> 1 kW/kg). Efforts at PRI to increase the surface area and the specific capacitance of the oxide layer, and to improve the electrode coating process to permit thicker layers on thinner metal substrates, may increase the energy density of their devices to 3 W·h/kg. Recent work reported in Reference 21 using hydrous ruthenium oxide shows promise of developing electrochemical capacitors with an energy density of 10 to 15 W·h/kg.

Recent results[15] on p-doped, polyaniline electrode devices from Los Alamos National Laboratory (LANL) indicate they are now fabricating 10 cm^2, sealed 1 V cells that have a high capacitance (2.5 F) and can be discharged at high currents (100 mA/cm^2). The energy density of these devices is $\approx$4 W·h/kg, based on the weight of the polyaniline in the electrodes. Projections by LANL[14] are that energy densities as high as 15 to 20 W·h/kg in packaged devices may be possible using n- and p-doped electrodes and organic electrolytes. Much work remains to be done to understand the charge and discharge characteristics of the doped polymer electrodes that utilize pseudo-capacitance mechanisms for charge storage and to determine how they differ from batteries in terms of cycle life and peak-power density.

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Table 1. Capacitor and battery characteristics.

	Electronic Capacitor	Ultracapacitor	Battery
Nominal discharge time	10^{-6} to 10^{-3} sec	1 to 30 sec	0.3 to 3 hrs
Nominal charge time	10^{-6} to 10^{-3} sec	1 to 30 sec	1 to 5 hrs
Energy density W·h/kg	< 0.1	1 to 10	20 to 100
Power density W/kg	> 10,000	1000 to 2000	50 to 200
Charge/discharge efficiency	Approx. 1.0	0.90 to 0.95	0.7 to 0.85
Cycle life	Infinite	> 100,000	500 to 2000

Table 2. Summary of electrochemical capacitor material characteristics.

1.	Specific capacitance of the electrode material	F/gm, F/cm^3
2.	Surface area of the electrode material	m^2/gm
3.	Porosity and pore size distribution	--
4.	Density of the electrode	gm/cm^3
5.	Specific electronic resistivity of the electrode material	Ohm-cm
6.	Specific ionic resistivity of the electrolyte	Ohm-cm
7.	Specific electronic resistivity of the current collector material	Ohm-cm
8.	Interface resistance between the electrode material and the current collector	Ohm-cm

Table 3. Summary of the characteristics of electrode materials.

Electrode Material	Specif Capac (F/gm)	Surface Area (m2/gm)	Density (gm/cm3)	Resistivity (ohm-cm)
Carbon/metal composites	100 to 200	1000 to 1500	0.5 to 0.7	< 0.01
Aerogel carbon	120 to 160	500 to 800	0.4 to 0.8	< 0.01
Cellulose-deriv. foamed carbon	70 to 180	500 to 800	0.8 to 1.0	0.015
Doped-polymer (Polyaniline)	400 to 500	200 to 400	0.5 to 0.9	0.01
Anhydrous Ruthenium oxide	100 to 150	100 to 150	2.5 to 3.0	< 0.001
Hydrous Ruthenium oxide	600 to 750	80 to 100	2.3 to 2.5	0.002 to 0.005
Aqueous Electrolytes	--	--	1.18 to 1.24	1.4 to 2.0
Organic Electrolytes	--	--	1.1 TO 1.2	12 TO 17

Table 4. Summary of cell characteristics for different electrode technologies.
Idaho National Engineering Laboratory (INEL) Test Results

Developer	Electrode/Electrolyte Material	W·h/kg*	W·h/L	W/kg	Voltage
Panasonic	Carbon/Organic	2.2	2.9	400	3 V
Pinnacle Research Institute	Mixed Metal Oxides/Aqueous	0.8	3	500	28 V
Maxwell Laboratories	Carbon/Organic	6	9	2,500	24 V
Maxwell Laboratories	Carbon/Organic	7	9	2,000	3 V
Livermore National Lab	Aerogel Carbon/Aqueous	2	1.5	2,000	1 V
Sandia National Lab	Synthetic Carbon/Aqueous	< 2	1.7	1,000	1 V
Los Alamos National Lab	Polymer/Aqueous	< 2	–	> 500	0.75 V
Note: Weight based on cell, including current collector, active material, separator, and electrolyte					

Table 5. Discharge characteristics of the Maxwell cells using an organic electrolyte.

