Evaluation of Energy Storage Devices for Aerospace Applications

by

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Abstract

Electrical energy storage devices are highly desirable for aerospace applications, such as the Space Vehicle (SV) and many systems/parts for the Space Lunch System (SLS). For this special application, devices that can work over a broad temperature and pressure range are critical. Many electrical energy storage devices, such as dielectric capacitors, supercapacitors, and batteries, are commercially available. However, most of devices for civil applications are not designed for aerospace applications. For those designed devices for aerospace applications, the performance at different temperatures and pressures is unknown. Therefore, it is important to characterize the performance of these devices in aerospace environments.

In this research, two types of devices (supercapacitors and batteries) are studied. In Chapter 1 and Appendix, commercial devices designed for aerospace applications are surveyed and summarized. In Chapter 2, the test system is built for the characterization of supercapacitors and batteries. In Chapter 3, four selected different supercapacitors are tested under different charge/discharge rates at different temperatures. The parameters such as discharge capacity, discharge energy, and ESR of four supercapacitors are determined at -40^{o}C, -20^{o}C, 0^{o}C, 20^{o}C, 40^{o}C and 60^{o}C under varying discharge rates. The PBM-1500 supercapacitor shows much higher temperature stability than other supercapacitors.

In Chapter 4, four samples of batteries are characterized. These batteries show a

similar trend of performance at different temperatures and under different discharging rates. At the low temperature, the resistance in batteries is large and the electrochemistry reaction velocity is low, the battery discharge capacity is small, which results in a low output power and energy. The battery discharge energy and capacity change with the discharge rate. If the discharge current is small, the discharge capacity is large.

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CHAPTER 1

Introduction and Research Objectives

1.1. Energy storage

In recent years, energy storage has played an important role in conserving available resource energy and improving the utilization of energy from its natural form to human control [1, 2]. To evaluate the most relevant storage solution, it is necessary to consider the lifetime, reliability, storage capacity, cost, and environmental impact of the target. Both short term storage (only a few hours) and long term storage (a few months) are essential depending on applications [3-5]. There are some major characteristics of an electric energy storage system which can be used to compare the advantages and disadvantages among different energy storage systems [6-8]: (1) Specific energy (energy density) is the amount of energy that can be stored per unit mass or volume; (2) Specific power (power density) is the rate concerning the electric energy storage per unit mass or volume which can accept and release power; (3) Service lifetime is its expected lifetime, or the acceptable period of use in service. Some energy storage systems have only a finite lifetime which varies greatly among available technologies, and depends very much on how the energy units are used; (4) Loss is a part of the energy that is put into an electric storage system will never be recovered.

In this thesis, the performance of commercially available energy storage devices (i.e. batteries and capacitors from different manufactures) are tested and evaluated. The performances (parameters) at different temperatures and pressures as well as under different charge/discharge rates are determined. The goal of this research is to establish a solid database of these devices for different aerospace applications.

1.2. Electrical Energy storage

Electrical energy storage (EES) systems accept and return the stored energy as electric power, although they may store the energy in another form. **Figure 1-1** shows the different types of electrical energy storage systems. EES systems include compressed air energy storage, fuel cells, batteries, flow batteries, flywheel, capacitors and supercapacitors, superconducting magnetic energy storage, chemical storage, and thermal energy storage system [9-11].

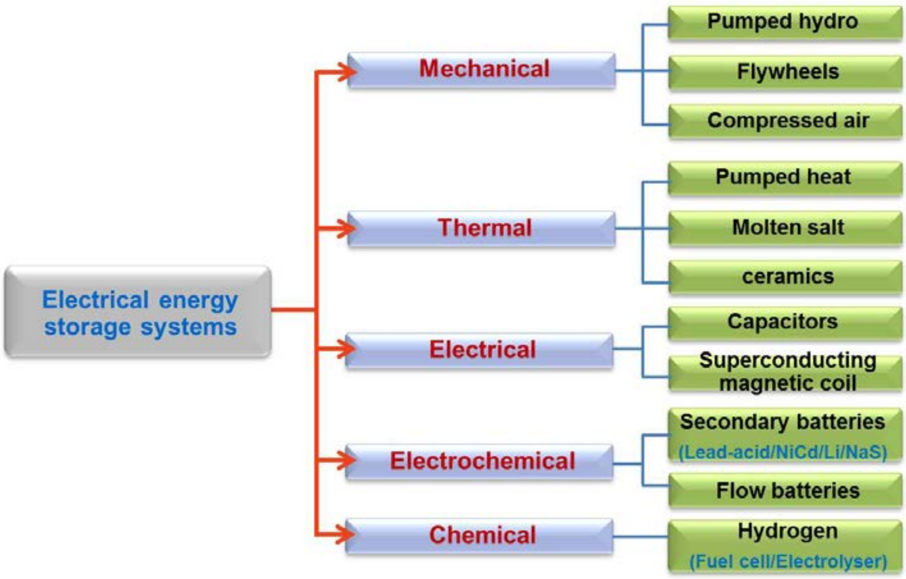

Figure 1-1. Different types of electrical energy storage systems.

There are four main roles for EES. First, EES can store electricity to reduce electricity costs by when its price is lower and using it when the price of electricity is higher. Second, EES can keep the system working if there are failures by any reason, such as natural disasters or maintenance. Third, EES can maintain the reliability of the power supply for long distance. Fourth, EES can be primary energy and power source for mobile devices and aerospace applications [12].

As a key technology for future development, EES technologies provide many primary functions of energy management, bridging power and power quality and reliability. A great deal of research effort has been given to the study of EES [13]. Capacitors (including dielectric capacitors and supercapacitors) and batteries are two types of primary devices for storing electrical energy, which can directly store the energy in electrical form. These EES are described in following sections.

1.2.1. Capacitor

A traditional capacitor is a non-conducting material (i.e. dielectric material) placed between two metal plates so that electrons cannot flow across, as shown in **Figure 1-2**. When a voltage is applied to the capacitor, positive and negative charges are forced onto the opposing electrode plates, creating an electric potential [14].

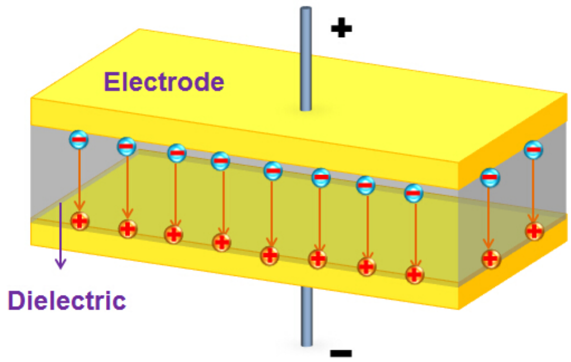

Figure 1-2. Schematic of a capacitor.

The defining characteristic of a capacitor is its ability to storage electric charge. This ability is called as capacitance C, and is defined by [14, 15]:

$$C = \frac{Q}{V} \tag{1-1}$$

where Q is the stored charge and V is the electric potential difference between the electrodes. When two parallel electrodes are separated by a distance *d* with dielectric materials, the capacitance can be expressed as:

$$C = \varepsilon_0 \varepsilon'_r \frac{A}{d} \tag{1-2}$$

where ε_0 is the permittivity in vacuum (8.8542×10^{-12} F/m), ε'_r is the relative permittivity (or dielectric constant) of the material, *A* is area, and *d* is thickness.

The electrical energy stored in a dielectric capacitor is characterized by the maximum energy density [16-19]. As described by Eq (1-3), the energy stored in a dielectric material under an electric field *E* can be expressed by the shadow area in **Figure 1-3** where different relationships between electric field *E* and electric displacement *D* are presented:

$$U_e = \int \vec{E} \cdot d\vec{D} \tag{1-3}$$

where U_e is energy storage density defined as the energy stored per unit volume (J/m^3).

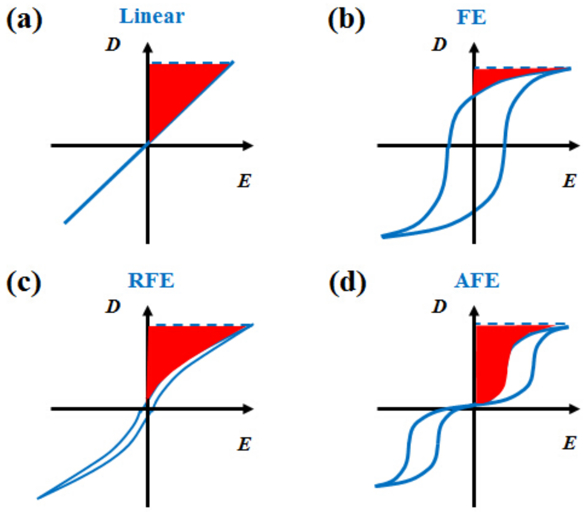

Figure 1-3. Relationship between electric displacement D vs. electric field E: (a) linear, (b) normal ferroelectric, (c) relaxor ferroelectric, and (d) antiferroelectric.

Based on **Figure 1-3** and Eq. (1-3), it can be concluded that a higher *D* and a higher *E* are very important to achieve a higher energy density. Additionally, the curvature of *D* vs. *E* is also very critical to the U_e. For linear dielectrics, it is well known that the energy density of a dielectric material is proportional to the product of permittivity and the square of the applied electric field, can be expressed as Eq.(1-4).

$$U_e = \frac{1}{2} \varepsilon'_r \varepsilon_0 \vec{E}^2 \tag{1-4}$$

The dielectric properties of a material can be characterized by three very important parameters: dielectric constant (ε'_r), dielectric loss (tanδ) and dielectric breakdown field (E_b) applied on that material. Higher dielectric constant and higher dielectric strength, are highly desirable for the dielectrics used in energy storage devices.

Table 1-1. Properties of linear dielectrics at room temperature

Materials	ε'_r	E_b (V/μm)	U_{max} (kJ/m^3)
Castor oil	3.7	14	3.2
Ethylene glycol	39.0	20	7.0
Kapton (Polyimide)	3.6	280	1,249
Kraft paper	6.0	80	170
Mylar	2.5	200	443
Polycarbonate	2.7	280	937
Polyethylene	2.2	180	315
Polypropylene	2.5	384	1,631
Polysulfone	3.1	320	1,405
Reconstituted mica	7.8	64	141
Polyethylene	3.2	400	2,266
Polyester	3.4	400	2,407
Quartz, fused	3.85	20	6.8
Tantalum oxide	11.-	4	0.78
Al_2O_3	9.0		
Ta_2O_5 (thin film)	40.0 (100)		

With regard to solid dielectrics, both polymers and inorganic compounds are widely used [16, 20]. In general, inorganic dielectrics can have a high dielectric constant (10^2 to 10^4), but a low dielectric strength (<10 V/μm), while polymers have a high dielectric strength (~10^2 V/μm), but a low dielectric constant (mostly <5). Currently, most electrical energy storage dielectric capacitors are made of polymers due to their very high dielectric strength. **Table 1-1** gives the dielectric constant, dielectric strength, and the energy density of some common dielectrics. The data shown in **Table 1-1** indicates that the energy density of dielectric capacitors is around 10^0 J/cc. Due to the packaging issues, the real energy density of a dielectric capacitor is usually smaller than the energy density of the dielectric itself. Commercial dielectric capacitors have a specific energy of 1 to 2 J/cc.

Table 1-2. Materials properties of ceramic-polymer composites for energy storage

Polymer Matrix	Ceramic	Size (nm)	Thickness (μm)	Composites					Ref
				Vol%	ε_r	$tan\delta$	U_e	E_b	
Polycarbonate	$BaTiO_3$	30-50	3.89	50%	20	<0.01	3.9	210	[23]
P(VDF-TrFE-CTFE)	$BaTiO_3$	50-70	25	30%	65	<0.07	7.0	150	[24]
P(VDF-HFP)	$BaTiO_3$	30-50	-	50%	32	<0.05	3.2	164	[28]
PVDF	$BaTiO_3$	100	10-30	20%	20	<0.03	3.54	200	[29]
Epoxy	$BaTiO_3$	30-50	70	5%	6.3	<0.01	4.6	406	[37]
P(VDF-TrFE-CTFE)	$BaTiO_3$			17.5%	70	0.09	10.48	300	[38]
PVDF	$BaTiO_3$	100	200	7%	14	<0.05	4	250	[39]
PVDF	$BaTiO_3$	100	10-30	2%	12	<0.05	6.28	340	[40]
P(VDF-TrFE) 50/50	PMN-PT	500	20	50%	250	<0.05	15	120	[41]
P(VDF-CTFE)94/6	BST	50	20	10%	45	<0.05	6.5	250	[42]
P(VDF-HFP)	kaolinite	1500	50-60		12	<0.05	19	750	[43]
PVB	oMMT		50-60	8.9%		-	0.3	130	[44]

There are generally two approaches to improving the energy storage density in dielectric capacitors. The first approach is about the development of polymers due to the facts that polymers have ultrahigh breakdown strength [19]. Polymers are flexible and easy to fabricate capacitors. For the development of new dielectric polymers for energy storage, one of the greatest achievements is the discovery of the record high energy storage density in the poly(vinylidene fluoride-chlorotrifluoroethylene) P(VDF-CTFE) copolymer, approximately 22 J/cc, which is roughly 10 times higher than the existing dielectric materials [21, 22]. The other is about the development of composites. Regarding composites, there are two types of materials can be used as fillers. The first type is to use inorganic ceramics as filler [23-29], which have relatively high dielectric constant. The dielectric constant increases gradually with increasing content of dielectric filler [30-36]. A great deal of research on the development of polymer-based composites including nanocomposites has been done and some great progress has been made in the area, as shown in **Table 1-2** [37-44]. The other type is to use conductive materials as filler in which the dielectric properties of composites show percolation behavior [45-47]. However, the energy density is limited by the high loss of the composites [48-50]. The energy density of the composite has also reached upwards of 5-10 J/cc.

Dielectric capacitors can be operated over a very broad temperature range and exhibit a very fast charge and discharge characteristics, both of which are favorable for many applications. Dielectric capacitor can work over a broad temperature range, which are favorable for aerospace applications. The highest operating temperature of a dielectric capacitor is determined by the electrical conductivity of the dielectric since the electrical conductivity increases with increasing temperature. A higher electrical conductivity results in a lower breakdown field and a shorter self-discharge time. It should be mentioned that the charge and discharge rate of a dielectric capacitor is not only determined by intrinsic factors (i.e. the dielectric/polarization relaxation process and conductivity of the materials), but also by extrinsic factors, such as the packaging of the capacitor. Since the dielectric relaxation time of the dielectric is usually in microsecond to nanosecond and electrical conductivity is usually very small, the real charge and discharge rate of a dielectric capacitor is mainly determined by its packaging since the packaging of a capacitor may introduce inductance. Due to its fast response, dielectric capacitors as electrical energy storage devices exhibit high peak current.

1.2.2. Supercapacitor

Supercapacitors were first produced in the United States during 1960s, and emerged into the commercial market for energy storage devices in the 1980s. This new type of energy storage device can have one order of magnitude on energy storage than conventional capacitor, and they have a high power density, a short charging time, long life and other advantages, which has aroused widespread interest around the globe in recent years. With a rapid development, supercapacitors not only raise the level of technological advances, but also expanding the scope of their application [51-53].

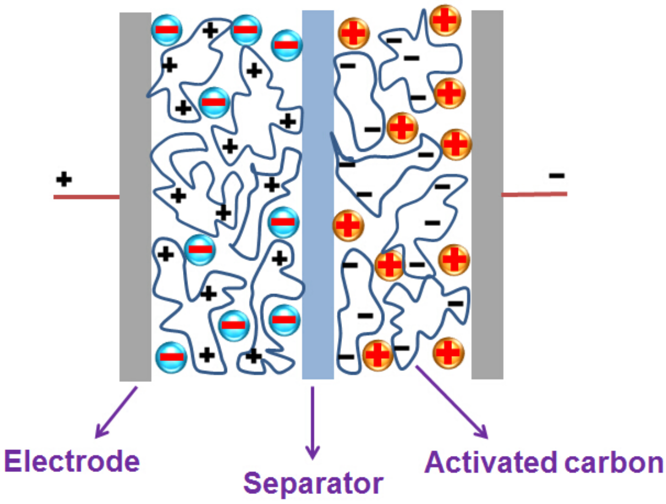

Figure 1-4. Schematic of supercapacitor.

There are two main types of supercapacitors. One is electrochemical double layer capacitor (EDLC). The capacitance proportional to the electrode surface area and activated carbon is generally used in electrolyte. The other type is pseudocapacitors, which use metal oxides or conducting polymers as electrode materials. This configuration, shown in **Figure 1-4**, is called an electrochemical double layer capacitor [51]. The potential from the applied current can exists between the surface of the electrode and the ions of electrolyte solution. Basically, a micro-capacitor, which can be assumed as a traditional capacitor, is created between an electrode and electrolyte interface. The separator between two electrodes is to prevent current flow between them. Charges accumulate on the surface of the pores within the electrode and attract the oppositely charged ions within the solution, creating an interface of charge separation in each electrode.

When the electrode contacts with the electrolyte solution, the electrode/solution interface of charged particles will be transferred between two phases, or to both sides of the charging circuit through the external interface. Therefore, there are two phases of the remaining charge. These residual charges concentrated on both sides of the interface, the electric double layer was formed. The size of the electrolyte ions is very important, which can effect on the separation distance of supercapacitor charge. The large capacitance of an electrochemical double layer capacitor is determined by large surface area, and a very small distance between the charges. The capacitance of a supercapacitor can be from one to several thousand Farads [51-55].

1.2.3. Characteristics and parameters of supercapacitors

The characteristics of supercapacitors can be described based on the main points [52-55]:

(1) Specific power: The resistance of supercapacitors is very small. The electrode/solution interface and electrode materials of supercapacitors are able to achieve rapid charge storage and release, which results the output specific power can be up to several kW/ kg.

(2) Charging and discharging cycle life: There is no electrochemical reaction during the charging and discharging process of supercapacitor. The cycle life can be up to million times.

(3) Charging time: Supercapacitors can be charged from little tens of seconds to up to tens of minutes.

(4) Storage life: The material used in the corresponding electrolyte is stable that is why the life of supercapacitor can be considered almost infinite. The little leakage currents is due to the internal capacitor ion or proton migration movements, not from chemical or electrochemical reaction.

(5) Reliability: The reliability of supercapacitor is very high.

The schematic of charge and discharge process of supercapacitor is shown in Figure **1-6**. The following parameters are always used to characterize supercapacitors [56-61]:

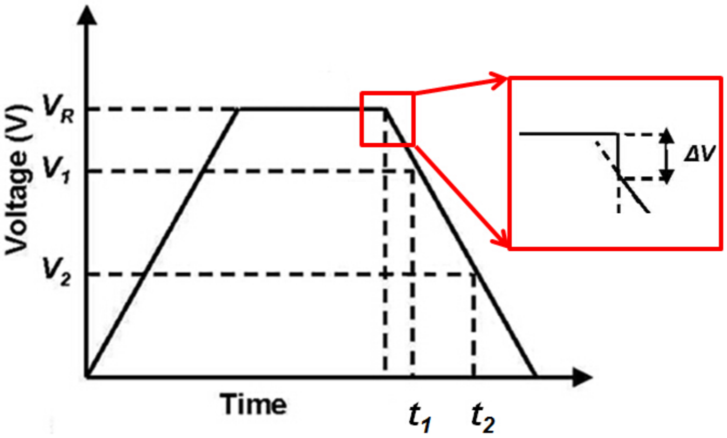

Figure 1-5. Schematic of charge and discharge process of supercapacitor..

(1) Capacitance:

Capacitance values for commercial capacitors are specified as "rated capacitance". This is the value for which the capacitor has been designed. The voltage has to be charged under a constant current to the rated voltage, the capacitor has to be charged under constant voltage until the current value decreases close to zero. Then the capacitor has to be discharged with a constant discharge current. From t_1 to t_2, the voltage drops from 80% (V_1) to 40% (V_2) of the rated voltage. The capacitance value is calculated as:

$$C = \frac{I\Delta t}{\Delta V} = \frac{I(t_2 - t_1)}{V_1 - V_2} \qquad (1\text{-}4)$$

where C is capacitance in F, I is discharge current in A, V is rated voltage in V, V_1 is 80% of rated voltage, V_2 is 40% of rated voltage, as shown in **Figure 1-5**.

(2) Rated voltage

The rated voltage V_R is the maximum value of DC voltage which the supercapacitor can be continuously charged.

(3) ESR$_{DC}$:

The internal resistance can be represented as an Equivalent Series Resistance (ESR) or as Equivalent Distributed Resistance (EDR). For the ideal case, capacitors do not have any loss of energy, but in reality, the capacitor dielectric has a loss. The loss manifest themselves like a resistor in series with the capacitor together, so it is called "equivalent series resistance". As shown in the insert figure in **Figure 1-5**, sample is charged at constant current to rated voltage, then charged at rated voltage before the current close to zero. There is an instantaneous voltage drop at the beginning of discharge step.

$$\mathrm{R}_d = \frac{\Delta V}{I} \tag{1-5}$$

where R_d is the ESR_{DC} in Ohms, ΔV is the voltage drop in 10 ms, I is discharge current.

(3) Maximum stored energy

$$E_{max} = \frac{\frac{1}{2} C {V_R}^2}{3600}\ (\mathrm{Wh}) \tag{1-6}$$

where C is the nominal capacitance (unit: F), V_R is the provided rated voltage (unit: V).

(4) Maximum specific energy

Maximum specific energy can be calculated by

$$E_{mass} = \frac{E_{max}}{m}\ (Wh/kg) \tag{1-7}$$

$$E_{volume} = \frac{E_{max}}{V}\ (Wh/l) \tag{1-8}$$

where m is the mass (unit: kg) provided by the company, V is the volume (unit: l) provided or calculated with the dimension.

(5) Maximum specific power

Maximum specific power can be calculated by

$$P_{mass} = \frac{{V_r}^2}{4R_d m} \ (W/kg) \tag{1-9}$$

$$P_{volume} = \frac{{V_r}^2}{4R_d V} (W/l) \tag{1-10}$$

(6) Short circuit current

Short circuit current can be calculated by

$$\mathrm{I}_{sc} = \frac{V_r}{R_d} \tag{1-11}$$

1.2.4. Battery

Battery is an energy storage device consisting of one or more electrochemical cells which can store chemical or physical energy directly into electrical energy. Battery can be divided into two major categories: chemical battery and physical battery. Chemical battery includes primary batteries and secondary battery categories, the former is one-time use only; latter can be repeatedly charged and discharged, such as lead-acid batteries, nickel cadmium batteries, nickel-hydrogen batteries, as shown in **Figure 1-6**.

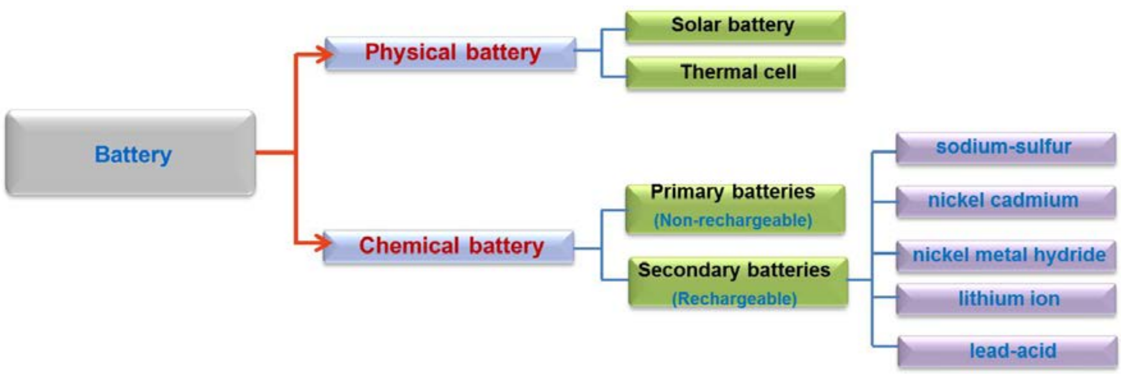

Figure 1-6. Different types of battery.