Dischg Current	Capaci. (F)	Dischg Time (sec)	Resistance (Ω)	Energy Out (J)	W·h/kg	W·h/L	(W/kg)$_{avg}$
1	12.5	37.6	0.08	55	6.8	8.1	666
3	11.6	11.6	0.67	49	6.1	7.2	2000
8	10.7	6.4	0.076	41	5.1	6.1	3333
Discharge 3 V to 0 V							
Device Characteristics:							

Device Characteristics:

Weight   2.25 gm

Area   20 cm^2

Volume   1.08 cm^3
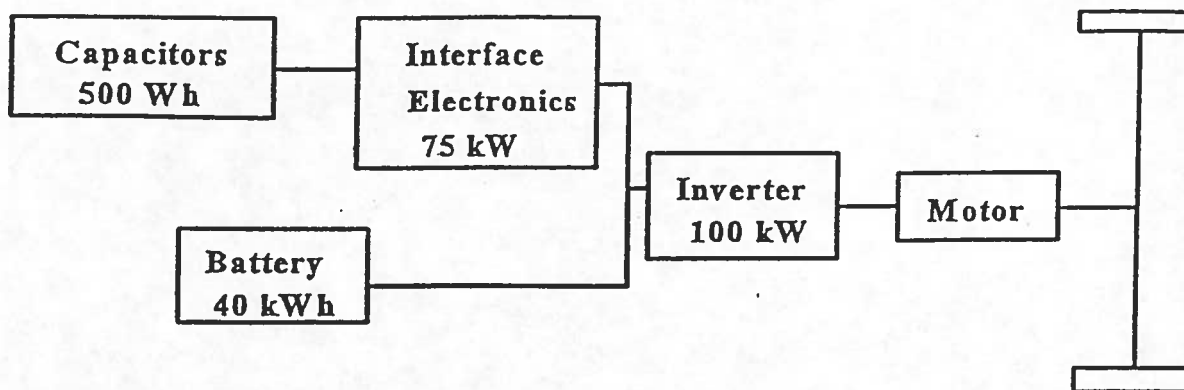
Figure 1. Electric vehicle driveline using electrochemical capacitors.

Bipolar Ultracapacitor Cells and Stack

High Energy Density Capacitor

- Porous, high surface area particles or fibers (1000-2000 m^2/gm)
- Electrolyte between particles or fibers
- Electronic conductor
- Separator (ionic conductor)
- Substrate (electrode)
- Electrolyte
- Electrical double-layer around the particles/fibers. Energy storage by charge separation in the double layer.
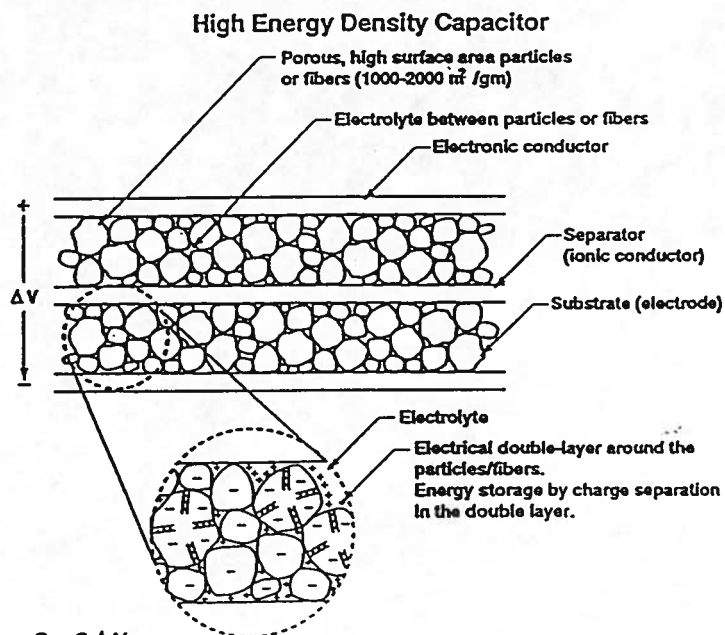
$Q = C \Delta V$

$E = 1/2 \, C \, (\Delta V)^2$

$C = 1/2 \left[(F/gm)wt \right]_{\text{Active material in cell}}$

$C \equiv$ Capacitance of cell

F/gm = Farads per gm of active material
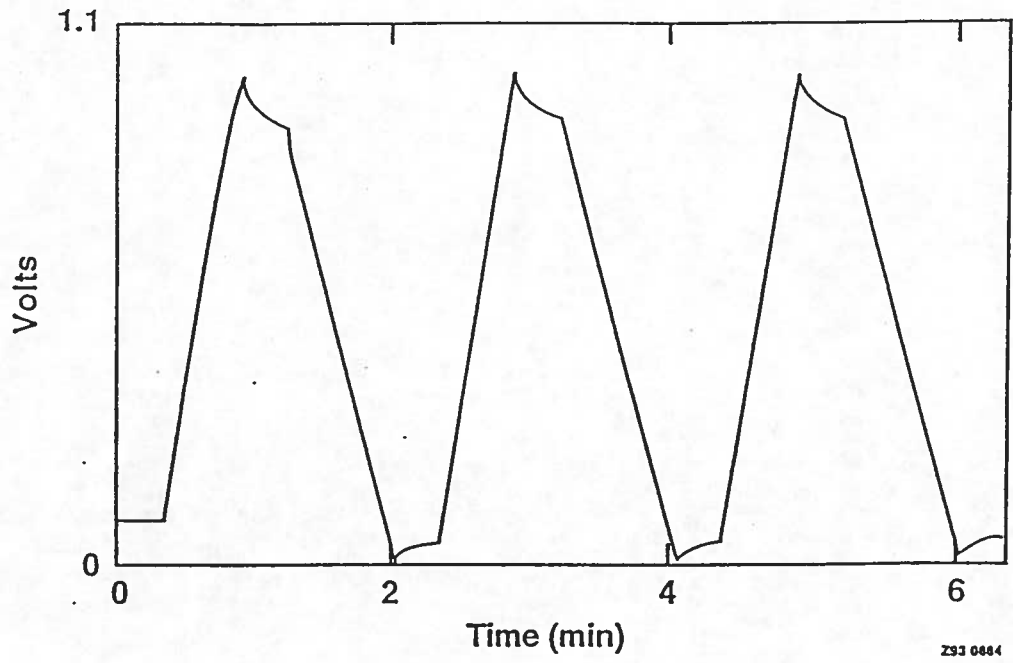
Figure 3. Charge/discharge traces for a Maxwell carbon/metal composite capacitor (1 A).
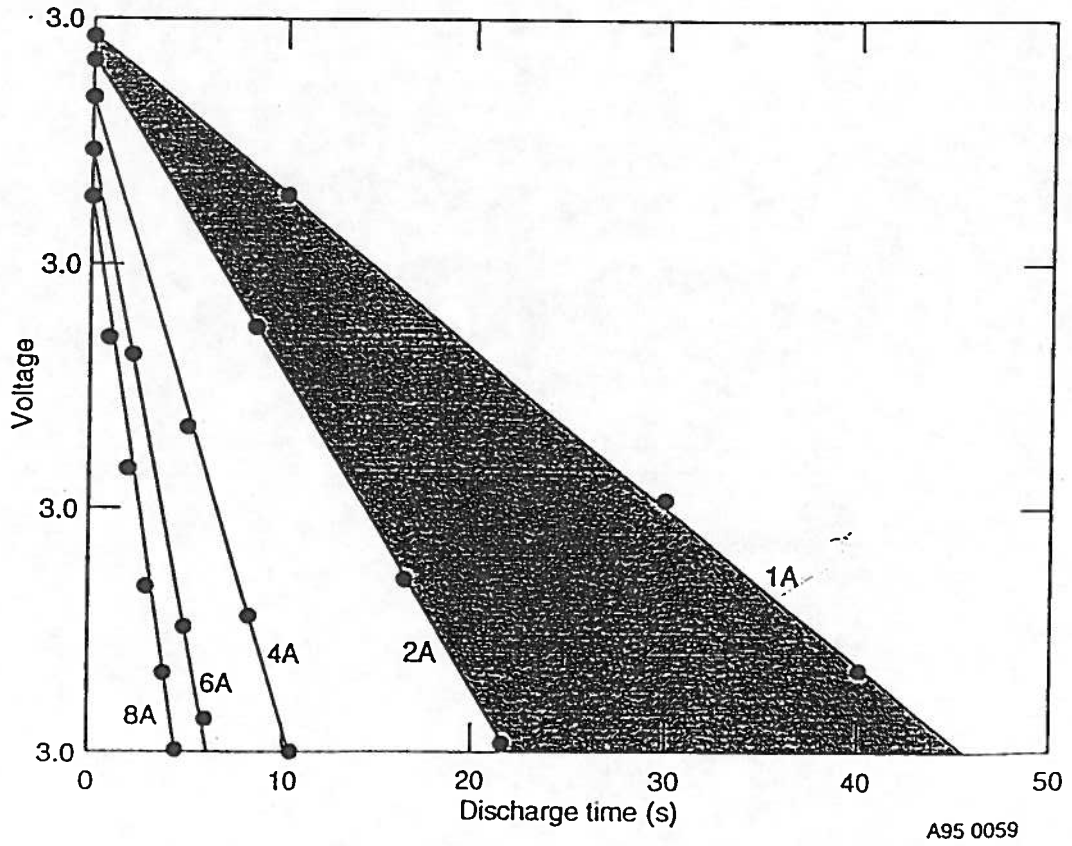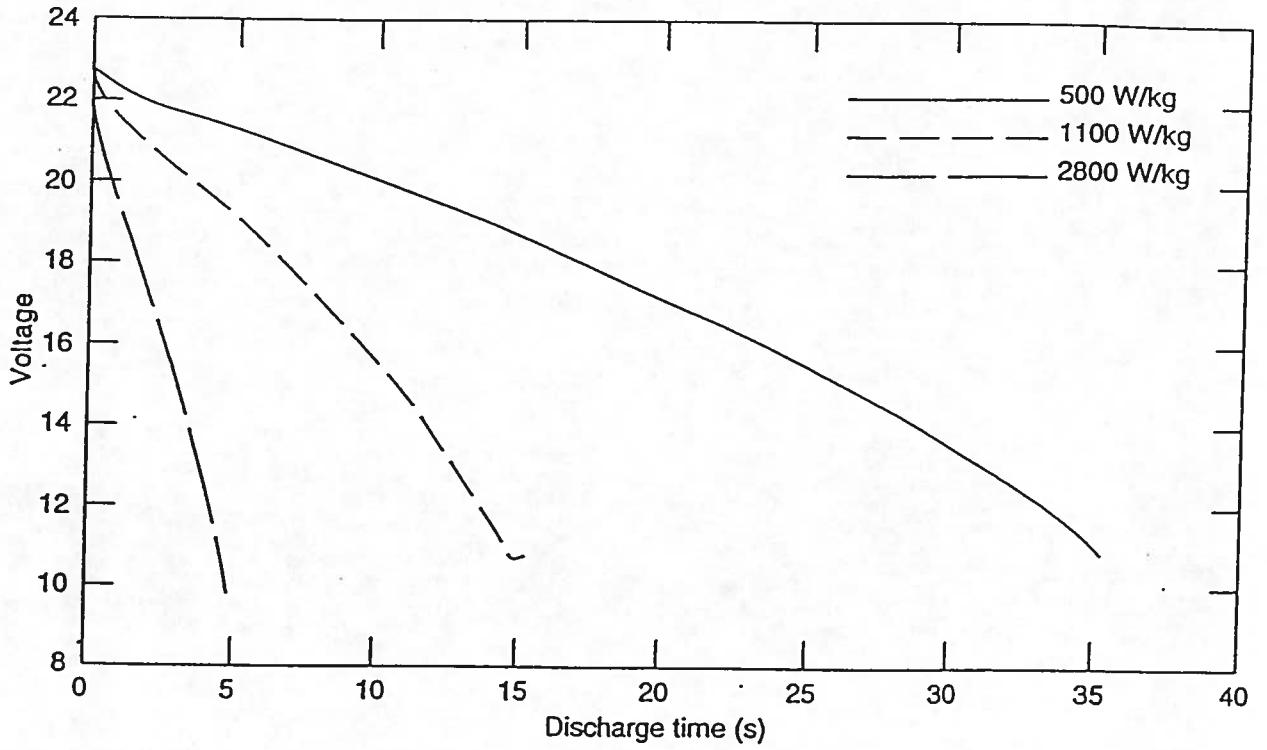