Lead-acid batteries use lead and lead oxide as electrode materials and sulfuric acid solution as electrolyte. As lead-acid batteries have excellent performance, stable quality, high energy, large-capacity, lower prices and other characteristics, they have played an important role in military and aerospace applications [62-70].

When a lead-acid battery is charged, electricity is added to the battery, causing the water and lead sulfate to be combined to produce electrolyte and the active plate, as shown in **Figure 1-7**. The efficiency of this charge-discharge cycle depends on the quality of the battery and the efficiency of the charger system. When the reaction takes place, both electrodes are coated with solid lead and the sulfuric acid is used up [62-64].

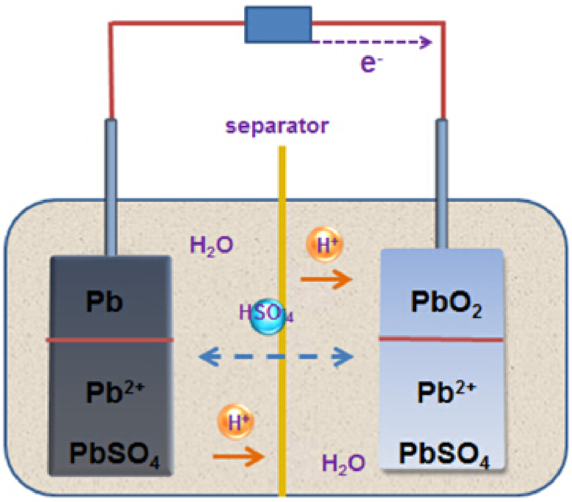

Figure 1-7. Schematic of battery with electrochemical reaction.

Table 1-3 Chemical reaction in discharge and charge cycles for lead-acid batteries

Discharge		Charge	
Positive Electrode Anode (+)	Negative Electrode Cathode (-)	Positive Electrode Anode (+)	Negative Electrode Cathode (-)
$PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$	$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$	$PbSO_4 + 2H_2O \rightarrow PbO_2 + HSO_4^- + 3H^+ + 2e^-$	$PbSO_4 + H^+ + 2e^- \rightarrow Pb + HSO_4^-$
Overall Cell Reaction		Overall Cell Reaction	

$Pb + PbO_2 + 2H^+ + 2HSO_4^- \rightarrow 2PbSO_4 + 2H_2O$	$2PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 2H^+ + 2HSO_4$-

The chemical reactions in the charge and discharge cycles for lead-acid batteries are shown in **Table 1-3**. In the battery discharging process, the active material in the positive electrode (PbO_2) and the active material in the negative electrode (Pb) both have reaction with sulfuric acid electrolyte. The lead sulfate ($PbSO_4$) is produced. These reactions are called "double-sulfation reaction" [62-65]. When the discharge stage finished, the active material in electrode is converted to lead sulfate. In the battery charging process, lead sulfate can be turned to lead dioxide and metallic lead under external charging current. Battery is fully charged again in the state. This is an electrochemical reaction which can be reversed, by this way the lead-acid battery have function to storage and release energy [62]. At the end of the discharge stage, the sulfuric acid concentration decreases after slow diffusion of hydrogen ions, causing the battery voltage drops quickly [67].

1.2.5. Characteristics and parameters of battery

Some information about batteries is shown in **Figure 1-8**.

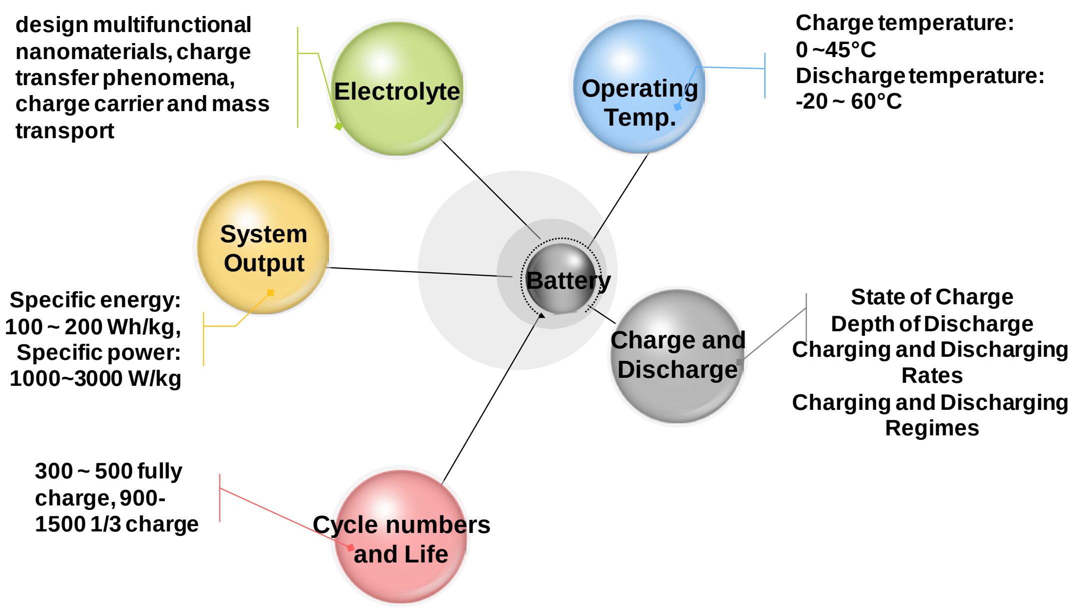

Figure 1-8. Factors for evaluating a battery

This section describes some of the variables used to describe the present condition and technical specifications of a battery [66-68].

(1) State of Charge (SOC)

SOC is the ratio of current capacity and maximum capacity. It is calculated by integration current to express the change in battery capacity.

(2) Depth of Discharge (DOD)

DOD is the inverse of SOC, which is the percentage of battery capacity that has been discharged.

(3) Terminal Voltage (V)

Terminal voltage is the voltage between the battery terminals and the load applied. Terminal voltage can be different when SOC and discharge/charge current are different.

(4) Internal Resistance

Internal resistance of the battery depends on the temperature, and state of charge. Effective internal resistance of the fully charged battery is lower than that of discharged battery. When the battery has to supply a large current in a short time, having the low effective resistance is very important. Low temperature and long-term storage will increase the battery's internal resistance.

(5) Nominal Voltage (V)

The nominal voltage is the reference voltage of the battery.

(6) Cycle Life

The cycle life is the number of discharge-charge cycles that the battery can withstand before losing its specific performance.

(7) Charge Voltage

The charge voltage is the voltage that the battery is charged to full capacity. The charging process includes two steps. One is charge under a constant current when the voltage reaches the rated voltage. The other is charge under a constant voltage, until charge current decrease to a very small value.

(8) Float Voltage

After charged to 100% SOC, the battery has self-discharge. The float voltage is the voltage to maintain capacity by compensating for self-discharge of the battery.

1.2.6. Summary

In general, as illustrated in **Figure 1-9**, a battery has a higher specific energy, but exhibits a lower specific power. Conversely, a capacitor, especially a dielectric capacitor, exhibits a higher output specific power, but has a smaller specific energy. Therefore, it has been a hot research topic for the development of so-called supercapacitors which is an electrochemical energy storage device. Besides specific energy and specific power, the efficiency of an energy storage device is also important. In general, the dielectric capacitor has the highest efficiency, while the battery has the lowest efficiency. Additionally, the reliability or stability of an electrical energy storage device is strongly dependent on the temperature, pressure, and possible mechanical vibration. The dielectric capacitors have a much broader operating temperature range, a much longer life time, and a much bigger cycle number than the batteries and supercapacitors. Regarding the output voltage, the dielectric capacitors have the highest output voltage, up to 10^2~10^4 volts, while the batteries have the lowest output voltage, about 10^0 volts. That is, each of these three types of electrical energy storage devices has some advantages and disadvantages. Therefore, the selection of an electrical energy storage device for a practical application should be based on the environment and power/energy needs of the application.

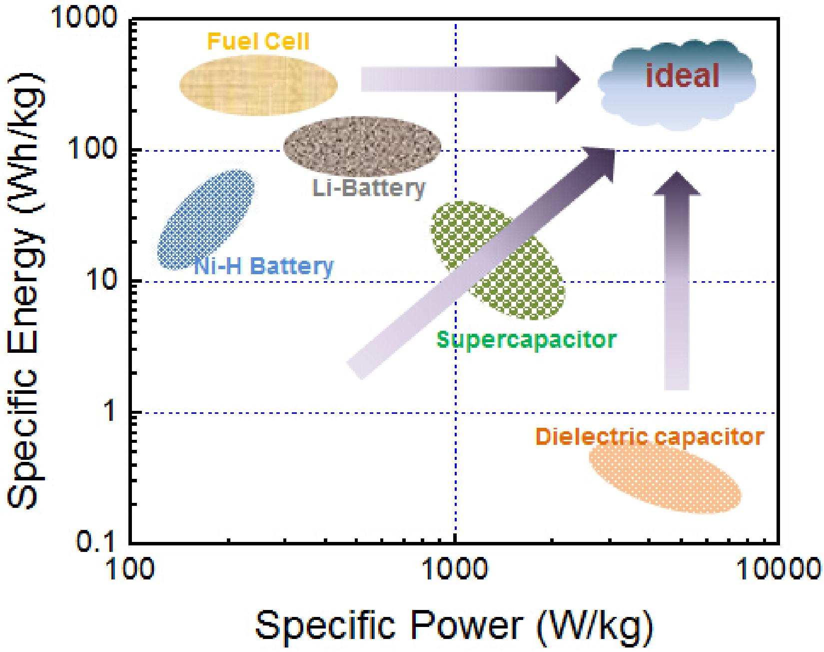

Figure 1-9. Specific energy versus specific power for three types of electrical energy storage devices: battery, supercapacitor, and dielectric capacitor.

1.3. Aerospace requirement

Electrical energy storage devices are highly desirable for aerospace applications. Devices that can work over a broad temperature and pressure range are critical. It is important to characterize the performance of these devices for aerospace applications at different temperatures and pressures.

For NASA's future mission to deep space, electrical energy storage devices with very different specifications are needed. For example, for planetary probes and Mars surface missions, these devices have to be operated at low temperature, as low as -100°C, while inner planetary missions require these devices to be operated at high temperatures, approaching more than 475°C. Most of these missions have a time span of more than 15 years, and the devices have to face a high radiation environment. Based on the NASA's requirement, the energy storage devices should be characterized in following specific conditions: Avionics system ± 28 Volts with current up to 27 Amps; Flight termination system ± 28 Volts with current of 8 to 12 Amps;

electromechanical actuation ± 270 Volts with current of 100 to 150 Amps. For 28 V systems, the capacitors should be designed for 50 V. To provide a factor of safety, the temperature range for military applications is -40 ^{o}C to 85 ^{o}C, while it is -55 to 125 ^{o}C for NASA's applications. Additionally, the performance of devices in vacuum is needed.

1.4. Limitation of specification of commercial devices

As we know, companies can provide some basic information and parameters for their products. The brief summaries of these commercial products are given in the Appendix 1 and 2. However, this is not enough for providing a comprehensive dynamic database that focus on aerospace applications. For example, parameters of supercapacitor or battery are listed in **Table 1-4**. First, some basic parameters, such as materials, mass, volume, operating temperature and rated voltage, are provided by company. Second, parameters related electrical test are partially provided, such as ESR, leakage current, capacitance under room temperature. Third, some parameters have to be calculated by formula, as discussed in section 1.2.3. Four, some parameters, such as discharge capacity and discharge energy at different temperatures and pressure under different discharge rates, cannot be provided by companies.

Table 1-4 Parameters of commercial supercapacitors

Parameters	Providing condition
Product series number	All provided
Company name	All provided
Materials	Partially provided
Nominal Capacitance	All provided
Tolerance capacitance	All provided
Rated voltage	All provided
Maximum continuous current	Partially provided
Maximum peak current	Partially provided
Leakage current	Partially provided
ESR, DC	Partially provided
ESR, AC	Partially provided
Mass specific energy	Partially provided
Mass	Most provided
Calculated mass specific energy	Calculated
Volume specific energy	Partially provided
Volume	Partially provided
Calculated volume specific energy	Calculated
Operating temperature	Most provided
Storage temperature	Partially provided
Lifetime	Partially provided
Cycle life	Partially provided
Dimensions	Most provided
Price	Partially provided

1.5. Research Objectives

In this research, two types of devices – supercapacitors and batteries – are studied, using devices selected and purchased from manufacturers in the United States. In Chapter 2, the test system is built for supercapacitor and battery. In Chapter 3 and 4, the test results of four selected different supercapacitors and four lead-acid batteries under different charge/discharge rates at different temperatures are discussed. For supercapacitors, the parameters such as discharge capacity, discharge energy, and ESR of four supercapacitors are determined in the range of -40^{o}C to 60^{o}C under varying current rates. The PBM-1500 supercapacitor show much higher temperature stability than other supercapacitors. For batteries, the four samples have similar performance within the temperature range. These results cannot be obtained directly from the manufacturers. Likewise, the results of this study will provide a solid and dynamic database of these devices for different aerospace applications.

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CHAPTER 2

Test System

2.1. Introduction

For the commercial products, although the manufactures provide the specifications of their products, many important parameters are missed as discussed in Chapter 1. Therefore, systemic evaluation of commercial products, which are designed for aerospace applications, is carried out. A system/set-up for characterizing electrical energy storage device was designed and built in our laboratory as shown in **Figure 2-1**.

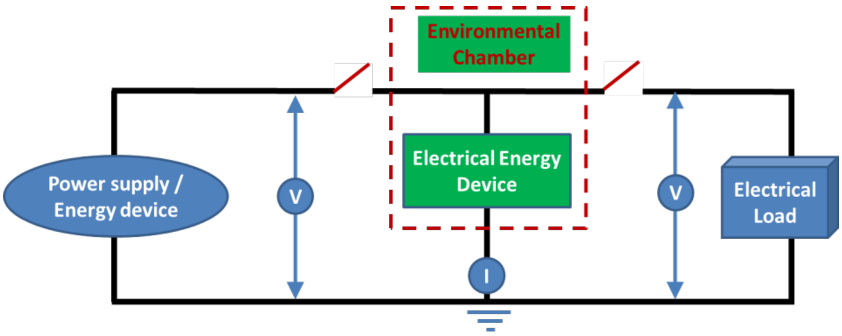

Figure 2-1. The schematic of the setup for the characterization of the charge and discharge behavior of electrical energy storage devices.

The electrical energy storage device to be tested is placed in a chamber where temperature is controlled. The system has the capability to characterize the devices at different temperatures from -73^{o}C to 180^{o}C. The system can charge/discharge the device under different voltages and currents.

2.2. System for devices test

2.2.1. Arbin test equipment for supercapacitor and battery

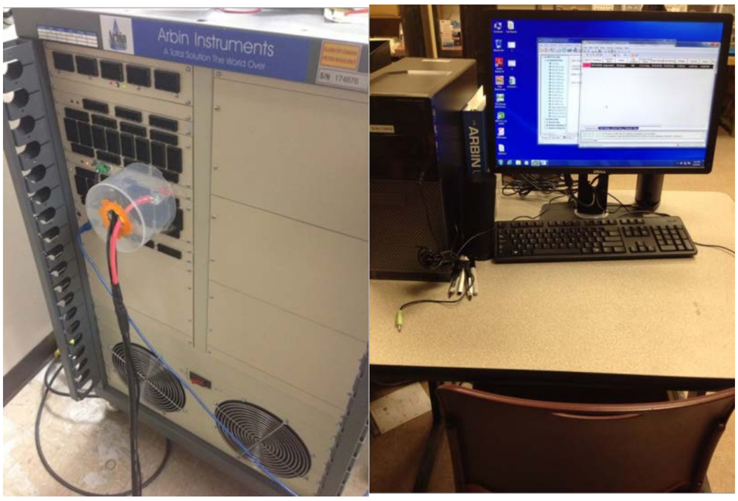

Figure 2-2. Arbin battery test equipment

Table 2-1 Information for Arbin battery test equipment

Devices	Battery Test Equipment
Company	Arbin
Voltage	2V to 40V
Voltage Accuracy (0.05% FSR)	±40mV
Current	High: 50A ±50mA Medium: 50A ±5mA Low: 500mA ±0.5mA
Power Source	3000VA-50/60Hz
Min.V at Max. Current	2V@50A
Current Rise Time	~200µS
Resolution	16bit
Room Operating Temp.	10 ~ 35^{o}C

Arbin Battery Test Equipment was selected as our testing system, as shown in **Figure 2-2**. The information and parameter are given in **Table 2-1**. It is a potentiostat and galvanostat which provides both voltage and current control for all charging and discharging requirements.

2.2.2. Environmental chamber

Figure 2-3. Environmental chambers ECT-3 from ESPEC Company.

Environmental chambers ECT-3 from ESPEC Company was selected for this study, as shown in **Figure 2-3** and **Table 2-2**.

Table 2-2 Information for two temperature chambers

Name	Company	Model	Temperature range	Temperature constant	Resolution	Power source
Chamber	ESPEC	ECT-3	-73 ^{o}C to 180^{o}C	±0.1 ^{o}C	0.1 ^{o}C	115 VAC±10%-50/60Hz

CHAPTER 3

Evaluation and Performance of Supercapacitor

3.1. Introduction

Capacitance, ESR and specific energy are the three major parameters used to evaluate the performance of supercapacitor as an energy storage device. In this chapter, before starting measurements, a detailed test plan is developed. Four selected supercapacitors are studied under different discharge current rates and at different temperatures. The performances of supercapacitors under different conditions are analysed.

3.2. Test sample, procedure, and parameters of supercapacitor

3.2.1. Samples

The selected four samples of supercapacitors were purchased from different companies. The information about these samples is listed in **Table 3-1**.

Table 3-1 Information for selected four samples of supercapacitors

No	Product series	Company	Nominal Capacitance (F)	Tolerance capacitance	Rated voltage (V)	Maximum peak current (A)	Leakage current (mA)	Resistance, mΩ (ESR, DC)	Resistance, mΩ	Volume (l)	Calculated volume specific energy (Wh/l)	Operating temp	Lifetime at 25 ℃ (years)	Dimensions L×W×T (mm)
A	PBLL-2.0/5.4	Tecate	2.0	-10%~20%	5.4	2.5	0.19	565	365	0.0059	1.36	-40°C to +65°C	10	23.5×22×11.5
B	PBL-2.5/5.4		2.5			3.4	0.19	385	245	0.0059	1.70			23.5×22×11.5
C	RS055105	Evans	1.0	± 20%	5.5		0.025	2000		0.0095	0.44	-55°C to 85 °C		D=27.94, H=15.49
D	PBM-1500/5.4	Tecate/Maxwell	5.4	+20%/ -0%	5.4		5.2	700		1.544	4.75 (Wh/kg)	-40° to +65°C	10	127×64×190

3.2.2. Test procedure

The test procedure includes constant current charging, constant voltage charging, and constant current discharging as discussed in Section 1.2.3 and **Figure 1-5**. The test procedure using sample A as the example is shown in **Figure 3-1** and **Table 3-2**.

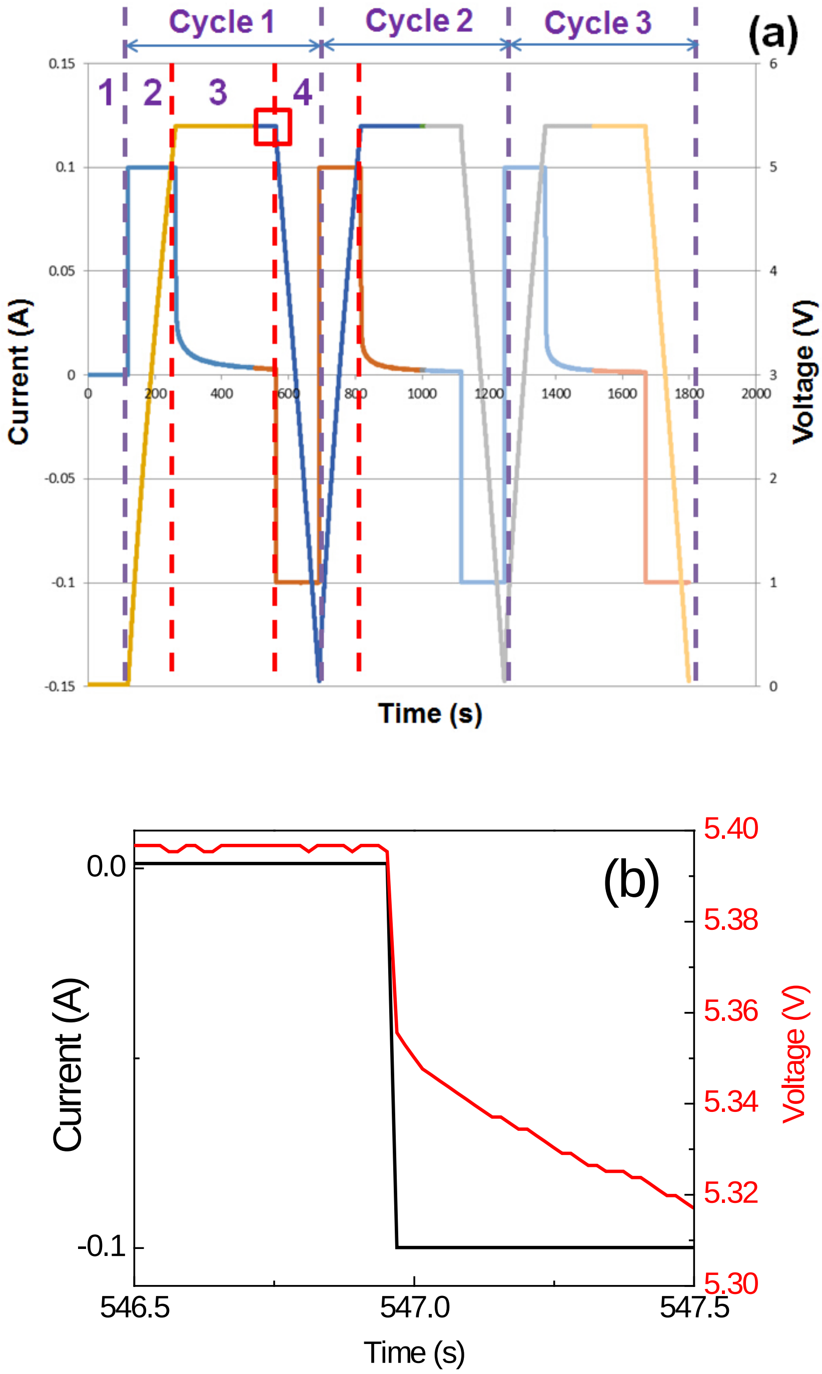

Figure 3-1. Schematic of charge and discharge process using sample A as example: (a) three cycles, (b) voltage drop in the first cycle.

In **Figure 3-1** (a), there are four steps for test procedure of supercapacitor. Before test, make sure the voltage of sample is smaller than 0.05 V. The sample can be in a short circuit at least one hour before test, this is step 1. Then sample is charged under a constant current rate at different temperatures, this is step 2. When the voltage reaches the rated voltage, the device is charged under a constant voltage (i.e. rated voltage) until the current value is very close to zero, this is step 3. Then the device is discharged under constant current, this is step 4. After sample discharged, the first cycle is finished. The test procedure can repeat for the second test. For the discharge step, it is important to make sure the voltage is smaller than 0.1V before stop the discharge step. As shown in **Figure 3-1** (b), there is a voltage drop when discharging is started.

Table 3-2 Test procedure of supercapacitor

Step	Task	rate	time
1	rest	start: voltage less than 0.05V	5 min
2	charge	different specified current	stop at rate voltage
3	hold	constant rated voltage	5 min
4	discharge	different specified current	stop at voltage <0.05V

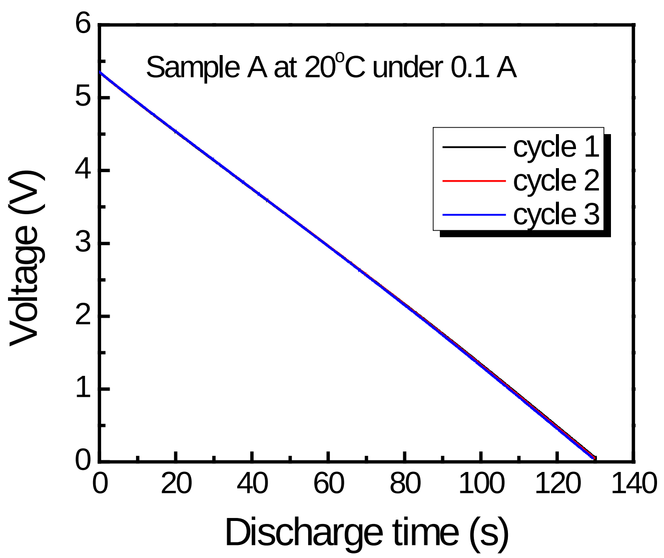

Figure 3-2. Voltage vs. discharge time of sample A in first three cycles.

In this study, at least 3 cycles are tested and used to make sure the results reliable.

For example, **Figure 3-2** shows the three-cycle test of supercapacitor sample A at room temperature under a discharge current of 0.1 A. The curves are very close to each other and the data is 130.16s, 129.79s, 129.87s at cycle 1, cycle 2, and cycle 3 respectively. The deviation of these data is 0.3%.

In this project, all the samples were tested at the temperatures ranging from -40°C to 60°C, which is smaller than the NASA's requirement. The reason for selected the temperature range is: by manufacture, the device is designed for -40°C to 60°C. Each device was tested firstly using a charge/discharge current for three cycles, then the device was rested for three hours. During the rest stage, two electrodes are shorted. After that, the device is tested under different charge/discharge current. The same method used in the other supercapacitor and battery samples.

To test the device at different temperatures, the temperature was controlled by the environment chamber. The device was kept in the designed temperature for three hours before the test started.

3.3. Test results

3.3.1. Sample A: PBLL-2.0/5.4

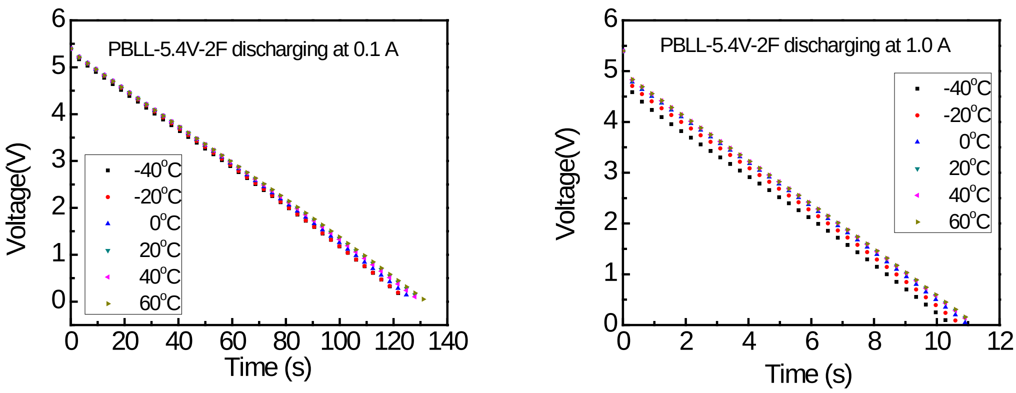

Figure 3-3. Voltage vs. time of PBLL-2.0/5.4 supercapacitor under different discharge currents of 0.1A and 1.0A at different temperatures.

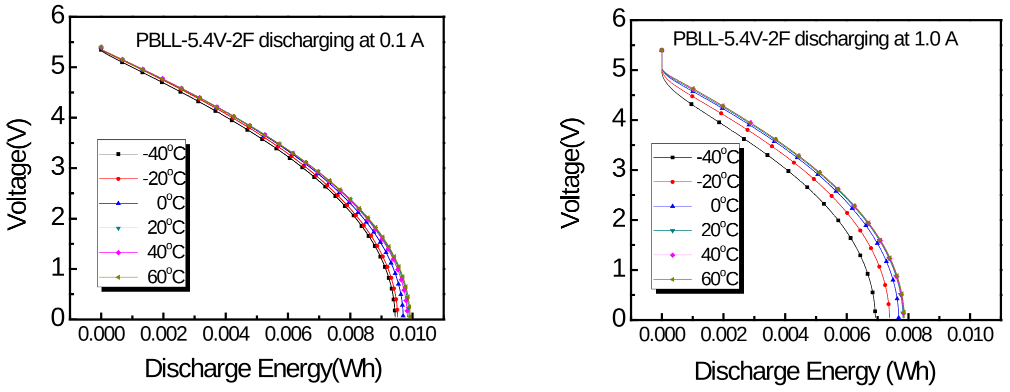

Figure 3-4. Voltage vs. Discharge energy of PBLL-2.0/5.4 supercapacitor under different discharge currents of 0.1A and 1.0A at different temperatures.

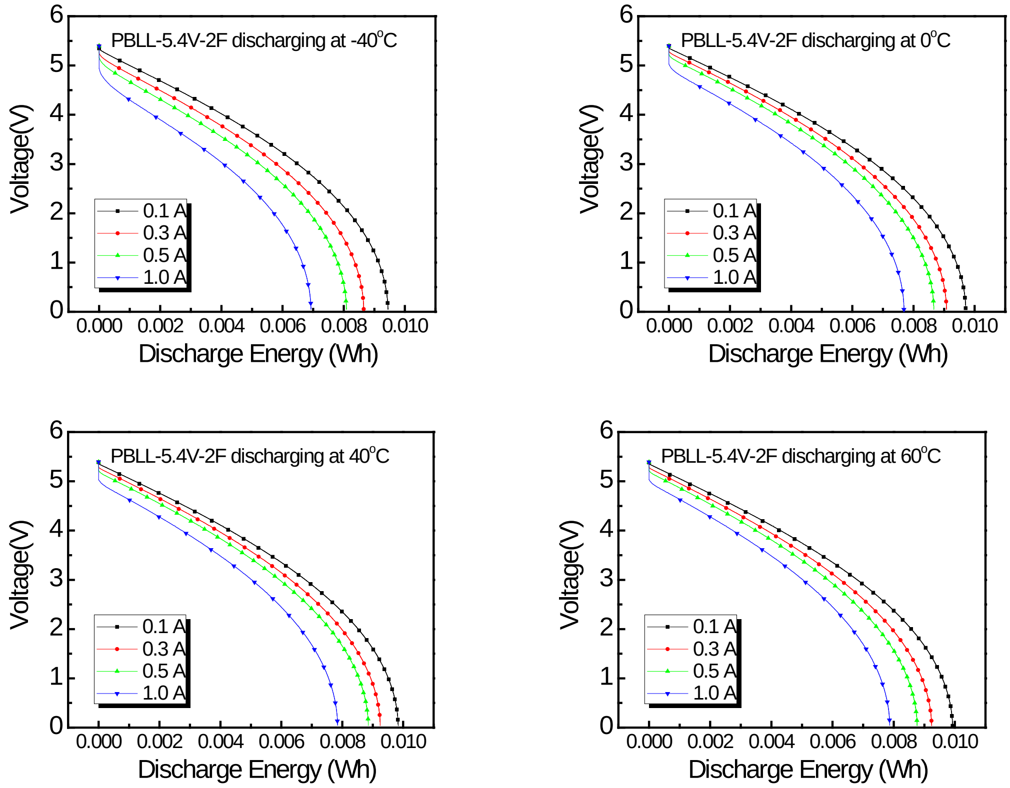

Figure 3-5. Voltage vs. Discharge energy of PBLL-2.0/5.4 supercapacitor at -40°C, 0°C, 40°C and 60°C under different discharge currents.

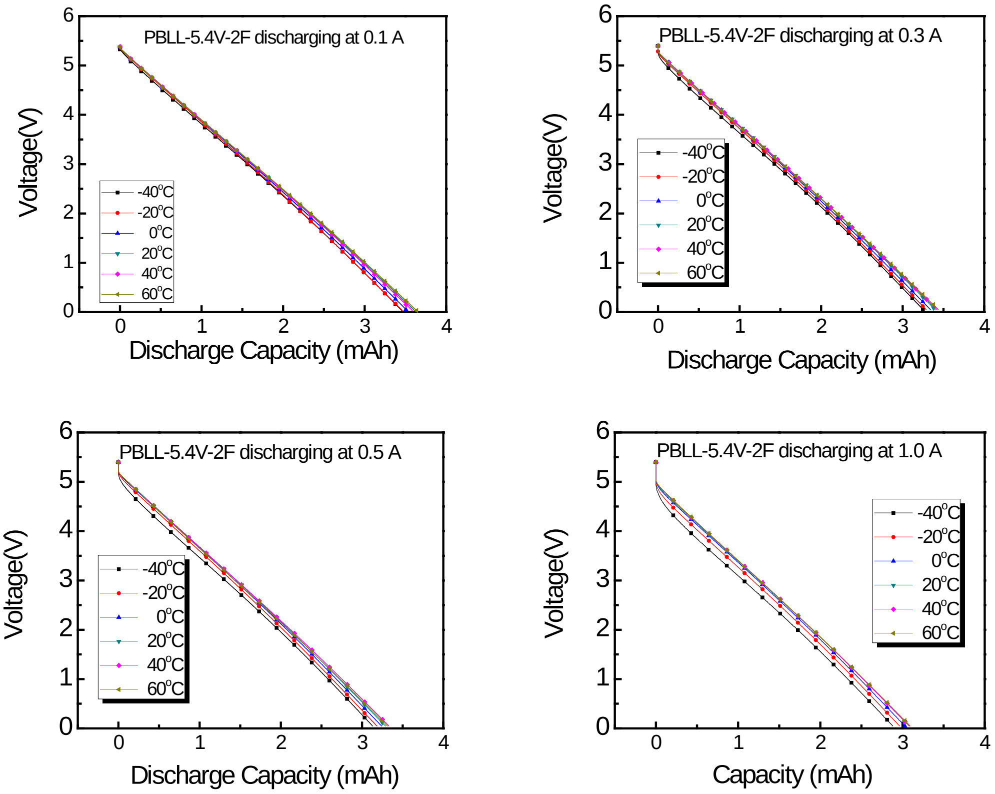

Figure 3-6. Voltage vs. Discharge capacity of PBLL-2.0/5.4 supercapacitor at -40°C, -20°C, 0°C, 20°C, 40°C and 60°C under different discharge currents.

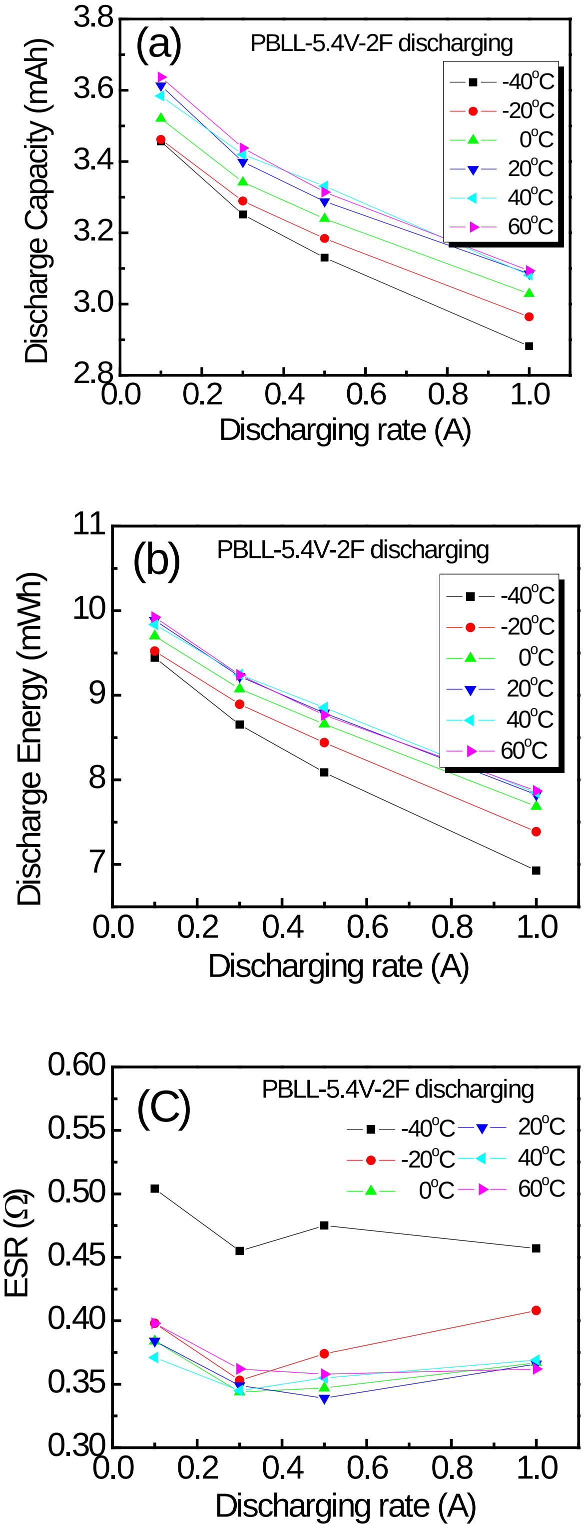

Figure 3-7. Discharge capacity (a) and discharge energy (b) and ESR (c) of PBLL-2.0/5.4 supercapacitor at -40°C, -20°C, 0°C, 20°C, 40°C and 60°C under different discharge currents.

Table 3-3 Sample A-constant current discharge data from 5.4 V to 0 V under different discharge current rates and at different temperatures

Current	Temp.	Time	Capacity	Energy	Specific energy	Capacitance	ESR_{DC}	I_{sc}	specific power
(A)	^{o}C	(Sec)	(mAh)	(mWh)	(Wh/l)	(F)	(Ω)	A	W/l
0.1	-40	124.5	3.456	9.444	1.60068	2.30415	0.504	10.71	2451.57
	-20	119	3.462	9.523	1.61407	2.42954	0.398	13.56	3104.50
	0	126.9	3.521	9.702	1.64441	2.47158	0.384	14.06	3217.69
	20	130.2	3.613	9.886	1.67559	2.5355	0.384	14.06	3217.69
	40	129.1	3.584	9.837	1.66729	2.52589	0.371	14.55	3330.43
	60	131.1	3.637	9.924	1.68203	2.57003	0.398	13.56	3104.50
0.3	-40	39.0	3.251	8.653	1.46661	2.41955	0.455	11.86	2715.58
	-20	36.4	3.289	8.893	1.50729	2.36035	0.353	15.29	3500.26
	0	40.1	3.342	9.074	1.53797	2.38228	0.344	15.69	3591.84
	20	37.7	3.399	9.222	1.56305	2.42326	0.349	15.47	3540.38
	40	41.1	3.420	9.247	1.56729	2.44101	0.345	15.65	3581.42
	60	41.3	3.438	9.240	1.5661	2.45761	0.362	14.91	3413.24
0.5	-40	22.5	3.130	8.088	1.37085	2.41721	0.475	11.36	2601.24
	-20	22.9	3.184	8.440	1.43051	2.33885	0.374	14.43	3303.72
	0	21.1	3.240	8.661	1.46797	2.35738	0.347	15.56	3560.78
	20	23.7	3.288	8.792	1.49017	2.38311	0.339	15.92	3644.81
	40	21.7	3.331	8.855	1.50085	2.41721	0.355	15.21	3480.54
	60	23.9	3.314	8.765	1.48559	2.399	0.358	15.08	3451.37
1.0	-40	10.4	2.882	6.928	1.17424	2.39975	0.457	11.81	2703.70
	-20	10.7	2.964	7.388	1.2522	2.35139	0.408	13.23	3028.41
	0	10.9	3.029	7.687	1.30288	2.3359	0.367	14.71	3366.73
	20	11.1	3.085	7.825	1.32627	2.35344	0.366	14.75	3375.93
	40	9.6	3.081	7.848	1.33017	2.33705	0.369	14.63	3348.49
	60	11.1	3.094	7.871	1.33407	2.34099	0.362	14.91	3413.24

Table 3-3 shows test results of sample A under different charge/discharge rates at different temperatures. Four current values were chosen as constant current, from 0.1 A to 1.0 A. **Figure 3-3** shows the voltage vs. time of PBLL-2.0/5.4 supercapacitor under different discharge currents of 0.1 A, 0.3 A, 0.5 A, 1.0 A at different

temperatures. It is almost a linear relationship between voltage and discharging time, which can be used to calculate the capacitance.

Figure 3-4 and **3-5** show the voltage vs. discharge energy of PBLL-2.0/5.4 supercapacitor under different discharge currents at different temperatures. From -40^{o}C to 60^{o}C, temperature has small effect on discharging performance of this sample.

Figure 3-6 shows working voltage of supercapacitors versus discharge capacity curves at each current. These curves show linear relationships which are different from batteries. In lead-acid batteries test, discussed in next chapter, it shows a flat voltage profile curve with sharp changes in voltage when the battery is in the fully charged or discharged condition. The reason is these two types of energy storage device have the different mechanisms. Supercapacitors do not have Faradic reaction which leads to fast kinetics and response in charge and discharge.

Figure 3-7 (a) shows capacitance versus current. The capacitance decreases as the current increases. The possible reason is that the temperature increases as the current increases due to self-heating, which could result in the dielectric constant of double layer decreases. **Figure 3-7** (b) shows discharge energy versus current. Energy indicates device's power capability. Energy decreases much when current increases. **Figure 3-7** (c) shows ESR versus discharge current. Except at very low discharge current, ESR of supercapacitors is near 360-400 mΩ, which is smaller than the value given by the manufacturer (565 mΩ). In this test, as introduced in chapter 1, the ESR is calculated during an "instantaneous" period (<0.02s) at the beginning of a constant-discharge step. According to different testers, the time can be different, which means the choice of this time interval may affect calculation results slightly. Due to the uncertainty of voltage drop, the value of ESR will be different. Another possible reason of ESR decreasing at higher current is related to internal mechanism. The higher current during charge and discharge process may raise the temperature of supercapacitors. The increasing temperature may cause the viscosity of solvent decrease and the solubility of conducting salt decrease. Both effects can increase the conductivity of the electrolyte.

3.3.2. Sample B PBLL-2.5/5.4

Figure 3-8 shows the voltage vs. time of PBLL-2.0/5.4 supercapacitor at different discharge currents of 0.1A, 0.3A, 0.5A, 1.0A at different temperatures. It is almost a linear relationship between voltage and discharging time, which can be used to calculate the capacitance.

Figure 3-9 shows discharge capacity, discharge energy, and ESR of PBLL-2.5/5.4 supercapacitor at -40^{o}C, -20^{o}C, 0^{o}C, 20^{o}C, 40^{o}C and 60^{o}C under different discharge currents. The trends are similar to sample A. Because of the ESR of sample A is larger than sample B, the discharge capacity and discharge energy of sample A are smaller than that of sample B. Another difference is the values of discharge energy and ESR at -20^{o}C are very close to the values of that at 0^{o}C, 20^{o}C, 40^{o}C and 60^{o}C.

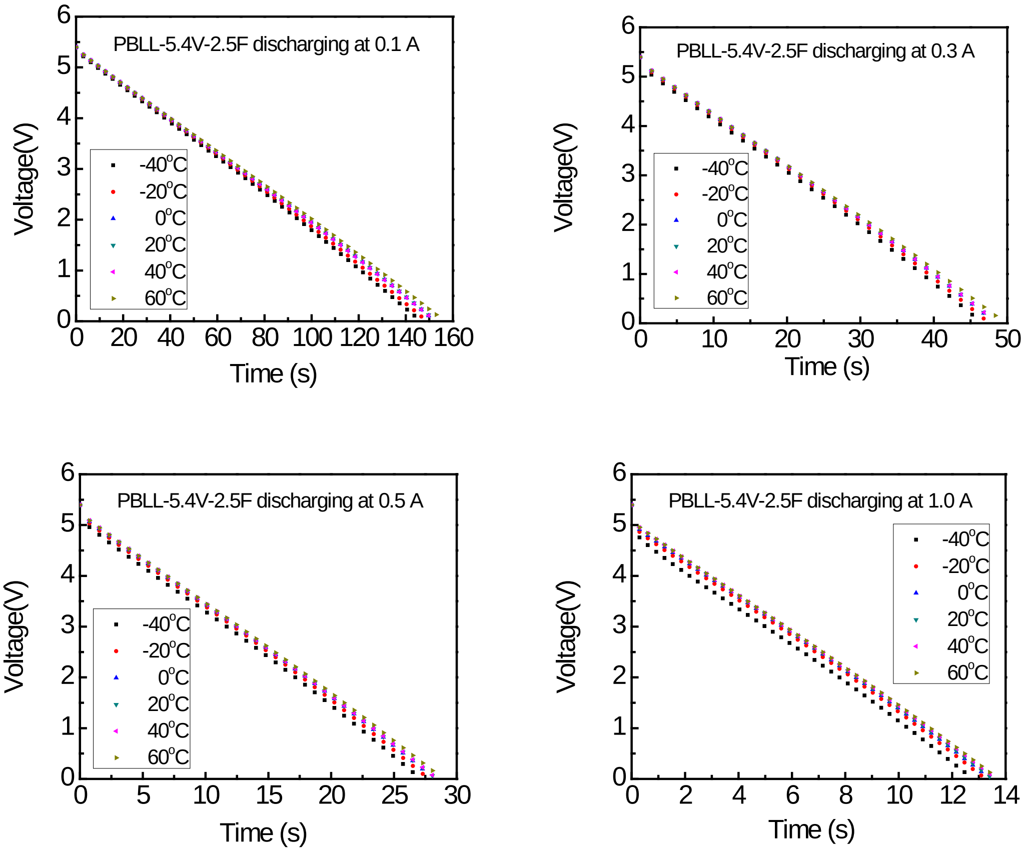

Figure 3-8. Voltage vs. time of PBLL-2.5/5.4 supercapacitor under different discharge currents of 0.1A, 0.3A, 0.5A, 1.0A at different temperatures.

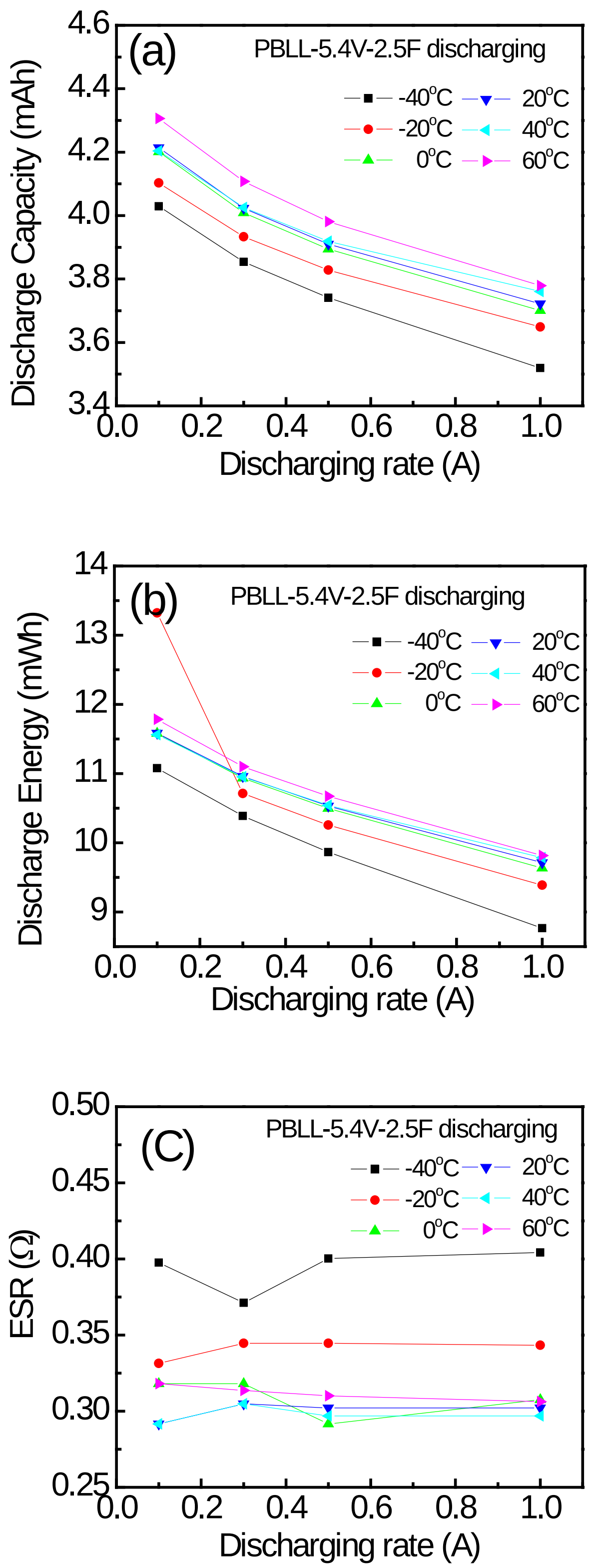

Figure 3-9. Discharge capacity (a), discharge energy (b), and ESR (c) of PBLL-2.5/5.4 supercapacitor at -40°C, -20°C, 0°C, 20°C, 40°C and 60°C under different discharge currents.