Figure 4. Discharge characteristics of a Maxwell capacitor at high currents.

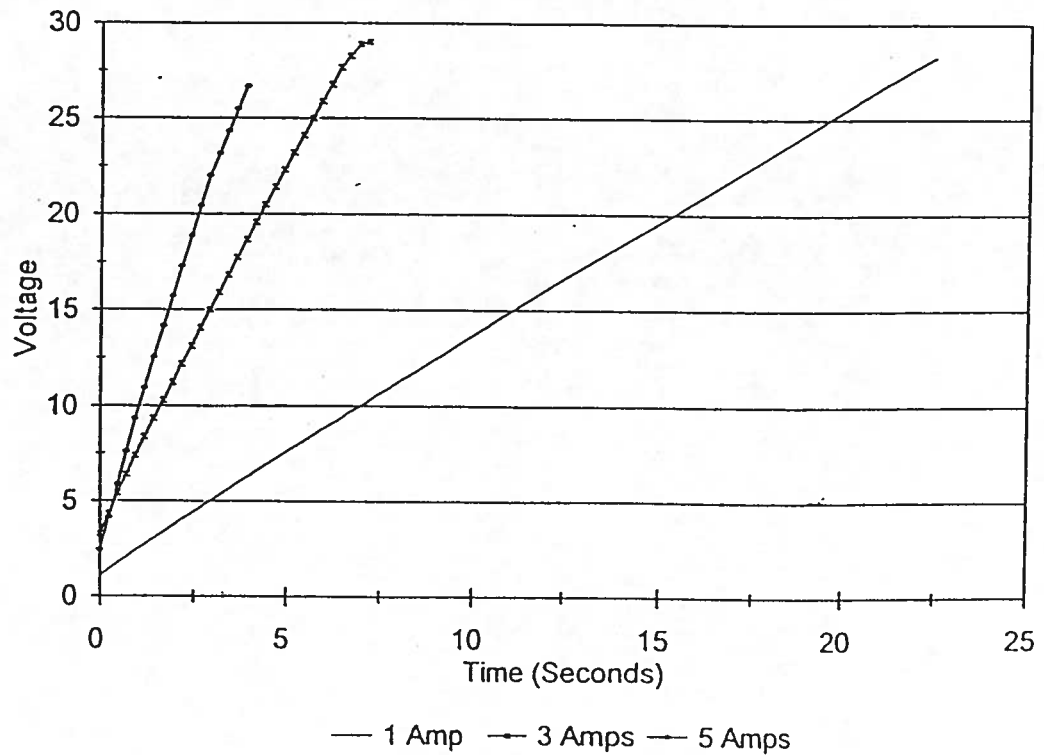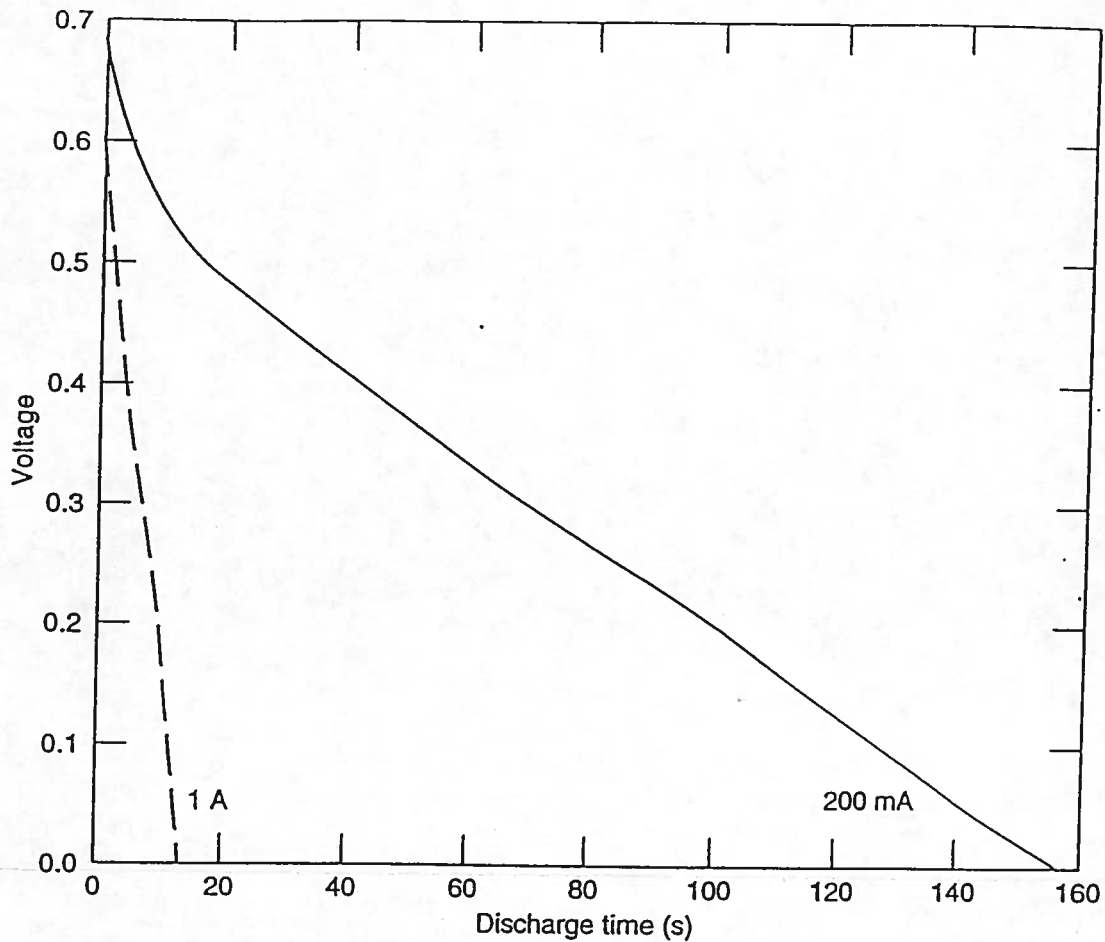**Figure 5.** Constant power discharges of a Maxwell capacitor up to 2800 W/kg.