Table 3-4 Sample B-constant current discharge data from 5.4 V to 0 V under different discharge current rates and at different temperatures

Current	Temp.	Time	Capacity	Energy	Specific energy	Capacitance	ESR_{DC}	I_{sc}	specific power
(A)	^{o}C	(Sec)	(mAh)	(mWh)	(Wh/l)	(F)	(Ω)	A	W/l
0.1	-40	145.1	4.029	11.077	1.87746	2.84576	0.3976	17.71	4052.45
	-20	147.8	4.103	13.322	2.25797	2.87604	0.3314	17.71	4052.45
	0	151.3	4.201	11.580	1.96271	2.95334	0.3181	17.21	3938.77
	20	151.8	4.214	11.584	1.96339	2.95508	0.2916	13.48	3086.66
	40	151.4	4.204	11.563	1.95983	2.94377	0.2916	15.67	3585.58
	60	155.1	4.306	11.785	1.99746	3.02939	0.3181	18.51	4237.28
0.3	-40	46.3	3.854	10.389	1.76085	2.80479	0.3712	17.86	4088.66
	-20	47.2	3.933	10.712	1.81559	2.81215	0.3446	18.18	4161.64
	0	48.1	4.009	10.935	1.85339	2.8509	0.3181	17.41	3984.49
	20	48.3	4.023	10.960	1.85763	2.84549	0.3049	13.35	3056.12
	40	48.3	4.025	10.952	1.85627	2.84468	0.3049	15.72	3599.16
	60	49.3	4.108	11.099	1.88119	2.91347	0.3137	17.56	4018.18
0.5	-40	26.9	3.741	9.865	1.67203	2.80206	0.4003	17.86	4088.66
	-20	27.5	3.828	10.256	1.73831	2.78971	0.3446	18.18	4161.64
	0	28.0	3.894	10.496	1.77898	2.81057	0.2916	17.63	4035.24
	20	28.1	3.910	10.532	1.78508	2.7972	0.3022	17.71	4052.45
	40	28.2	3.919	10.542	1.78678	2.80411	0.2969	17.71	4052.45
	60	28.7	3.981	10.671	1.80864	2.85927	0.3101	17.21	3938.77
1.0	-40	12.67	3.519	8.766	1.48576	2.82103	0.4043	13.48	3086.66
	-20	13.14	3.649	9.389	1.59136	2.79916	0.3433	15.67	3585.58
	0	13.32	3.701	9.633	1.63271	2.78995	0.3075	18.51	4237.28
	20	13.40	3.722	9.714	1.64644	2.76679	0.3022	17.86	4088.66
	40	13.54	3.761	9.783	1.65814	2.79135	0.2969	18.18	4161.64
	60	12.06	3.779	9.816	1.66373	2.80639	0.3062	17.41	3984.49

3.3.3. Sample C RS055105

Figure 3-10 shows the voltage vs. time of RS055105 supercapacitor under different discharge currents of 0.1A, 0.3A, and 0.5A at different temperatures. Different from sample A and B, it is a non-linear relationship between voltage and discharging time.

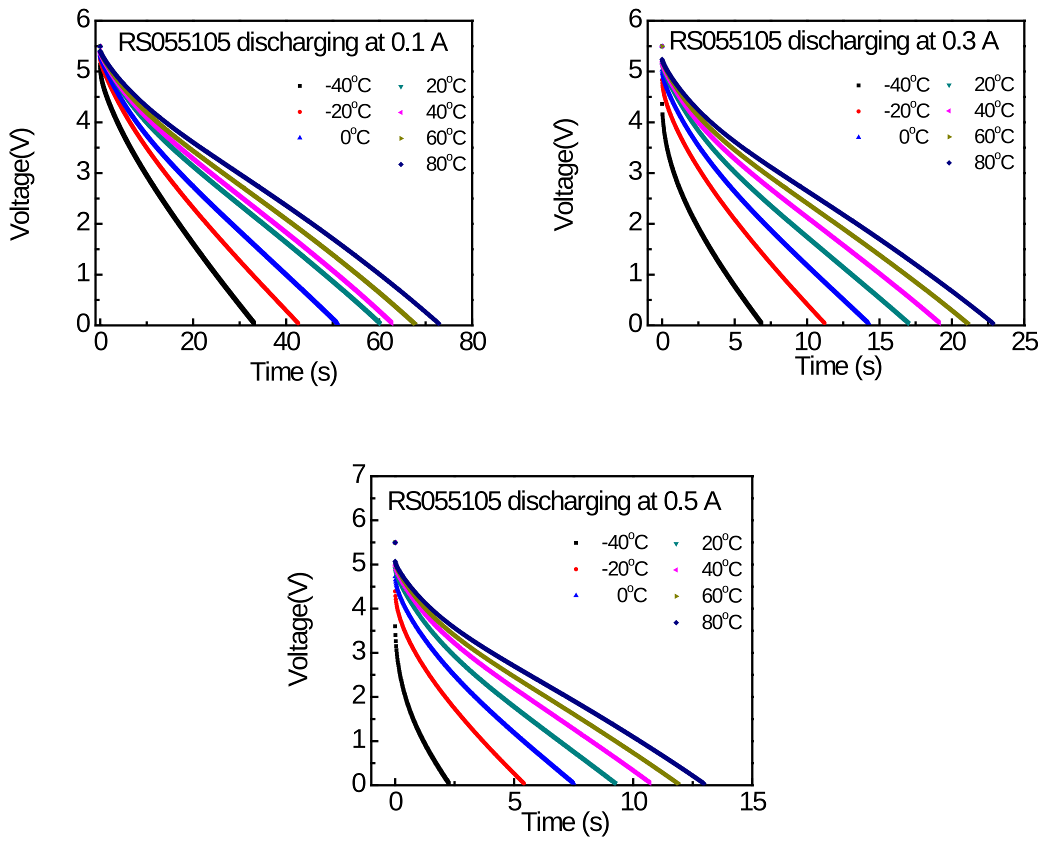

Figure 3-10. Voltage vs. time of RS055105 supercapacitor under different discharge currents of 0.1A, 0.3A, and 0.5A at different temperatures.

Different from sample A and B, sample C has relatively broad work temperature range from -55°C to 85°C. **Figure 3-11** shows discharge capacity, discharge energy, and ESR of sample C at -40°C, -20°C, 0°C, 20°C, 40°C, 60°C and 80°C under different currents. The trends are very different from sample A and B. Most of parameters of this sample are various at different temperatures and discharging currents.

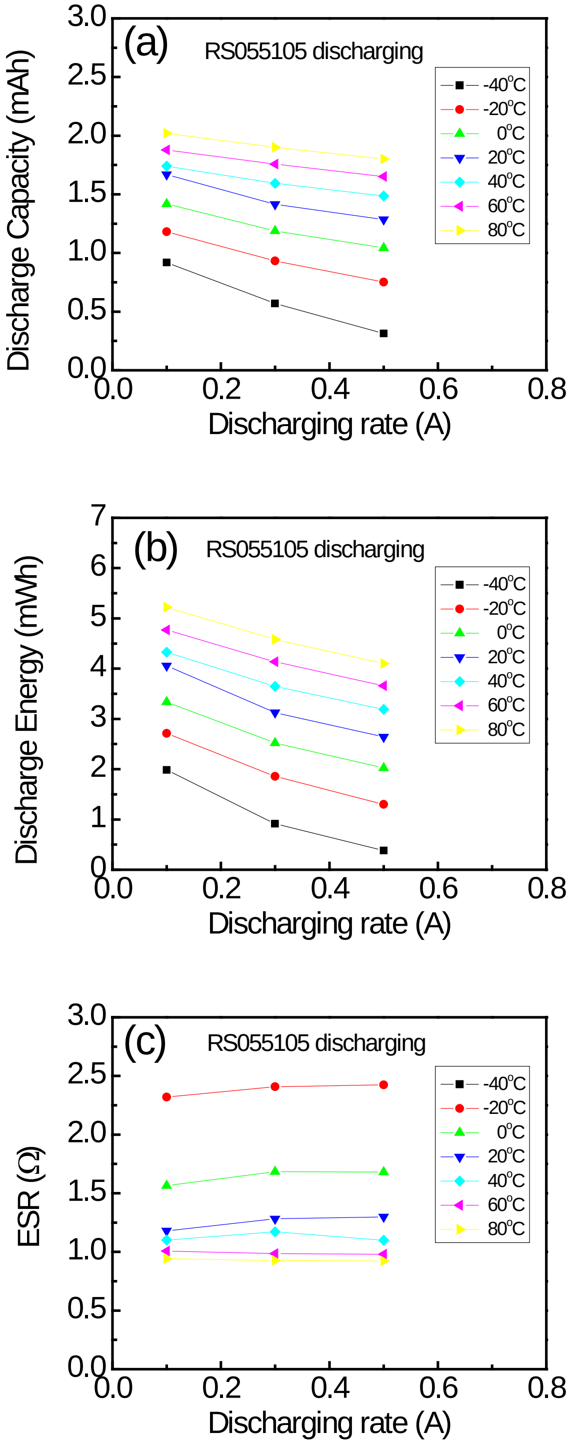

Figure 3-11. Discharge capacity (a), discharge energy (b) and ESR (c) of RS055105 supercapacitor at -40°C, -20°C, 0°C, 20°C, 40°C and 60°C at different currents.

Table 3-5. Sample C-constant current discharge data from 5.4 V to 0 V under different discharge currents and at different temperatures

Current	Temp.	Time	Capacity	Energy	Specific energy	Capacitance	ESR_{DC}	I_{sc}	specific power
(A)	^oC	(Sec)	(mAh)	(mWh)	(Wh/l)	(F)	(Ω)	A	W/l
0.1	-40	33.12	0.919	1.986	0.20905	0.67078	4.0828	5.843	845.7847
	-20	42.59	1.182	2.713	0.28558	0.83689	2.3198	1.231	178.1994
	0	51.09	1.418	3.336	0.35116	1.03734	1.5642	2.283	330.5729
	20	60.12	1.669	4.058	0.42716	1.28304	1.1798	3.267	472.8557
	40	62.73	1.741	4.328	0.45558	1.34753	1.1003	4.292	621.2366
	60	67.64	1.878	4.767	0.50179	1.47558	1.0075	4.697	679.8638
	80	72.78	2.020	5.224	0.54989	1.60154	0.9412	5.582	807.9291
0.3	-40	6.85	0.570	0.914	0.09621	0.37805	4.4672	5.927	857.9077
	-20	11.20	0.933	1.859	0.19568	0.68092	2.4081	1.311	189.8029
	0	14.26	1.188	2.520	0.26526	0.85353	1.6835	2.269	328.5265
	20	16.99	1.415	3.128	0.32926	1.05511	1.2814	3.272	473.6153
	40	19.13	1.593	3.648	0.384	1.23839	1.1709	4.234	612.8195
	60	16.11	1.757	4.137	0.43547	1.40417	0.9853	4.999	723.5526
	80	22.82	1.901	4.581	0.48221	1.54631	0.9279	5.607	811.5533
0.5	-40	2.26	0.314	0.383	0.04032	0.15686	4.1941	5.961	862.8361
	-20	5.14	0.752	1.299	0.13674	0.53574	2.4231	5.843	845.7847
	0	7.50	1.043	2.024	0.21305	0.7465	1.6808	1.231	178.1994
	20	9.25	1.285	2.640	0.27789	0.93712	1.2990	2.283	330.5729
	40	10.70	1.486	3.190	0.33579	1.14176	1.1002	3.267	472.8557
	60	11.89	1.652	3.660	0.38526	1.31454	0.9809	4.292	621.2366
	80	9.45	1.801	4.100	0.43158	1.47215	0.9226	4.697	679.8638

3.3.4. Sample D PBM-1500

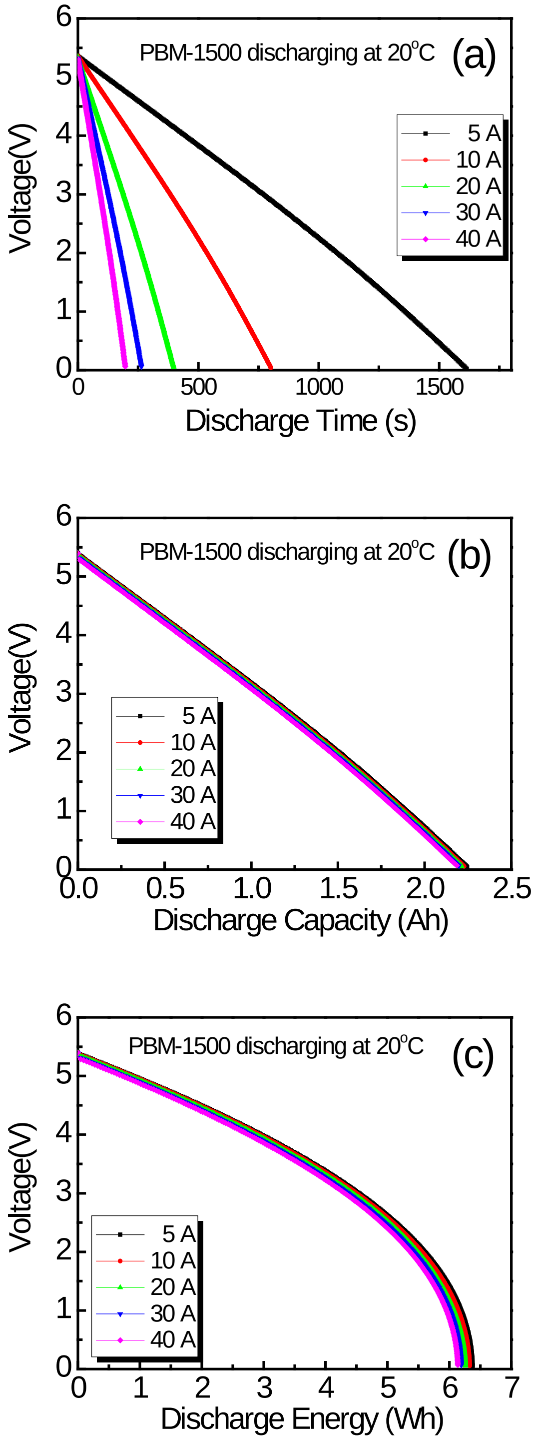

Figure 3-12. Voltage vs. time (a), voltage vs. discharge capacity (b), and voltage vs. discharge energy (c) of PBM-1500 supercapacitor under different discharge currents at 20°C.

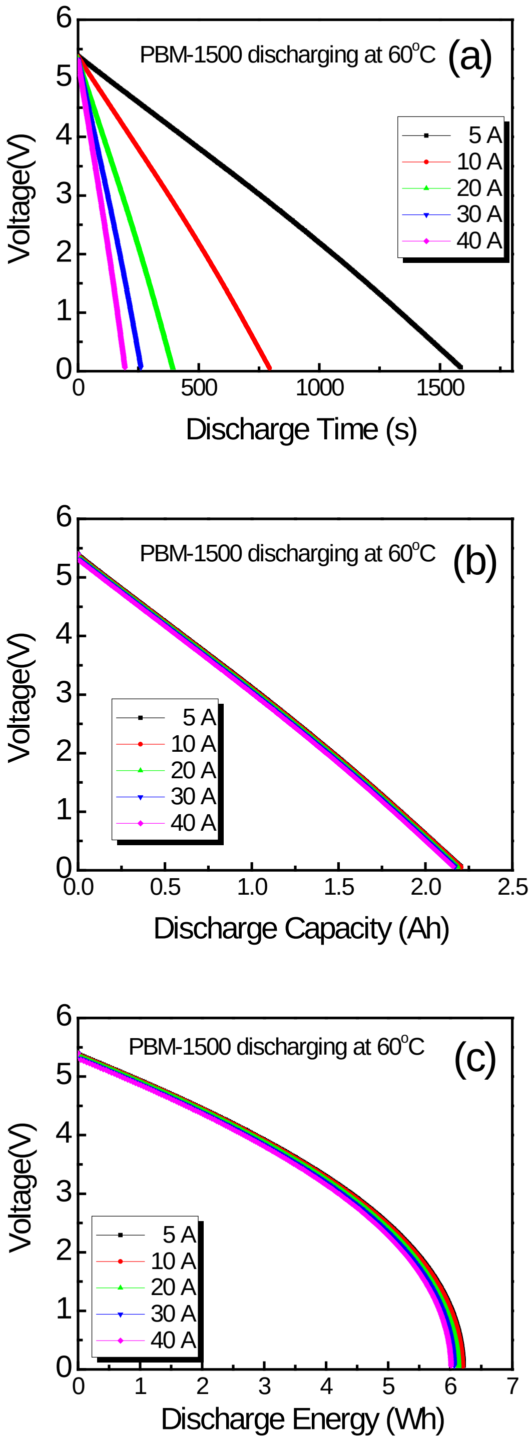

Figure 3-13. Voltage vs. time (a), voltage vs. discharge capacity (b), and voltage vs. discharge energy (c) of PBM-1500 supercapacitor under different discharge currents at 60^{o}C.

Table 3-6 Sample D-constant current discharge data from 5.4 V to 0 V under different discharge current rates and at different temperatures

Current	Temp.	Time	Capacity	Energy	Specific energy	Cap.	ESR_{DC}	I_{sc}	Specific power
(A)	^oC	(Sec)	(mAh)	(mWh)	(Wh/kg)	(F)	(mΩ)	A	W/kg
5	-40	1603.0	2227.3	6353.0	4.96328	1592.35	0.795	6792	7163.915
	-20	1609.6	2236.1	6374.8	4.98031	1592.35	0.95	5684	5995.065
	0	1606.0	2231.3	6355.5	4.96523	1582.27	0.95	5684	5995.065
	20	1615.1	2243.5	6376.0	4.98125	1597.44	1.05	5142	5424.107
	40	1602.2	2225.6	6307.7	4.92789	1582.27	1.05	5142	5424.107
	60	1590.1	2209.2	6220.4	4.85969	1562.50	1.20	4500	4746.093
10	-40	797.6	2216.0	6304.9	4.92570	1589.82	0.95	5684	5995.065
	-20	801.4	2226.4	6338.1	4.95164	1589.82	0.95	5684	5995.065
	0	800.5	2224.2	6320.7	4.93805	1589.82	0.95	5684	5995.065
	20	802.7	2230.2	6328.1	4.94383	1584.78	1.00	5400	5695.312
	40	797.6	2216.0	6267.1	4.89617	1587.30	1.10	4909	5177.556
	60	794.4	2207.1	6204.5	4.84727	1564.94	1.15	4695	4952.445
20	-40	396.5	2202.9	6234.7	4.87086	1587.30	0.95	5684	5995.065
	-20	398.2	2212.5	6270.8	4.89906	1587.30	0.95	5684	5995.065
	0	398.4	2213.8	6260.3	4.89086	1583.53	1.00	5400	5695.312
	20	398.9	2216.7	6259.9	4.89055	1584.78	1.05	5142	5424.107
	40	396.4	2202.6	6201.9	4.84523	1572.32	1.05	5142	5424.107
	60	394.2	2190.4	6138.5	4.79570	1561.28	1.10	4909	5177.556
30	-40	262.8	2190.3	6166.8	4.81781	1587.30	1.00	5400	5695.312
	-20	264.0	2200.4	6207.5	4.84961	1587.30	1.00	5400	5695.312
	0	264.9	2207.8	6208.6	4.85047	1586.46	1.00	5400	5695.312
	20	264.4	2203.2	6193.7	4.83883	1582.27	1.05	5142	5424.107
	40	262.7	2189.4	6136.1	4.79383	1569.85	1.10	4909	5177.556
	60	261.0	2175.5	6068.6	4.74109	1556.82	1.10	4909	5177.556
40	-40	196.2	2179.8	6106.8	4.77094	1587.30	1.00	5400	5695.312
	-20	197.1	2190.2	6152.2	4.80641	1587.30	0.95	5684	5995.065
	0	197.2	2191.1	6140.2	4.79703	1582.27	1.00	5400	5695.312
	20	197.3	2191.9	6135.6	4.79344	1581.65	1.05	5142	5424.107
	40	196.0	2177.7	6075.1	4.74617	1568.62	1.05	5142	5424.107
	60	194.7	2163.9	6014.1	4.69852	1554.60	1.10	4909	5177.556

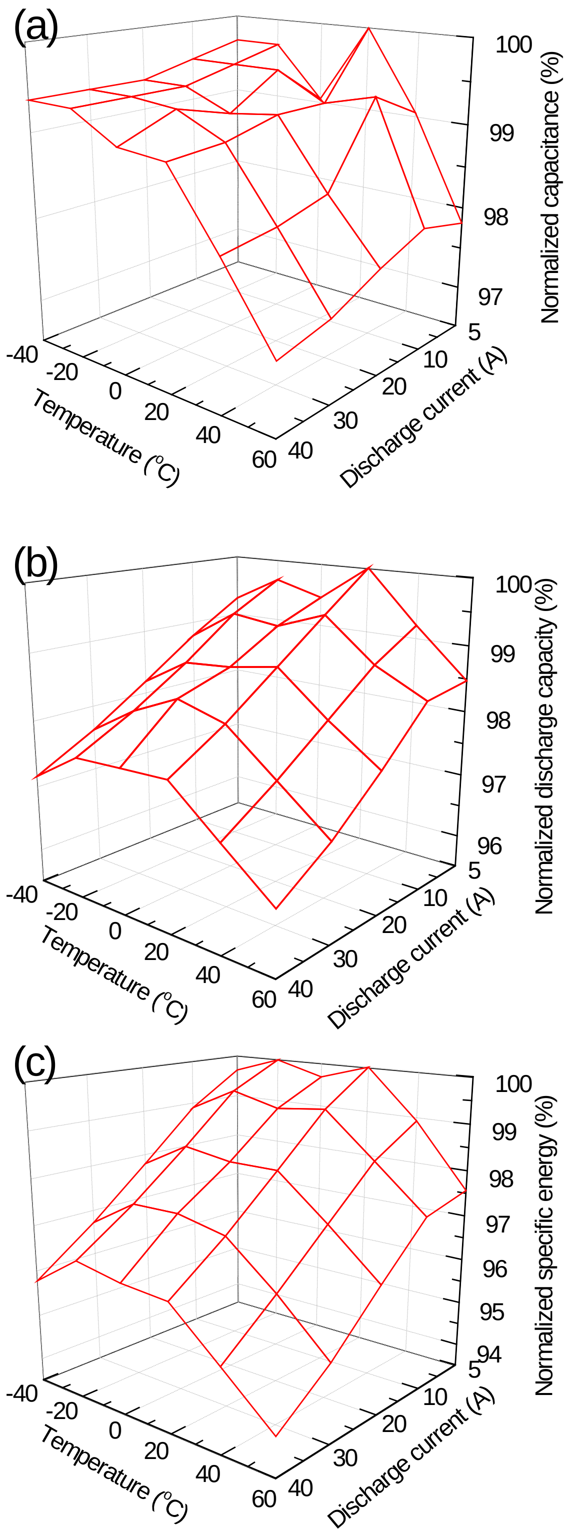

Figure 3-14. Normalized capacitance (a), normalized discharge capacity (b), and normalized discharge specific energy (c) of sample D under different discharge currents at different temperatures.

To systematic study the supercapacitor properties under different discharge currents and temperatures, sample D (PBM-1500 supercapacitor) were charged and discharged under 5 different currents and at six different temperatures. As an example, **Figure 3-12** and **Figure 3-13** show the voltage change with time, discharge capacity, and discharge energy of PBM-1500 supercapacitor under different discharge currents of 5A, 10A, 20A, 30A, and 40A at 20^{o}C and 60^{o}C. The performance of sample D shows similar results with previous 2 samples.

Table 3-6 shows the parameters obtained from the tests. Due to different configurations of supercapacitors, sample D show much higher capacitance and energy than other samples. The calculated capacitance is around 1550~1600 F, which is slightly larger than 1500 provided from company's datasheet. The stored energy is close to 4.75 Wh/kg. From the **Table 3-6**, it is easy to obtain that sample D shows high stability in different environments. To clear study the parameters, the normalized capacitance, normalized discharge capacity, and normalized discharge energy of sample D under different discharge currents and at different temperatures are shown in **Figure 3-14**. The X-axis, Y-axis, and Z-axis are the discharge current, temperature, and normalized parameter, respectively. The normalization was made using the one under 5A discharge at 20^{o}C as references. The results show the normalized specific energy decreases when current increases. The possible reason is that higher charge/discharge current may raise the temperature due to the self-heating. The capacitance decreases because the dielectric constant of double layer decreases and heat diffusion dramatically increases. At each discharge current rate, the temperature also has effect on the normalized parameters. The results show the variation of parameters are similar in threes figures in **Figure 3-14**. The normalized parameters decrease when temperature increases or decreases. It indicates that the supercapacitor has a proper working environment. Lower or higher temperature may decrease the value of parameters. Although discharge rate and temperature have some effects on the performance, sample D still shows good stability in performance, because most of the normalized parameters are in 97~100%, which is a good supercapacitor for aerospace applications.

3.4. Summary

By the principle of the electric double layer supercapacitors, the adsorption reaction during charge/discharge is heat sensitive, since it is an endothermic/ exothermic process. When temperature rising, the ionic mobility increases and the stability of the adsorption reaction decreases. The amount of charge adsorbed on the same area reduces, which results a decrease in the capacity. On the other hand, ion motion is another issue. When the temperature rises, ionic conductivity of the electrolyte increases, the resistance decreases, which is confirmed from study in section 3.3 that the ESR decreases. In a word, the temperature changes have both effects on capacity and ESR of supercapacitor. The effect of temperature on the adsorption process is the main factor affecting the ESR and capacity for supercapacitor. The changes on the resistance with temperature have relatively small impact on the capacity.

The sample D is much different from other three samples. **Figure 3-15** shows the discharge capacity (solid) and discharge energy (open) of three different samples at -40^{o}C, -20^{o}C, 0^{o}C, 20^{o}C, 40^{o}C and 60^{o}C under different currents. The results show the discharge capacity and discharge energy of sample A and B are almost independent of temperature, while the discharge capacity and discharge energy of sample C are strongly dependent on the temperature. Because the discharge capacity and discharge energy show the similar temperature dependence, the discharge capacity is used as example for the following analysis. To quantify the temperature dependence of the supercapacitor performance, a temperature coefficient (Temp-Coef) is defined as

$$\mathrm{Temp-Coef} = \frac{Max(cap)-Min(cap)}{Max(cap)+Min(cap)} \quad (3\text{-}1)$$

where Max(cap) and Min(cap) are the maximum and minimum values of the discharge capacity at a discharge current over the temperature range from -40^{o}C to 60^{o}C (using the same range for Sample C). The Temp-Coef defined above represents the maximum derivation of the discharge capacity from its median value. The value of Temp-Coef at some discharge current for different samples is summarized in **Figure 3-15 (d)**. The Temp-Coef is less than 4% of sample A and B under different currents. The stability of performances of sample B may be slightly better than which of sample A. However, The Temp-Coef of sample C is larger than 30% at very low discharge rate (0.1 A), increases with increasing discharge current dramatically, and reaches 70% at 0.5 A. It indicates sample C is not suitable for aerospace applications because the poor stability of performance on temperature.

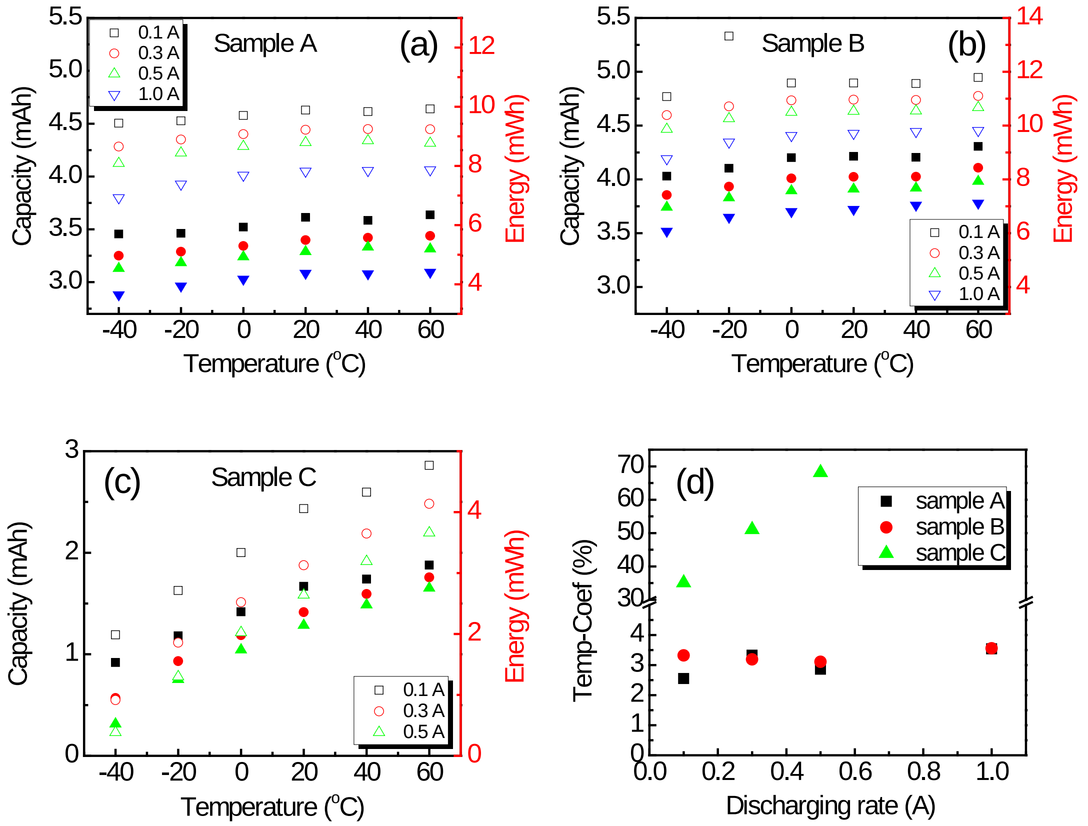

Figure 3-15. Discharge capacity (solid) and discharge energy (open) of three different samples (a) sample A, (b) sample B, (c) sample C at -40°C, -20°C, 0°C, 20°C, 40°C and 60°C at different currents, (d) Temp-Coef of three samples under different discharging currents.

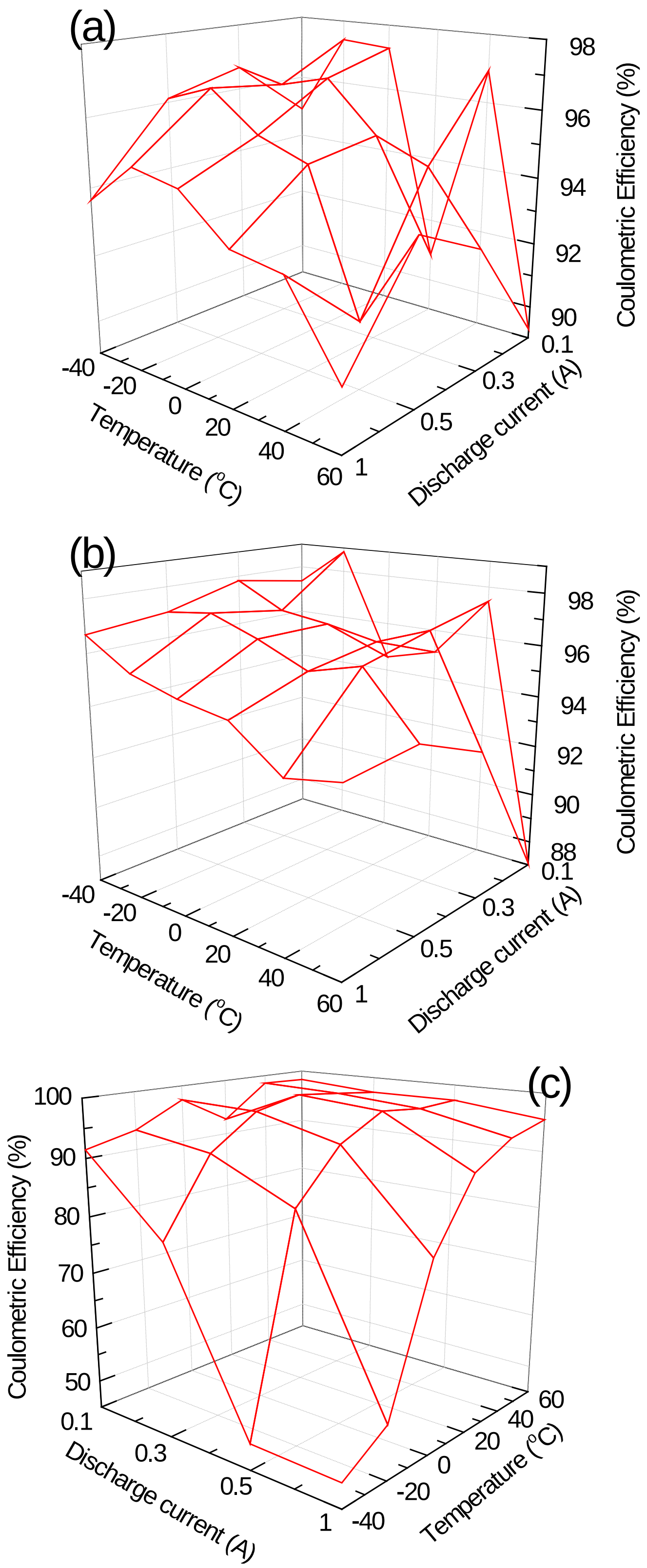

Figure 3-16. Coulometric efficiency of (a) sample A, (b) sample B, and (c) sample C.

Coulometric efficiency is also an important parameter for supercapacitor, which indicates the stored charge in energy storage device can be recoverable during discharging. It is the ratio of device's charge/discharge capacity which shows the reversible capability of supercapacitor. It can be observed from **Figure 3-16** that supercapacitor holds relatively high Coulometric efficiency (above 95%) along whole discharge current range. There is a slight decrease in the efficiency as the discharge current increases. For sample C, the efficiency changed more than other two samples. At very low temperature, the efficiency can be lower than 50% as shown in **Figure 3-16** (c).

CHAPTER 4

Evaluation and Performance of Battery

4.1. Introduction

In this chapter, before starting measurements, a detailed test procedure was given. Four selected lead-acid batteries are studied under different discharge rates and at different temperatures. The performance of lead-acid batteries are analyzed.

4.2. Test sample and procedure

4.2.1. Devices

The selected four batteries were purchased from Concorde company. The information about these samples is listed in **Table 4-1**.

Table 4-1 Parameters of selected batteries

Sample Number	Part Number	Company	Materials	Nominal Capacity(Ah)	Nominal Voltage(V)	Dimensions L×W×H(mm)
A	RG 24-9	Concorde	Lead Acid	8.5	24	185.70×219.70×151.10
B	RG 24-10			8.5	24	184.80×186.20×144.40
C	RG12LSA			11	12	131.60×195.90×172.90
D	RG-25			22	12	131.60×195.90×172.90

4.2.2. Test procedure

1) Sample A: RG 24-9, 24 volts nominal, 8.5 ampere hour capacity (C1).

As shown in **Figure 4-1**, the battery was charged at designed constant current until the voltage reached 28 volts, this is the first step. Then the battery continue charged at constant voltage around 28 volts (maximum discharge voltage) until the current is smaller than 1/100 C (0.085A), this is the second step. The battery was discharged in designed constant current until the voltage reach 22 volts (minimum discharge voltage), this is the third step. Then battery was rested for 6 hours. The sample A was tested at 8 different discharge rates from 1/20C to 1.5C at room temperature (22°C), and also tested at different temperatures from -20°C to 40°C. After the tests under different discharge rates and at different temperatures, the sample is tested after being putted into vacuum for 3 days.

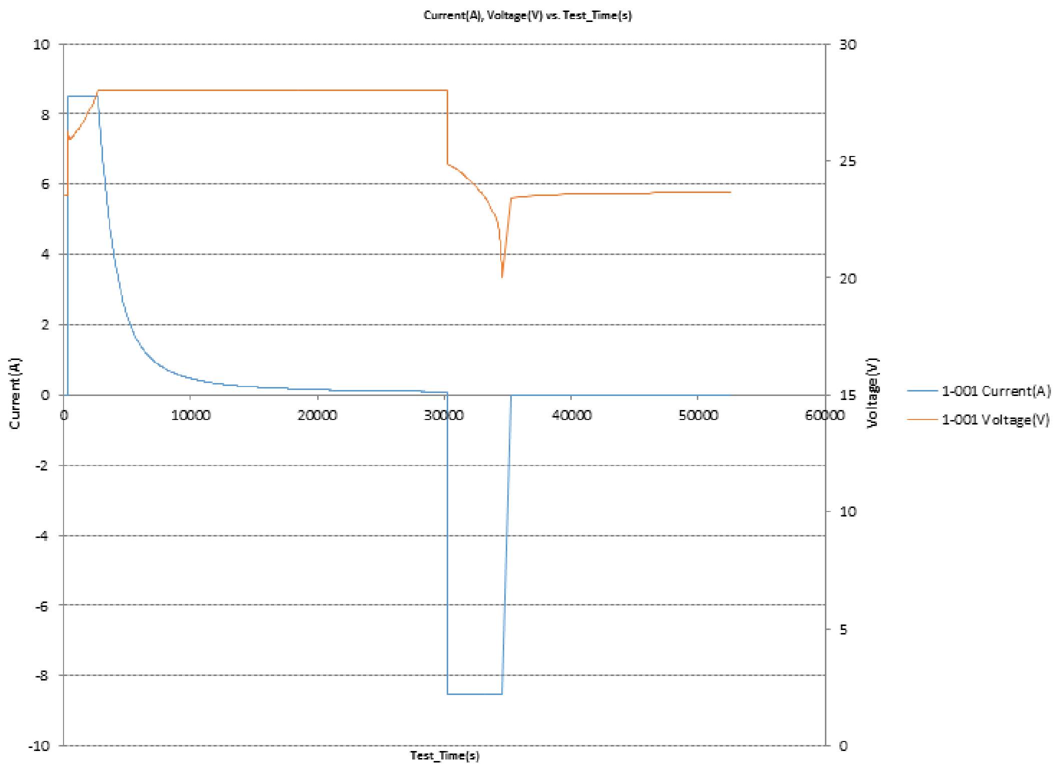

Figure 4-1. Sample A test at 22°C at 1.5C.

2) Sample B: RG 24-10, 24 volts nominal, 8.5 ampere hour capacity (C1).

As shown in **Figure 4-2**, the battery was charged at designed constant current until the voltage reached 28 volts, this is the first step. Then the battery continue charged at constant voltage around 28 volts until the current is smaller than 1/100 C (0.085A), this is the second step. The battery was discharged in designed constant current until the voltage reach 22 volts, this is the third step. Then battery was rested for 6 hours. The sample B was tested at 4 different discharge rates from 1/4 C to 1C at room temperature (22°C), then was tested at different temperatures that from 0°C to 60°C. After the tests under different discharge rates and at different temperatures, the sample is tested after being putted into vacuum for 3 days.

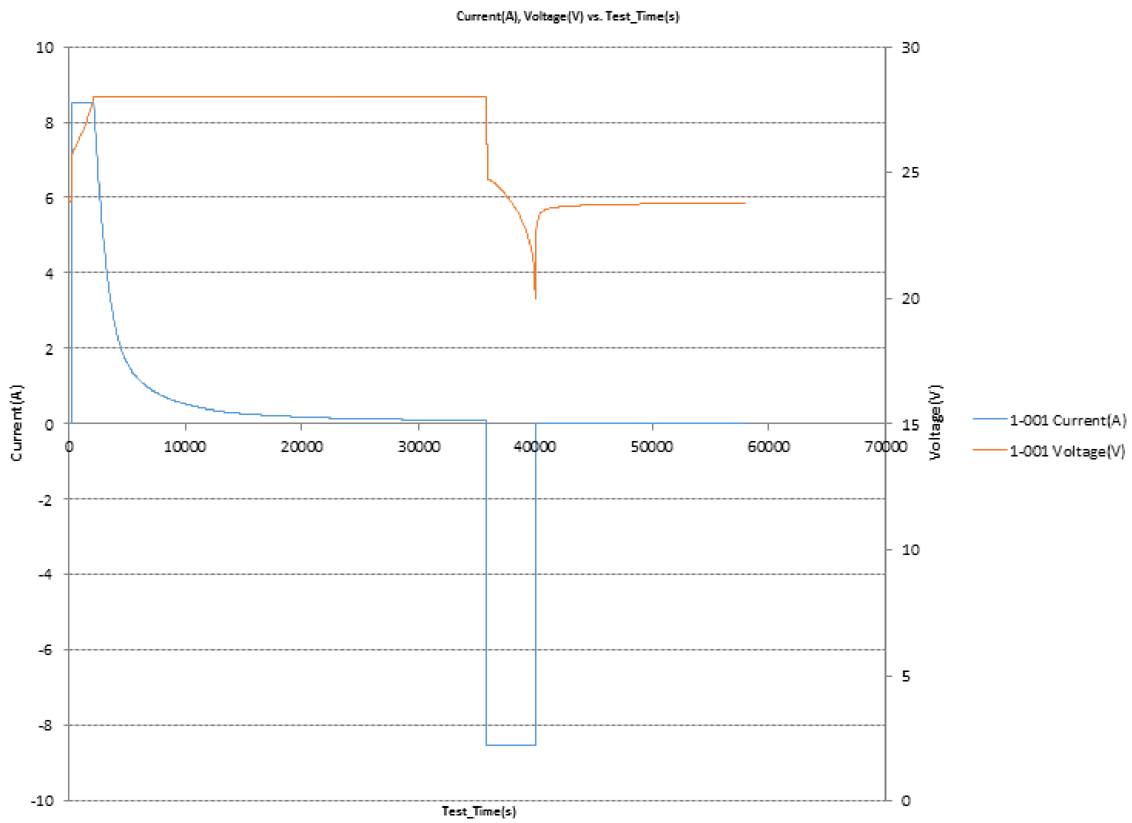

Figure 4-2. Sample B test at 22°C at 1C.

3) Sample C: RG-12LSA, 12 volts nominal, 11 ampere hour capacity (C1).

As shown in **Figure 4-3**, the battery was charged at designed constant current until the voltage reached 14 volts, this is the first step. Then the battery continue charged at constant voltage around 14 volts until the current is smaller than 1/100 C (0.11A), this is the second step. The battery was discharged in designed constant current until the voltage reach 10 volts, this is the third step. Then battery was rested for 6 hours. The sample C was tested at 6 different discharge rates from 1/10 C to 1C at room temperature (22^{o}C), and then sample C was tested at different temperatures that from -40^{o}C to 60^{o}C. After the tests under different discharge rates and at different temperatures, the sample is tested after being putted into vacuum for 3 days.

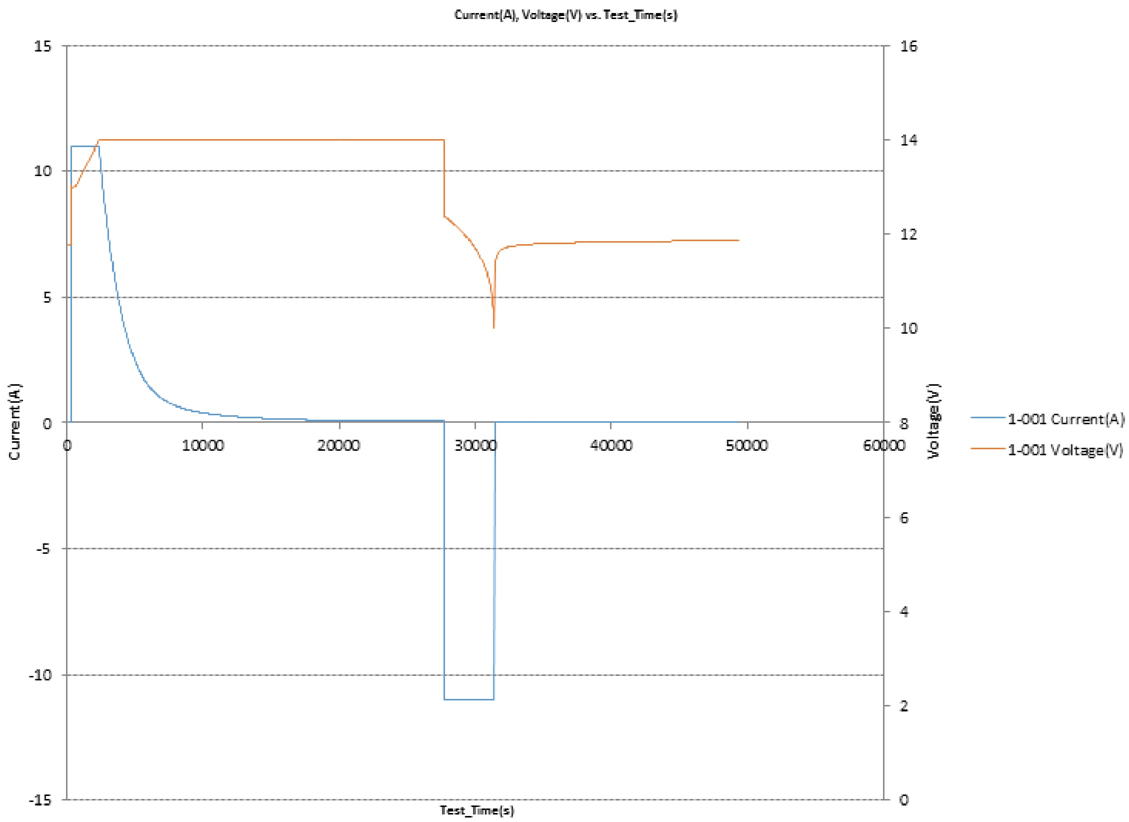

Figure 4-3. Sample C test at 22^{o}C at 1C.

4) Sample D: RG-25, 12 volts nominal, 22 ampere hour capacity (C1).

As shown in **Figure 4-4**, the battery was charged at designed constant current until the voltage reached 14 volts, this is the first step. Then the battery continue charged at constant voltage around 14 volts until the current is smaller than 1/100 C (0.22A), this is the second step. The battery was discharged in designed constant current until the voltage reach 10 volts, this is the third step. Then battery was rested for 6 hours. The sample D was tested at 6 different discharge rates from 1/10C to 1C at room temperature (22°C), and then sample D was tested at different temperatures that from -40°C to 60°C. After the tests under different discharge rates and at different temperatures, the sample is tested after being putted into vacuum for 3 days.