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Figure 6. Constant current charging of the PRI RuO2 capacitor.

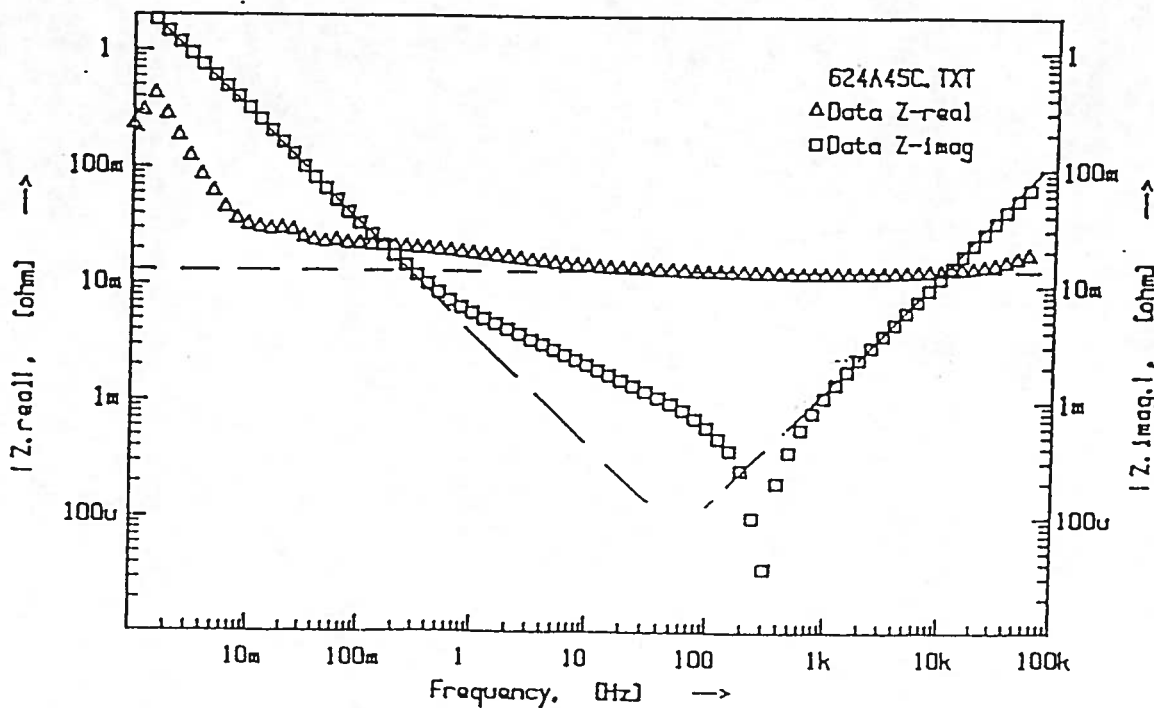**Figure 7.** Discharge characteristics of the doped-polymer capacitor.

Figure 8. AC impedance data for the Maxwell capacitor over a range of frequency.