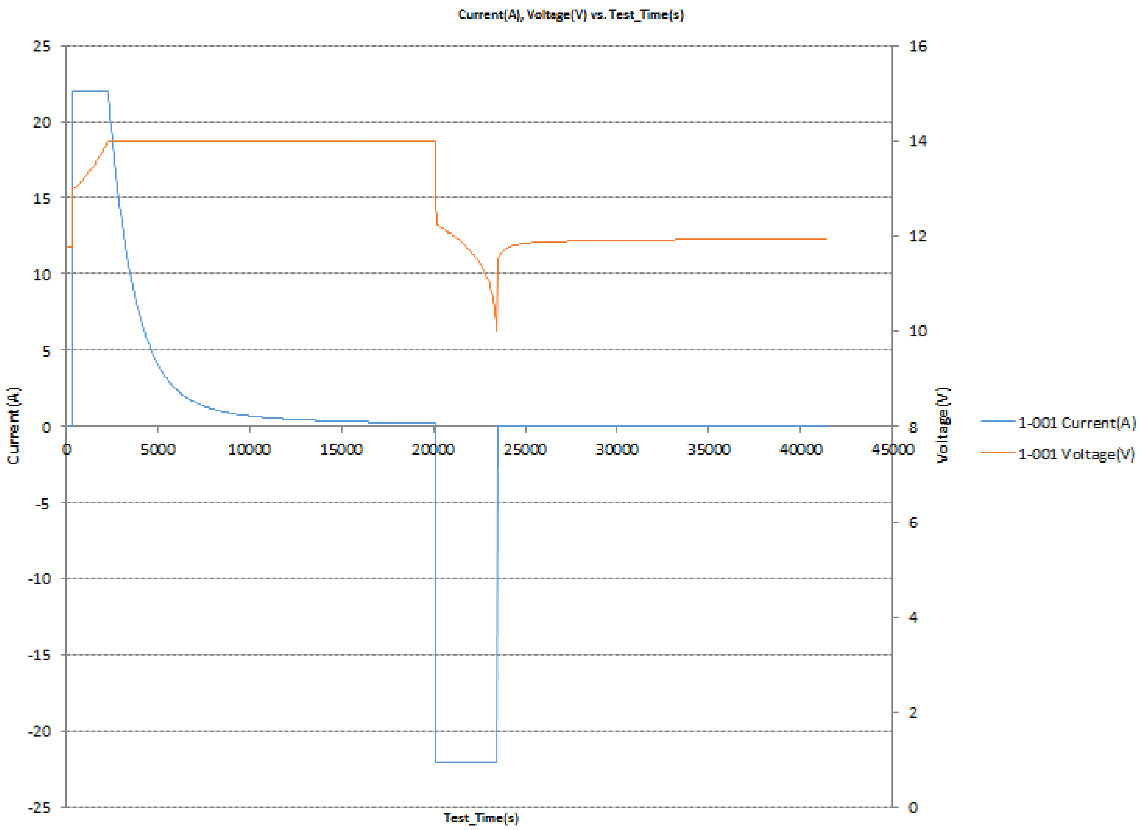

Figure 4-4. Sample D test at 22°C at 1C

4.3. Test results

4.3.1. Sample A

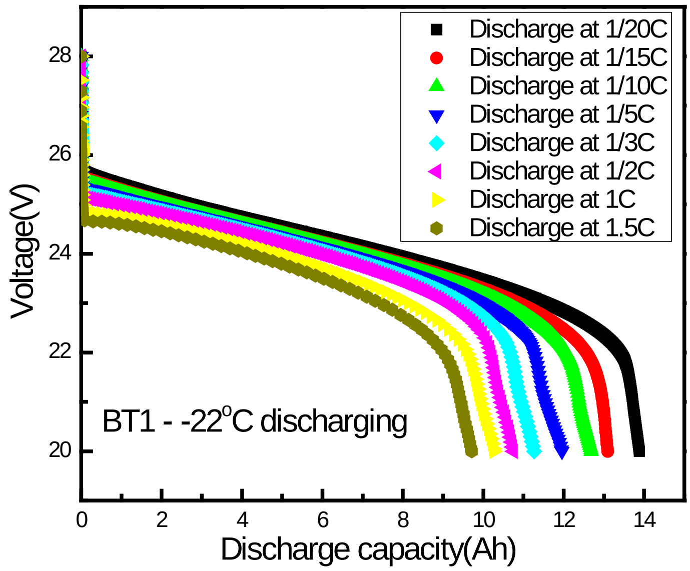

Figure 4-5. Discharge capacity vs. voltage of sample A at different discharge rates at 22°C

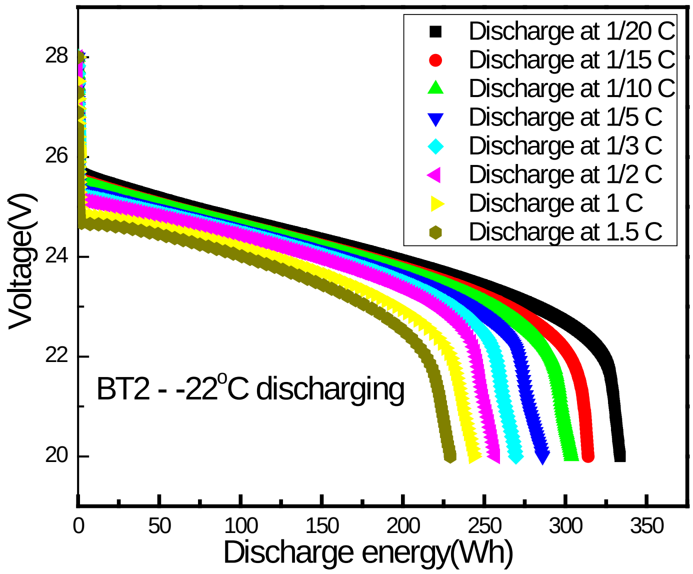

Figure 4-6. Discharge energy vs. voltage at different discharge rates at 22°C.

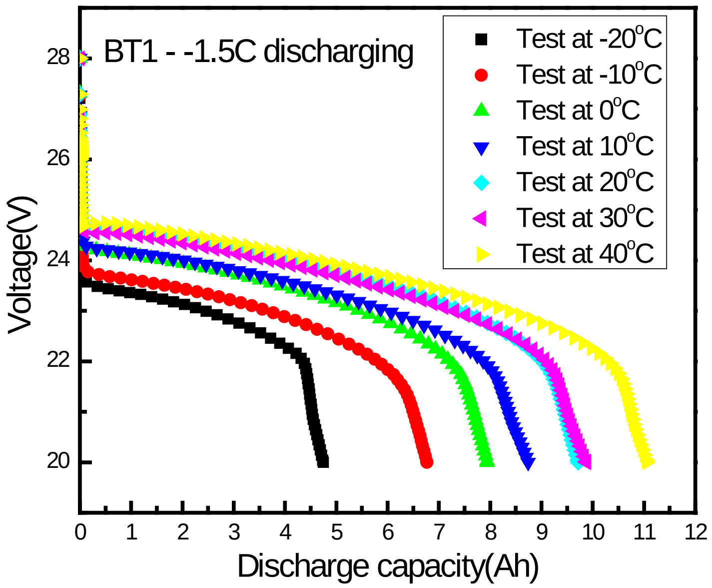

Figure 4-7. Discharge capacity vs. voltage of sample A at different test temperatures at 1.5 C.

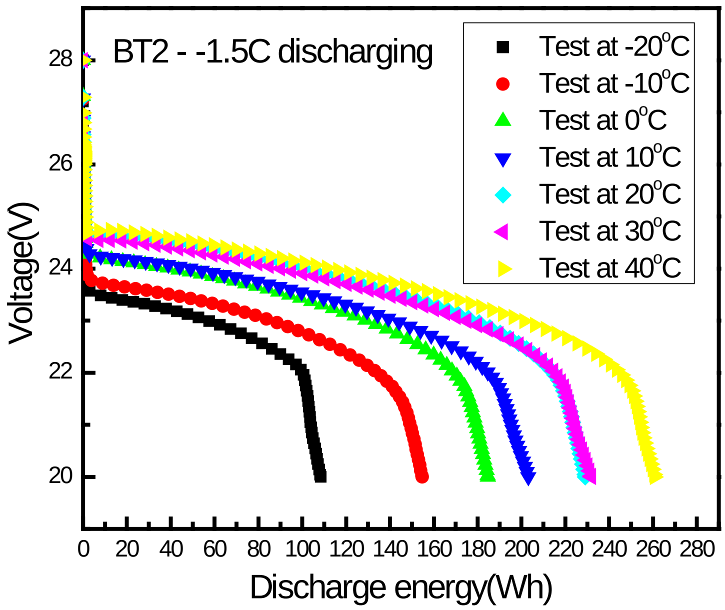

Figure 4-8. Discharge energy vs. voltage of sample A at different test temperatures at 1.5 C.

Table 4-2 Last test point of Sample A at different discharge rates at 22°C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
A-22-1/20C	116279.71	19.9992	13.89	333.69
A-22-1/15C	82625.99	19.9992	13.09	314.11
A-22-1/10C	53328.11	19.9992	12.69	303.81
A-22-1/5C	25229.07	19.9992	11.95	285.91
A-22-1/3C	14295.21	19.9992	11.27	269.55
A-22-1/2C	9085.55	19.9992	10.75	256.95
A-22-1C	3800.54	19.9992	10.27	243.43
A-22-1.5C	2673.83	19.9992	9.71	229.13

Table 4-3 Last test point of Sample A at different temperatures at 1.5C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
A-neg20-1.5C	1338.69	19.9992	4.75	108.41
A-neg10-1.5C	1909.21	19.9992	6.77	154.76
A-0-1.5C	2241.31	19.9992	7.95	184.77
A-10-1.5C	2466.34	19.9992	8.74	203.12
A-22-1.5C	2673.83	19.9992	9.71	229.13
A-30-1.5C	2787.76	19.9992	9.88	231.88
A-40-1.5C	3118.14	19.9992	11.06	260.72

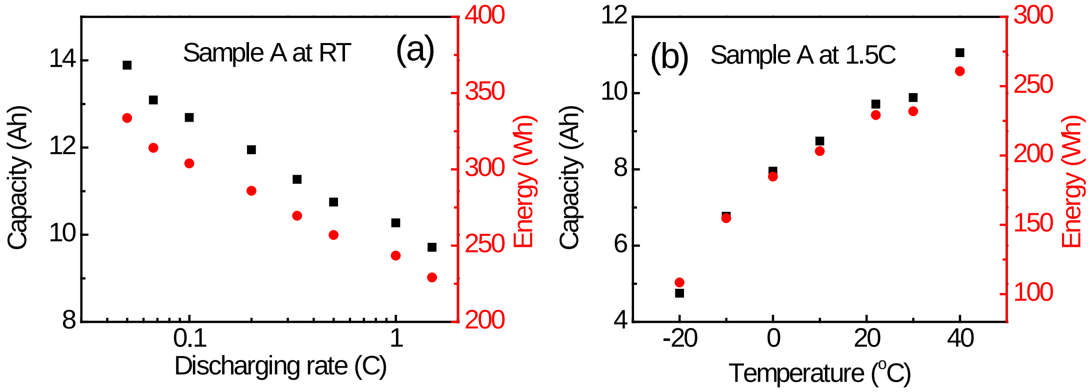

Figure 4-9. (a) Discharge capacity and energy sample A (a) under different discharging rates at RT and (b) at different temperatures at 1.5 C.

4.3.2. Sample B

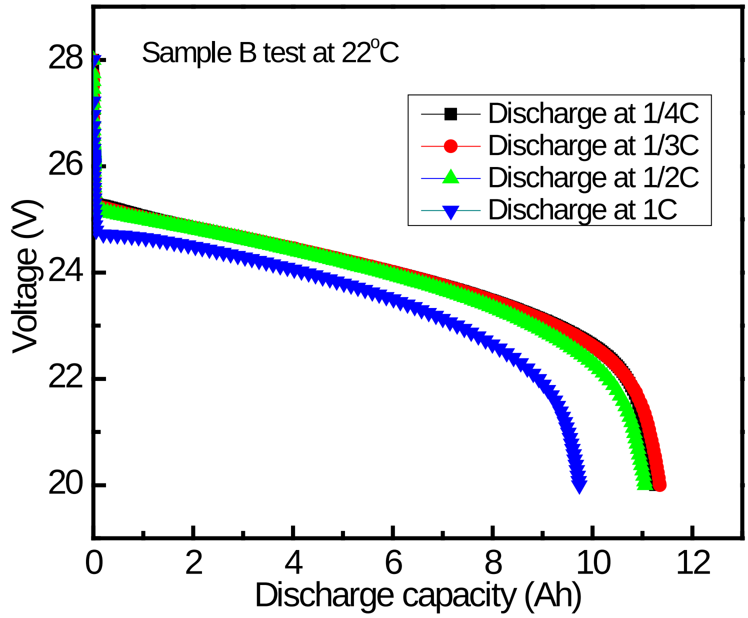

Figure 4-10. Discharge capacity vs. voltage of sample B at different discharge rates at 22°C.

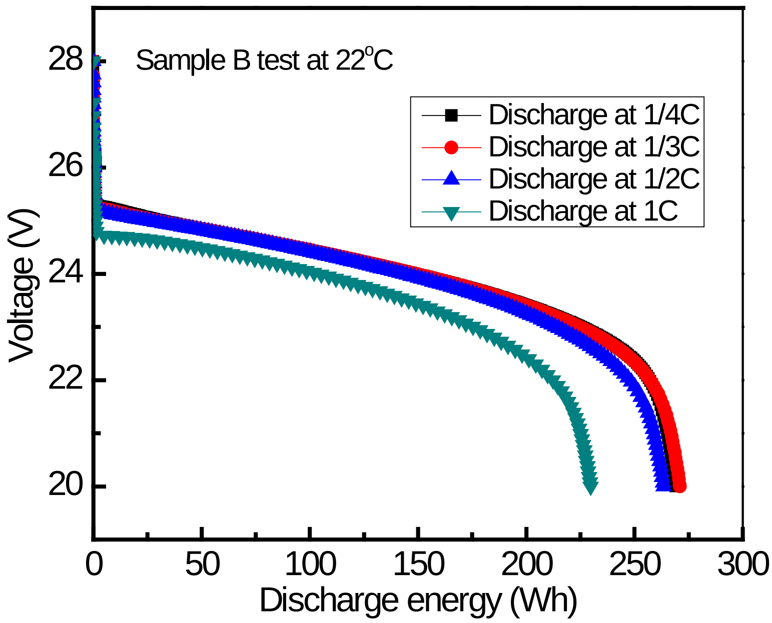

Figure 4-11. Discharge energy vs. voltage of sample B at different discharge rates at 22°C.

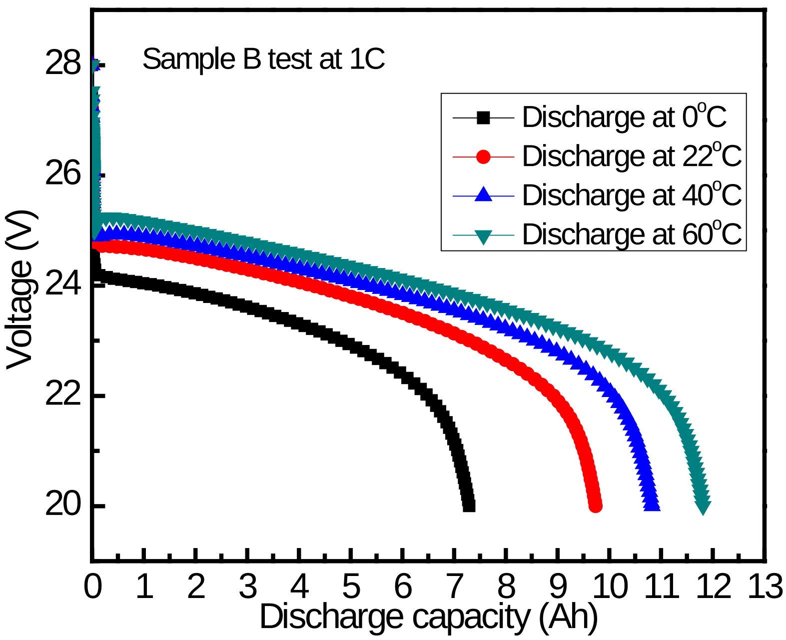

Figure 4-12. Discharge capacity vs. voltage of sample B at different test temperatures at 1 C.

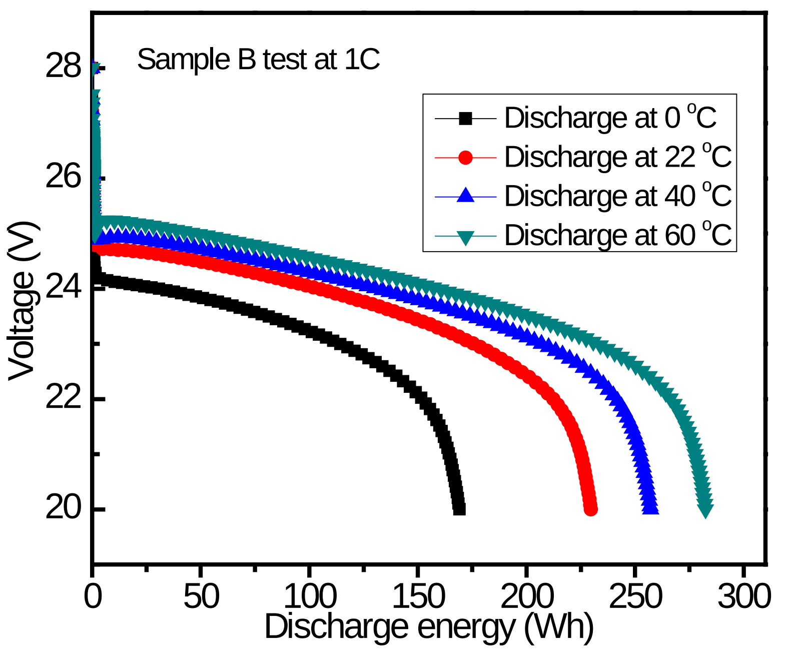

Figure 4-13. Discharge energy vs. voltage of sample B at different test temperatures at 1 C.

Table 4-4 Last test point of Sample B at different discharge rates at 22°C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
B-22-1/4C	19012.80371	19.9992	11.25557467	269.0272625
B-22-1/3C	14385.16062	19.9992	11.34999498	270.9989446
B-22-1/2C	9346.169822	19.9992	11.05644617	263.4953106
B-22-1C	3809.330217	19.9992	8.998509849	212.2451132

Table 4-5 Last test point of Sample B at different temperatures at 1C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
B-0-1C	3087.783735	19.9992	7.295455498	169.1346425
B-22-1C	3809.330217	19.9992	8.998509849	212.2451132
B-40-1C	4581.904852	19.9992	10.82984136	257.2211112
B-60-1C	4995.046613	19.9992	11.81108304	282.4290651

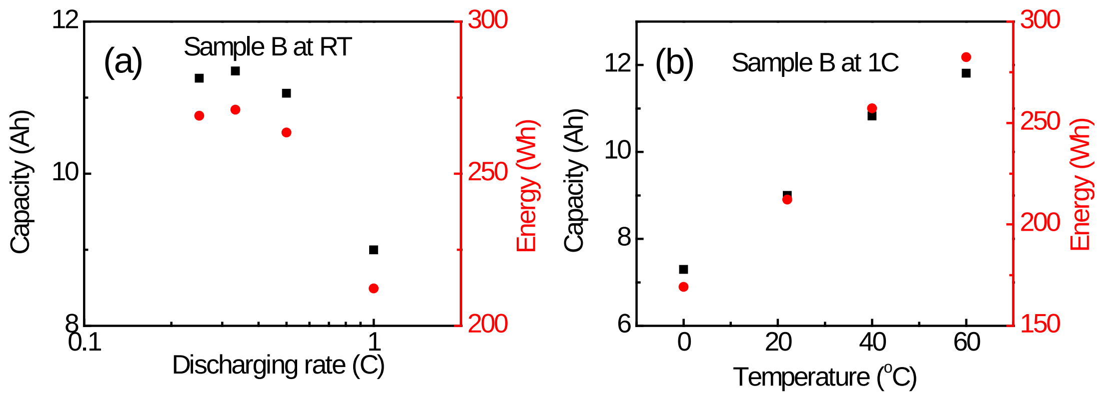

Figure 4-14. (a) Discharge capacity and energy of sample B (a) under different discharging rates at RT and (b) at different temperatures at 1C.

4.3.3. Sample C

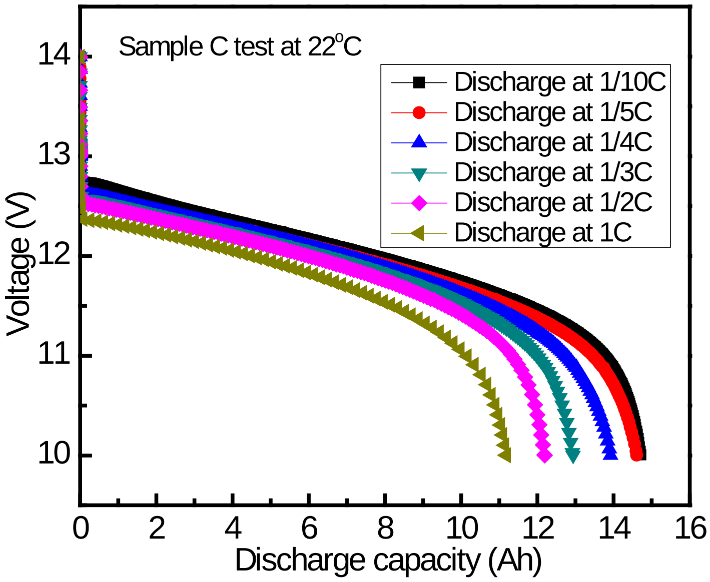

Figure 4-15. Discharge capacity vs. voltage of sample C at different discharge rates at 22°C.

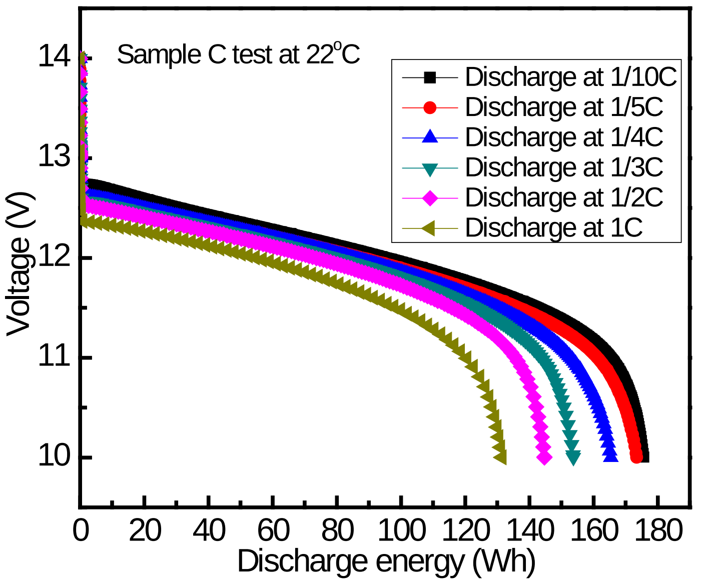

Figure 4-16. Discharge energy vs. voltage of sample C at different discharge rates at 22°C.

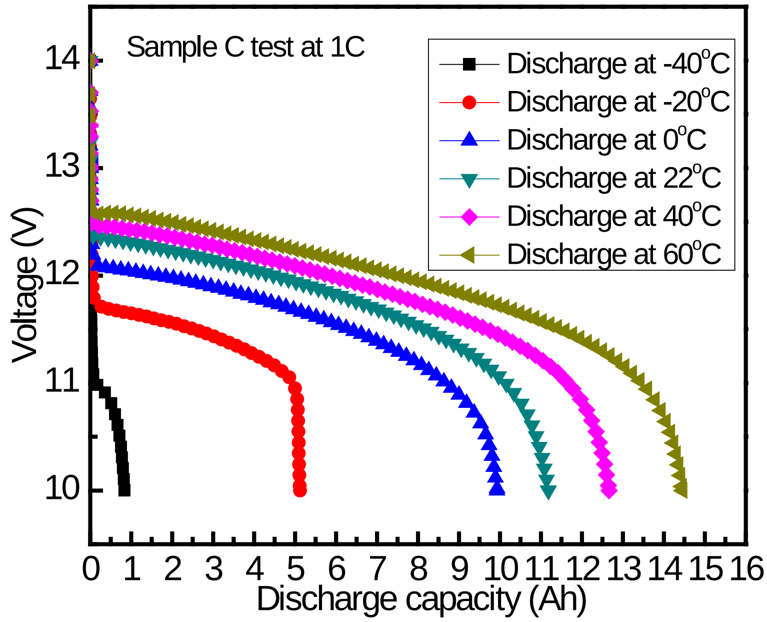

Figure 4-17. Discharge capacity vs. voltage of sample C at different temperatures at 1C.

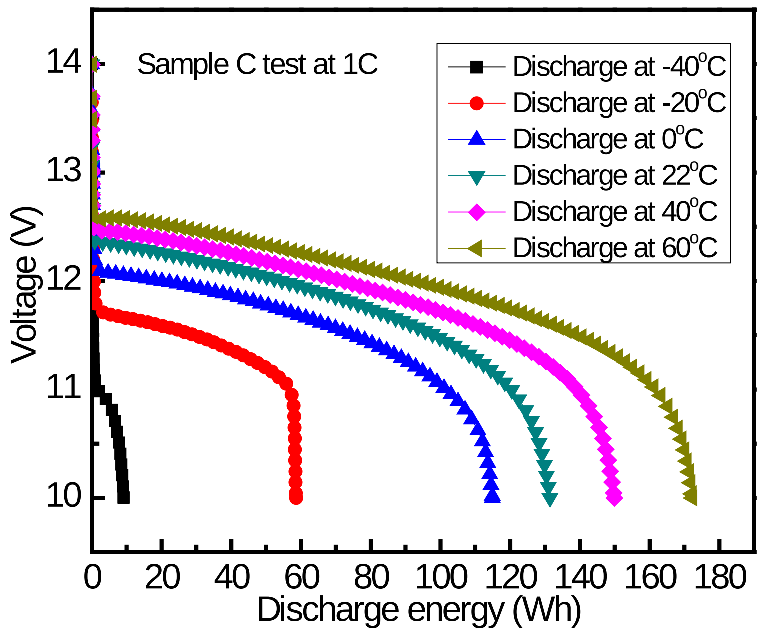

Figure 4-18. Discharge energy vs. voltage of sample C at different temperatures at 1C

Table 4-6 Last test point of Sample C at different discharge rates at 22^{o}C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
C-22-1/10C	47923.31	9.9991	14.71	175.64
C-22-1/5C	23864.47	9.9991	14.60	173.46
C-22-1/4C	18191.66	9.9991	13.92	165.39
C-22-1/3C	12676.57	9.9991	12.93	153.77
C-22-1/2C	7973.85	9.9991	12.18	144.73
C-22-1C	3658.71	9.9991	11.18	131.44

Table 4-7 Last test point of Sample C at different temperatures at 1C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
C-neg40-1C	274.83	9.9991	0.8400	9.10
C-neg20-1C	1674.78	9.9991	5.1198	58.61
C-0-1C	3247.93	9.9991	9.9329	114.95
C-22-1C	3658.71	9.9991	11.1817	131.44
C-40-1C	4143.14	9.9991	12.6624	149.87
C-60-1C	4728.97	9.9991	14.4529	172.28

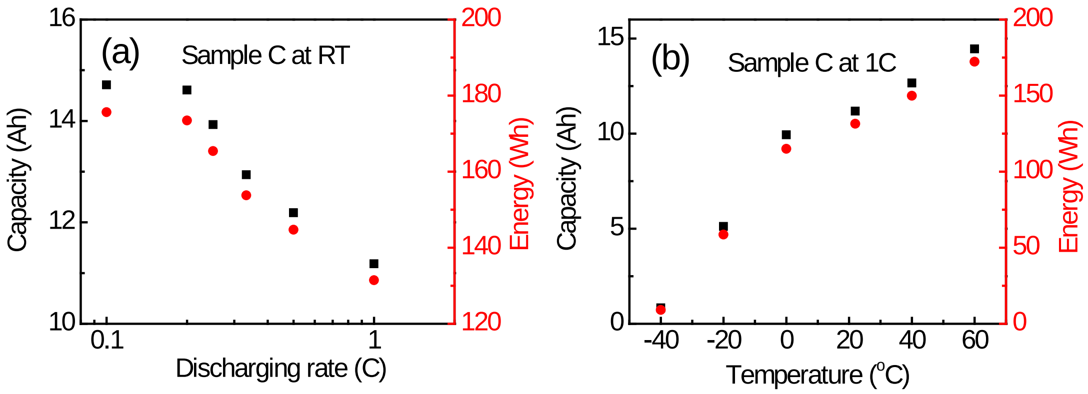

Figure 4-19. (a) Discharge capacity and energy of sample C (a) under different discharging rates at RT and (b) at different temperatures at 1C.

4.3.4. Sample D

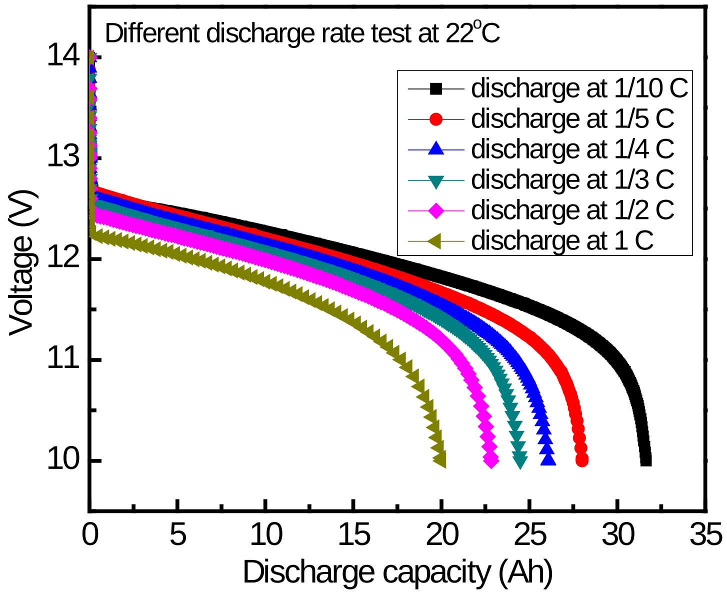

Figure 4-20. Discharge capacity vs. voltage of sample D at different discharge rates at 22°C.

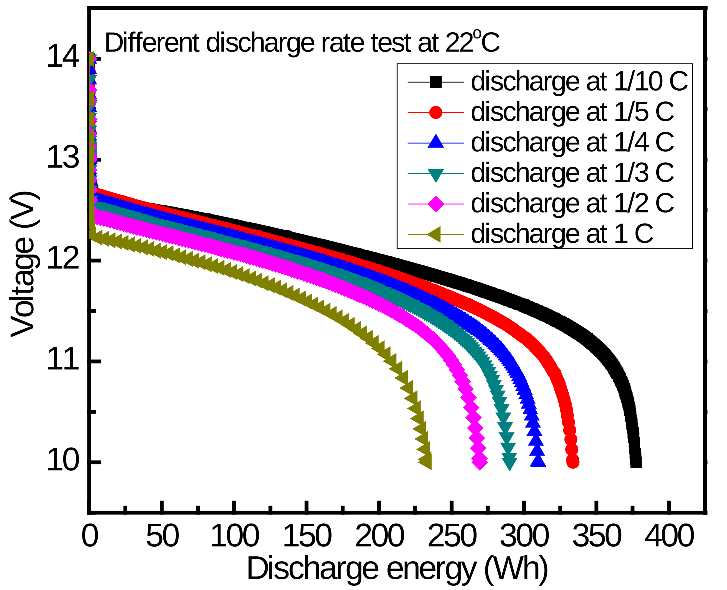

Figure 4-21. Discharge energy vs. voltage of sample D at different discharge rates at 22°C.

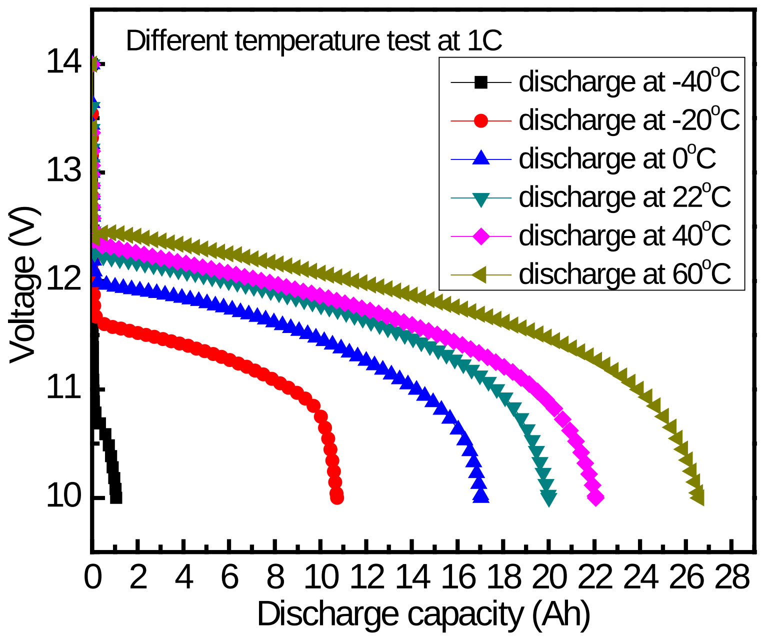

Figure 4-22. Discharge capacity vs. voltage of sample D test at different temperatures at 1C.

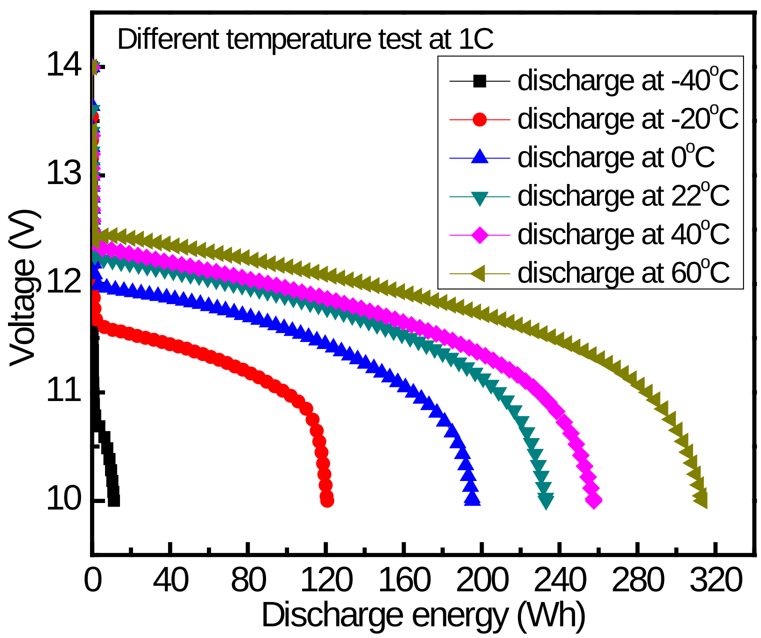

Figure 4-23. Discharge energy vs. voltage of sample D at different temperatures at 1C.

Table 4-8 Last test point of Sample D at different discharge rates at 22°C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
D-22-1/10C	51650.14901	9.9991	31.63441638	377.3656645
D-22-1/5C	22870.69505	9.9991	28.00701844	333.8834079
D-22-1/4C	17054.48313	9.9991	26.07992315	309.8711128
D-22-1/3C	12064.47526	9.9991	24.48208572	290.2458122
D-22-1/2C	7471.539117	9.9991	22.83524391	269.5124369
D-22-1C	3273.965891	9.9991	20.00891013	233.146242

Table 4-9 Last test point of Sample D at different temperatures at 1C

	Test time (s)	voltage (V)	Discharge capacity (Ah)	Discharge energy (Wh)
D-neg40-1C	173.7804196	9.9991	1.062084059	11.2602659
D-neg20-1C	1755.790046	9.9991	10.73081089	120.7604967
D-0-1C	2787.833192	9.9991	17.03831162	195.275491
D-22-1C	3273.965891	9.9991	20.00891013	233.146242
D-40-1C	3609.998387	9.9991	22.06252609	257.6121701
D-60-1C	4351.02971	9.9991	26.59331075	313.3704567

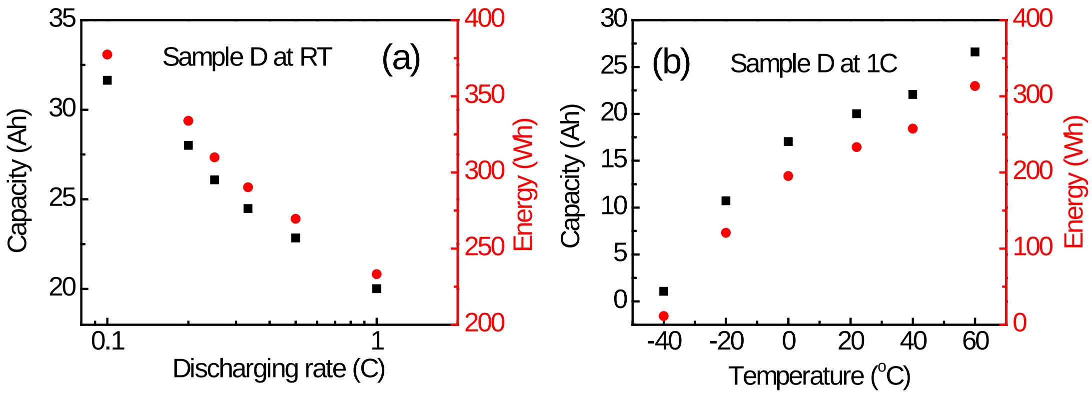

Figure 4-24. (a) Discharge capacity and energy of sample D (a) under different discharging rates at RT and (b) at different temperatures at 1C.

4.4. Summary

As it is shown in the test result part, samples show similar trend of performance at different temperatures and under different discharging rates. At the low temperature, the resistance is large and the electrochemistry reaction velocity is slow, the battery discharge capacity and discharge energy are small. At the high temperature, the discharge capacity and discharge energy are obviously larger than that in the low temperature.

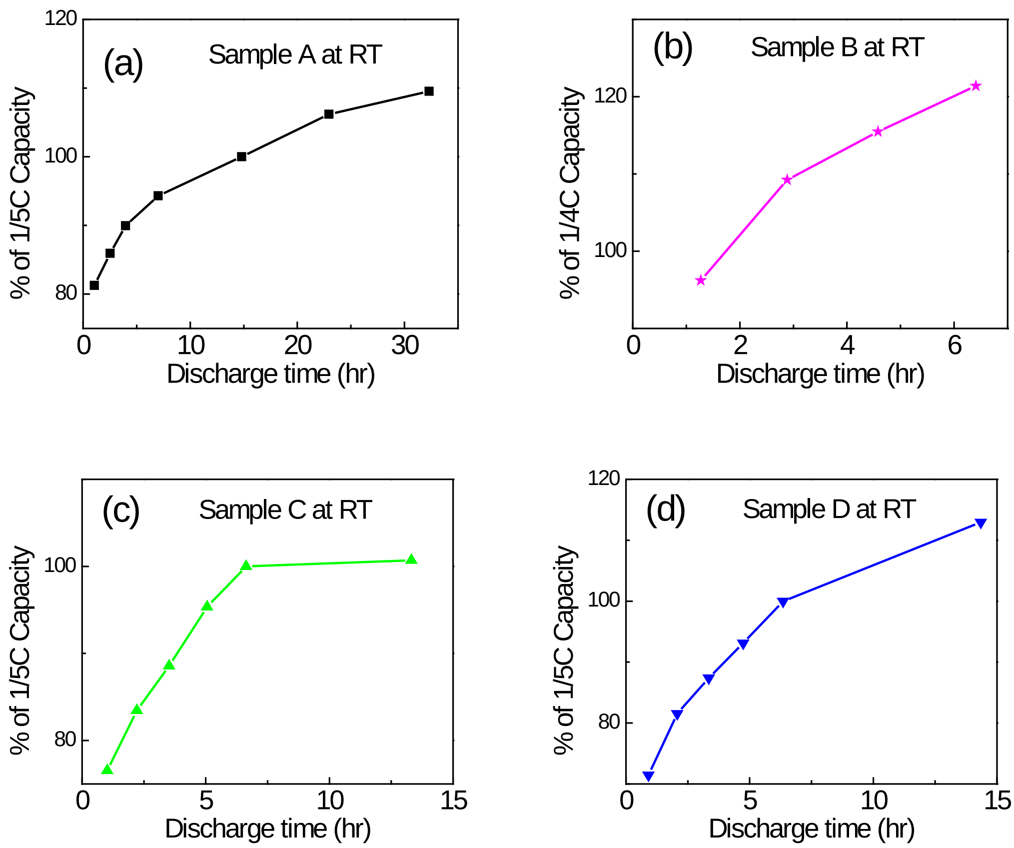

Figure 4-25. (a) Ratio of discharge capacity and (b) energy of samples at different discharging rates at room temperature.

At a given temperature, the discharge energy and discharge capacity also change with the discharge rate. As shown in tables in section 4.3, if the discharge rate is small, the discharge capacity is large, that is because the active materials react well when the discharge current is small. For example, the capacity at 1/3 C rate is only 90% of the capacity at the 1/5 C and the capacity at 1 C rate is only 81% of the capacity at the 1/5 C. The relationship between the discharge time and capacity is shown in **Figure 4-25**. The capacity of a battery at different discharge rates is shown as percentage of the certain discharge capacity.

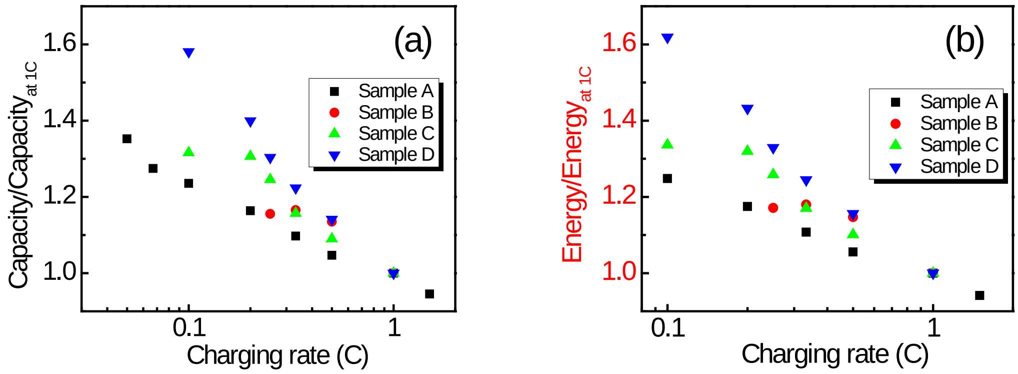

Figure 4-26. (a) Ratio of discharge capacity and (b) energy of samples at different discharging rates at room temperature.

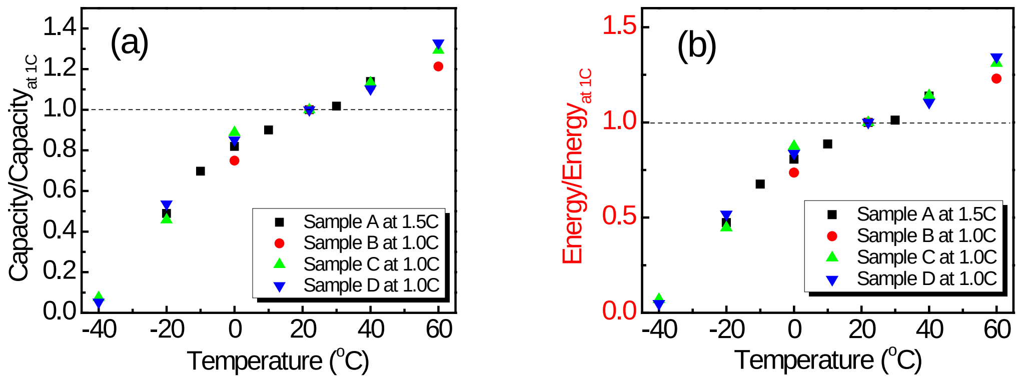

Figure 4-27. (a) Ratio of discharge capacity and (b) energy of samples at same discharging rates at different temperature.

Figure 4-26 shows the normalized discharge capacity and discharge energy of samples at different discharging rates at room temperature. The ratio is to compare the change of discharge capacity and discharge energy between different discharging rates with 1C. The results show that a lower discharging rate can obtain a higher capacity. The ratio of capacity/capacity$_{at1C}$ has the linear relationship with discharging rate in log-scale. **Figure 4-27** shows the normalized discharge capacity and discharge energy of samples at different temperatures with the same discharging rate. For temperature concern, sample D shows largest normalized parameters compared with other samples. It indicates sample D cannot show consistent performance over a broad temperature range.

In lead acid battery, the sulfuric acid solution as electrolyte may cause leakage issue during the performance of lead acid battery under extreme environment. For example, overcharging with high charging voltage may generate gas (H_2 and O_2) by electrolysis of water. Low temperature may cause electrolyte freezes so that the battery loses its function. The environment pressure change or placing the battery in vacuum would result in significant problems in the lead acid battery due to the leakage of liquid component. Although the vacuum chamber in our lab only can provide the pressure around 10^{-3} atm which is higher than NASA's requirement, it still can check the leakage issue of lead acid battery in different pressures. The only purpose of NASA's requirement on pressure is to make sure whether there is leakage occurs in lead acid battery at 10^{-6} atm or not, so there is no difference to test the battery under 10^{-6} atm and 10^{-3} atm. Thus, the pressure environment is provided by vacuum machine could reach the NASA's requirement and the test result is reliable for pressure issue.

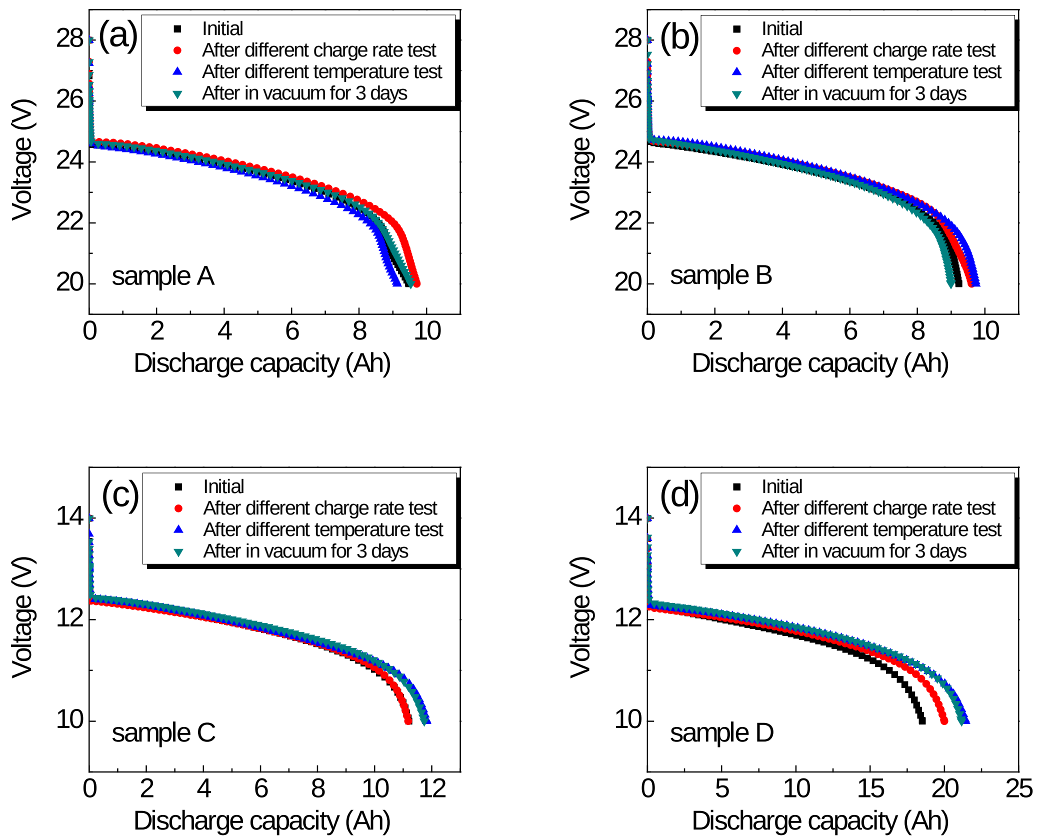

Figure 4-28. Discharge capacity vs. voltage of battery test at different conditions at 1C at 22°C (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D.

Figure 4-28 shows discharge capacity vs voltage of battery test at different conditions under a discharge rate of 1C at 22°C. There are four different curves can represent different conditions of test under a discharge rate of 1C at room temperature, including initial test, after different discharge rates test at room temperature, after different temperatures test, and test after put in vacuum for 3 days. For sample A, the curve shifts to low capacity after tested under different conditions then shifts back to initial position, which seems the sample A can be recovered by vacuum. For sample B, the curve shifts to high capacity after tested under different conditions then shifts back to initial position, which also seems the sample B can be recovered by vacuum. However, sample C and D do not show this trend.

As discussed in Chapter 1, a battery has a higher specific energy, but exhibits a lower specific power. Conversely, a capacitor, especially a dielectric capacitor, exhibits a higher output specific power, but has a smaller specific energy. The supercapacitors resolve the contradiction between high specific energy vs. high specific power output. Comparing supercapacitors and lead acid batteries used in this study, the most obvious difference is discharge time. The discharge time of three supercapacitors (sample A, B, and C) is in the range of 10s to 120s. The discharge time of supercapacitors sample D is in the range of 200s to 1600s. The time is less than 1/10 of that obtained on battery, which is in the range of 1000 to 20000s. For specific energy concern, the discharge specific energy of lead acid battery is around 15~35 Wh/kg which is larger than supercapacitors sample D of 5 Wh/kg.

CHAPTER 5

Conclusions and Future Work

5.1. Conclusions

In this research, two types of devices – supercapacitors and battery – are studied. In Chapter 2, the test system is built for the characterization of supercapacitor and battery. In Chapter 3 and 4, four selected different supercapacitors and four lead-acid batteries are tested under different charge/discharge rates at different temperatures. The parameters such as discharge capacity, discharge energy, and ESR of four supercapacitors are studied at -40^{o}C, -20^{o}C, 0^{o}C, 20^{o}C, 40^{o}C and 60^{o}C at different current rates. Sample D (PBM-1500 supercapacitor) shows much higher temperature stability than other supercapacitors. For supercapacitor, the specific energy is clearly much smaller than that of the battery.

The effects of temperature and charge/discharge rate can be explained by the materials inside. When temperature rising, the ionic mobility increases and the stability of the adsorption reaction decreases. The amount of charge on the adsorption of the same area reduces, which results capacity decreases. There are many driving factors for ion moving, such as by electrolyte medium or by proton flow. When the temperature increases, ionic conductivity of the electrolyte increases, the resistance decreases, which is confirmed from study in Chapter 3. In a word, temperature changes have effects on capacity and ESR of supercapacitor. Based on the test data from the experiments, the effect of temperature on the adsorption process is the main factor affecting the capacity for supercapacitor. The changes on resistance with temperature have relatively small impact on the capacity change.

For battery, the four samples show similar trend of performance at different temperatures and under different discharging rates. At the low temperature, the resistance is large and the electrochemistry reaction velocity is slow, the discharge capacity and discharge energy are small. At a given temperature, the discharge energy and discharge capacity also change with the discharge rate. If the discharge rate is small, the discharge capacity is large, that is because the active materials react well when the discharge current is small.

These studies on performance of supercapacitors and batteries at different temperatures and under different discharging rates cannot be directly obtained from the manufacturers. This work provides an opportunity to establish a solid and dynamic database of these devices for different aerospace applications.

5.2. Future Work

Based on the survey, more electrical energy storage devices from companies for aerospace applications will be selected. More experimental parameters will be characterized under different charge/discharge rates, at much broader temperature range, and under different pressures. Cycling test and lifetime in aerospace environment will be characterized in future.

Appendix 1

Table A1 Supercapacitors designed for aerospace applications

Product series	Company	Materials	Nominal Capacitance (F)	Tolerance capacitance	Rated voltage (V)	Current (A) (Maximum continuous)	Maximum peak current (A), 1 sec	Leakage current (mA)	Resistance, mΩ (ESR, DC)	Resistance, mΩ (ESR, AC)	Mass specific Energy (Wh/kg)	Mass (g)	Calculated mass specific energy (Wh/kg)	Volume specific Energy (Wh/kg)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating temp	Storage temp	Lifetime at 25 ℃ (years)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×T (mm)	Price (each)	Ref
PC10	Maxwell Technologies		10	-10%~20%	2.5	2.5	12.5	0.04	180	130	1.4	6.3	1.38		0.0034	2.55	-40°C to +70°C	-40°C to +85°C	10	500,000	29.6×23.6×4.8	$6.44	[1, 2]
PC10-90															0.0041	2.13					35.9×23.6×4.8	$6.55	
PC10-270															0.0041	2.13					35.9×23.6×4.8	$6.55	
PC10HT			10		2.2	2.5	12.5	0.04	180	130	1.1	6.3	1.07		0.0034	1.98	-40°C to +85°C	-40°C to +85°C	10	500,000	29.6×23.6×4.8	$6.90	
PC10HT-90															0.0041	1.65					35.9×23.6×4.8	$7.02	
PC10HT-270															0.0041	1.65					35.9×23.6×4.8	$7.02	
PBLL	Tecate		0.25	-10%~20%	5.4		0.36	0.08	3600	1400					0.0027	0.38	-40°C to +65°C	-40°C to +70°C	10	500,000	15.5×18×9.5	$4.75	[3, 4]
			0.5				0.79	0.08	1400	630					0.0027	0.76					15.5×18×9.5	$4.75	
			0.75				1.25	0.08	820	380					0.0030	1.02					17.5×18×9.5	$6.00	
			1				1.59	0.09	700	360					0.0033	1.21					19.5×18× 9.5	$6.75	
			1.65				2.28	0.18	580	300					0.0059	1.12					23.5×22×11.5	$7.50	
			2				2.7	0.19	500	300					0.0059	1.36					23.5×22× 11.5	$9.00	
			2.5				3.75	0.19	320	180					0.0059	1.70					23.5×22×11.5	$10.00	
			3				4.55	0.19	260	140					0.0059	2.04					23.5×22×11.5	$10.00	
			4				6	0.19	200	120					0.0072	2.25					28.5×22× 11.5	$10.50	
			5				7.3	0.2	170	120					0.0085	2.39					33.5×22× 11.5	$11.75	
			11				14.92	0.58	90	60					0.0135	3.30					38.5×26× 13.5	$15.00	
			15				19.76	0.62	70	50					0.0205	2.96					34.5×34×17.5	$19.00	

Table A1 Supercapacitors designed for aerospace applications (continued)

Product series	Company	Materials	Nominal Capacitance (F)	Tolerance capacitance	Rated voltage (V)	Current (A) (Maximum continuous)	Maximum peak current (A), 1 sec	Leakage current (mA)	Resistance, mΩ (ESR, DC)	Resistance, mΩ (ESR, AC)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Volume specific Energy (Wh/kg)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating temp	Storage temp	Lifetime at 25 ℃ (years)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×T (mm)	Price (each)	Ref
PBLL	Tecate		0.25	-10%~20%	5.4		0.35	0.08	3660	1460					0.0027	0.38	-40°C to +65°C	-40°C to +70°C	10	500,000	15.5×18× 9.5	$5.75	[5, 6]
			0.5				0.78	0.08	1460	690					0.0027	0.76					15.5×18×9.5	$5.75	
			0.75				1.2	0.08	880	440					0.0030	1.02					17.5×18×9.5	$7.00	
			1				1.5	0.09	760	425					0.0033	1.21					19.5×18×9.5	$7.75	
			1.65				2.1	0.18	645	365					0.0059	1.12					23.5×22×11.5	$8.50	
			2				2.5	0.19	565	365					0.0059	1.36					23.5×22×11.5	$10.00	
			2.5				3.4	0.19	385	245					0.0059	1.70					23.5×22×11.5	$11.00	
			3				4.1	0.19	325	205					0.0059	2.04					23.5×22×11.5	$11.00	
			4				5.2	0.19	265	185					0.0072	2.25					28.5×22×11.5	$11.50	
			5				6.2	0.2	235	185					0.0085	2.39					33.5×22×11.5	$12.75	
			11				10	0.58	160	130					0.0135	3.30					38.5×26×13.5	$16.00	
			15				13	0.62	135	115					0.0205	2.96					34.5×34×17.5	$20.00	
RS055105	Evans capacitor company	carbon-sulfuic acid double layer capacitor	1	± 20%	5.5			0.025	2000						0.0095	0.44	-55°C to 85 °C	-62°C to 95 °C			D=27.94, H=15.49	$400	[7-9]
RS100564			0.56		10																	$425	
RS110474			0.47		11			0.025	2000						0.0142	0.56					D=32.51, H=17.15	$425	
RES 160504			0.5		16																	$425	
RSS055105			1		5.5																	$425	

Table A1 Supercapacitors designed for aerospace applications (continued)

Product series	Company	Materials	Nominal Capacitance (F)	Tolerance capacitance	Rated voltage (V)	Current (A) (Maximum continuous)	Maximum peak current (A), 1 sec	Leakage current (mA)	Resistance, mΩ (ESR, DC)	Resistance, mΩ (ESR, AC)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Volume specific Energy (Wh/kg)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating temp	Storage temp	Lifetime at 25 ℃ (years)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×T (mm)	Price (each)	Ref
PBM-325/5.4, 1x2	Tecate		325	+20%/-0%	5.4			1.5	1.72	1.28	2.26	0.58	2.27		0.8291	1.59	-40°C to +65°C	-40°C to +70°C	10	1,000,000	127×64×102		[10, 11]
PBM-108/16.2, 1x6			108		16.2			1.5	5.4	4	2.28	1.72	2.29		2.4872	1.58					381×64×102		
PBM-108/16.2, 2x3			108		16.2			1.5	5.4	4	2.28	1.72	2.29		2.4613	1.60					190×127×102		
PBM-54/32.4, 3x4			54		32.4			1.5	10.92	8.08	2.19	3.59	2.19		4.9225	1.60					254×190×102		
PBM-54/32.4, 2x6			54		32.4			1.5	10.92	8.08	2.3	3.42	2.30		4.9355	1.60					381×127×102		
PBM-36/48.6, 3x6			36		48.6			1.5	16.44	12.16	2.19	5.38	2.20		7.3838	1.60					381×190×102		
PBM-36/48.6, 2x9			36		48.6			1.5	16.44	12.16	2.3	5.13	2.30		7.3838	1.60					570×127×102		
PBM-27/64.8, 4x6			27		64.8			1.5	21.96	16.24	2.31	6.81	2.31		9.8709	1.60					381×254×102		
PBM-27/64.8, 3x8			27		64.8			1.5	21.96	16.24	2.2	7.17	2.20		9.8063	1.61					506×190×102		
PBM-1500/5.4, 1x2			1500		5.4			5.2	0.7	0.53	4.75	1.28	4.75		1.5443	3.93					127×64×190	$298	
PBM-500/16.2, 1x6			500		16.2			5.2	2.34	1.7	4.77	3.82	4.77		4.6330	3.93					381×64×190	$799	
PBM-500/16.2, 2x3			500		16.2			5.2	2.34	1.7	4.77	3.82	4.77		4.5847	3.98					190×127×190	$799	
PBM-250/32.4, 3x4			250		32.4			5.2	4.8	3.45	4.68	7.79	4.68		9.1694	3.98					254×190×190	$1,482	
PBM-250/32.4, 2x6			250		32.4			5.2	4.8	3.45	4.68	7.79	4.68		9.1935	3.96					381×127×190	$1,482	
PBM-166/48.6, 3x6			166		48.6			5.2	7.26	5.2	4.64	11.73	4.64		13.7541	3.96					381×190×190	$1,950	
PBM-166/48.6, 2x9			166		48.6			5.2	7.26	5.2	4.64	11.73	4.64		13.7541	3.96					570×127×190	$1,950	
PBM-125/64.8, 4x6			125		64.8			5.2	9.72	6.96	4.69	15.53	4.69		18.3871	3.96					381×254×190	$2,930	
PBM-125/64.8, 3x8			125		64.8			5.2	9.72	6.96	4.69	15.53	4.69		18.2666	3.99					506×190×190	$2,930	

Table A1 Supercapacitors designed for aerospace applications (continued)

Product series	Company	Materials	Nominal Capacitance (F)	Tolerance capacitance	Rated voltage (V)	Current (A) (Maximum continuous)	Maximum peak current (A), 1 sec	Leakage current (mA)	Resistance, mΩ (ESR, DC)	Resistance, mΩ (ESR, AC)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Volume specific Energy (Wh/kg)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating temp	Storage temp	Lifetime at 25 ℃ (years)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×T (mm)	Price (each)	Ref
QynCap ultracapacitor	Qynergy Corporation	aqueous electrolyte			14						10						-55°C to 65°C			100,000	D=114.30, H=120.65		[12,13]
3-D Nanofilm™ ultracapacitor	Ionova Technologies	water-based electrolytes, mixed-oxide nanofilmcathode			2.5						4-6												[14,15]
10V - 1200V Series	United States Energy Co., Ltd.		0.2~ 500		10 – 1200																		[16]

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Appendix 2

Table A2 Battery for aerospace application

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
QL038KM			38	25.9	135	100			142			-25~85		247.65×206.38×134.62		[1]
QL015KA			15	3.6	15	142	0.38	142.11	295	0.1820	296.70	0~42	>100,000	88.3×54.5×38.0		[2]
QL075KA			72	3.6	72	142	1.82	142.42	330	0.7900	328.10	0~42	>100,000	173.7×80.9×56.2		[3]
QL1820			1.8	3.6		105	0.063	102.86	215	0.0302	214.57	10~30	>20,000	73×46×9.0		[4]
QLI250-18650	Quallion	Lithium ion	1.25	3.7	20	103	0.045	102.78	277	0.0167	276.95	-20~60		D=18.1, H=64.8		[5]
QLI1500-18650			1.5	3.7	19.5	116	0.046	120.65	332	0.0167	332.34	-20~60		D=18.1, H=64.8		[6]
QLI1900-18650			1.9	3.7	5.7	163	0.043	163.49	421	0.0167	420.96	-20~60		D=18.1, H=64.8		[7]
QL0045A			4.5	3.6	9		0.078	207.69	205	0.0373	434.55	-20~50		50×105×7.1		[9]
QL2300A			2.3	3.6		110	0.075	110.40	162	0.0507	163.29	-40~71		57×139.7×6.4		[10]

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
QL038KM	Quallion	Lithium ion	38	25.9	135	100			142			-25~85			247.65×206.38×134.62		[1]
QL015KA			15	3.6	15	142	0.38	142.11	295	0.1820	296.70	0~42		>100,000	88.3×54.5×38.0		[2]
QL075KA			72	3.6	72	142	1.82	142.42	330	0.7900	328.10	0~42		>100,000	173.7×80.9×56.2		[3]
QL1820			1.8	3.6		105	0.063	102.86	215	0.0302	214.57	10~30		>20,000	73×46×9.0		[4]
QLI250-18650			1.25	3.7	20	103	0.045	102.78	277	0.0167	276.95	-20~60			D=18.1, H=64.8		[5]
QLI1500-18650			1.5	3.7	19.5	116	0.046	120.65	332	0.0167	332.34	-20~60			D=18.1, H=64.8		[6]
QLI1900-18650			1.9	3.7	5.7	163	0.043	163.49	421	0.0167	420.96	-20~60			D=18.1, H=64.8		[7]
QL0032A			3.15	3.7	9	120	0.097	120.15	260	0.0444	262.50	-20~45			50×120×7.4		[8]
QL0045A			4.5	3.6	9		0.078	207.69	205	0.0373	434.55	-20~50			50×105×7.1		[9]
QL2300A			2.3	3.6		110	0.075	110.40	162	0.0507	163.29	-40~71			57×139.7×6.4		[10]

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
TLM-1520M	Tadiran Batteries	Li Metal Oxide	0.105	3.78	1		0.009	44.10		0.0034	115.41	-40~85	-55~85		D=14.8, H=20.0		[11]
TLM-1530M			0.19	3.83	2.5		0.011	66.15		0.0047	154.46	-40~85	-55~85		D=14.8, H=27.4		
TLM-1550M			0.425	3.88	4.3		0.02	82.45		0.0087	188.64	-40~85	-55~85		D=14.8, H=51.0		
NCSP-B53060 RM	HBL Power Systems Limited	Nickel Cadmium	53	24			44.5	28.58		22.1844	57.34				278×280×285		[12]
NCSP-B40060			40	24			36.5	26.30		16.1324	59.51				361×168×266		
NCSP-B40060A RM			40	24			36.5	26.30		16.1324	59.51				361×168×266		
NCSP-B40060B RM			40	24			36.5	26.30		16.1324	59.51				361×168×266		
NCSP-B30060 RM			30	24			24	30.00		12.1862	59.08				436×130×215		
NCSP-B25150 RM			25	24			25	24.00		12.2298	49.06				311×174×226		
NCSP-B25150AN RM			25	24			28	21.43		16.7688	35.78				411×170×240		

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
NCSP-B27060	HBL Power Systems Limited	Nickel Cadmium	27	24			28	23.14		11.9746	54.11				252.5×247×192		[12]
NCSP-B27060 MRM			27	24			22.5	28.80		11.2572	57.56				424×118×225		
NCSP-B23060			23	24			25	22.08		11.1893	49.33				253×197×224.5		
NCSP-B23060 LM			23	24			25.5	21.65		12.0468	45.82				253×248×192		
NCSP-B23060 RM			23	24			25	22.08		11.1893	49.33				253×197×224.5		
NCSP-B16060			16	24			18.2	21.10		9.6025	39.99				409×129×182		
NCSP-B18060-B			18	24			19.5	22.15		7.8383	55.11				247×193.5×164		
SS28300	HBL Power Systems Limited	Pure Lead-Tin, Valve Regulated Lead Acid Monobloc	28	21			26	22.62		14.9321	39.38	-40~50			D=366, H=142		[13]
SS10060			10	24			13	18.46		5.4956	43.67				187×186×158		[14]
SS18060			18	24			21	20.57		11.4758	37.64				325×165×214		
SS25060			25	24			27	22.22		11.5295	52.04				253×199×229		
SS42060			42	24			42	24.00		16.4364	61.33				252×248×263		

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
SBS J16	Hawker		16	12			6.8	28.24		2.3281	82.47	-4~60			177.8×77.8×168.3	$194	[15]
M3-17-2 P/N 32855-001	MarathonNorco	Nickel-Cadmium	17	24	770		17.5	23.31		8.3463	48.88				271.78×163.83×187.45		[16]
M3X-23-1P/N 32955-002			23	24	1300		27.2	20.29		11.8646	46.52				250.95×244.60×193.29		[17]
M3-25-1 P/N			25	24	1000		31.2	19.23		15.0888	39.76				548.13×120.02×229.36		[18]
M3-28-1 P/N			28	24	700		24.9	26.99		11.4781	58.55				254×198.12×228.09		[19]
M3-44-1 P/N			44	24	1375		36.3	29.09		16.1789	65.27				252.48×246.13×260.35		[20]
M3X-54-1 P/N 33183-001			54	24	1400		43.5	29.79		19.9281	65.03				277.62×247.90×289.56		[21]
7-75M3120 P/N 32364-001			75	8.4	1200		20.4	30.88		8.5205	73.94				199.39×165.10×258.83		[22]
TSP-1749L P/N 33283-001			17	24	800		17.5	23.31		7.5004	54.40				194.31×196.09×196.85		[23]
TSP-408L-1 P/N 32441-002			40	25.2	1200		34.7	29.05		17.0901	58.98				266.70×246.13×260.35		[24]

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
3PD0015	Electrochem	Li ion	15	3.9			0.1202	486.69				-20~93					[25]
3PD0757			30	3.9			0.22	531.82									
5100-102			1	5								-40~100					
RG-380E/40B	Concorde	Lead Acid	38	24			36.7	24.85		16.5761	55.02				260.50×243.80×261.00	$2,625	[26]
RG-380E/40K			38	24			38.1	23.94		17.9217	50.89				264.30×260.40×260.40	$3,170	
RG-380E/40KS			38	24			39	23.38		16.8893	54.00				264.30×245.40×260.40	$5,813	
RG-380E/40L			38	24			38.1	23.94		16.8893	54.00				264.30×245.40×260.40	$2,657	
RG-380E/44			42	24			39	25.85		16.5761	60.81				260.50×243.80×261.00	$2,180	
RG-380E/44K			42	24			40.4	24.95		16.6337	60.60				260.30×245.40×260.40	$5,309	
RG-380E/44KH			42	24			41.1	24.53		17.3239	58.19				264.3×249.7×262.5	$4,614	
RG-380E/44KS			42	24			41.3	24.41		16.6337	60.60				260.30×245.40×260.40	$3,339	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-380E/44KS	Concorde	Lead Acid	42	24			42	24.00		16.7667	60.12				249.7×262.5×255.8		[26]
RG-380E/44L			42	24			44.1	22.86		17.0683	59.06				267.10×245.40×260.40	$2,188	
RG-380E/44LH			42	24			41.1	24.53		17.3239	58.19				264.30×249.7×262.5	$4,840	
RG-380E/44LS			42	24			41.3	24.41		16.8893	59.68				264.30×245.40×260.40	$3,498	
RG-380E/44LSH			42	24			42	24.00		17.3239	58.19				264.30×249.70×262.50	$4,783	
RG-380E/46			46	24			39	28.31		16.5761	66.60				260.5×243.8×261.0	$2,368	
RG-380E/46L			46	24			40.4	27.33		16.8893	65.37				264.30×245.40×260.40	$2,697	
RG-380E/46LS			46	24			41.3	26.73		16.8893	65.37				264.30×245.40×260.40	$3,176	
RG-380E/46KS			46	24			41.3	26.73		16.8893	65.37				264.30×245.40×260.40	$2,824	
RG-380E/60B			48	24			43.6	26.42		17.0592	67.53				264.30×249.40×258.80	$4,623	
RG-380E/60K			48	24			43.6	26.42		16.8893	68.21				264.30×245.40×260.40	$3,254	
RG-380E/60KS			48	24			44.5	25.89		16.8893	68.21				264.30×245.40×260.40	$3,392	
RG-380E/60L			48	24			43.5	26.48		16.8893	68.21				264.30×245.40×260.40	$2,748	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-380E/60LS	Concorde	Lead Acid	48	24			44.5	25.89		16.8893	68.21				264.30×245.40×260.40	$3,923	[26]
RG-390E/25			25	24			24	25.00		11.4974	52.19				265.0×193.0×224.80	$2,296	
RG-390E/25L			25	24			24.9	24.10								$2,892	
RG-390E/25S			25	24			24	25.00		11.4974	52.19				265.0×193.0×224.80	$2,360	
RG-390E/25LS			25	24			25.9	23.17		11.5876	51.78				266.2×194.6×224.70	$2,728	
RG-390E			28	24			28.1	23.91		11.4974	58.45				265.00×193.00×224.80	$2,085	
RG-390E/L			28	24			28.1	23.91		14.9059	45.08				266.20×249.20×224.70	$3,087	
RG-390E/LS			28	24			29	23.17		14.9059	45.08				266.20×249.20×224.70	$3,413	
RG-390ES			28	24			28.1	23.91		12.9510	51.89				265.00×217.40×224.80	$2,518	
RG-365A			38	24						20.0267	45.54				207.20×362.00×267.00		
RG-365E			38	24						20.0267	45.54				207.20×362.00×267.00		
RG-385			13	24			15.4	20.26		6.4065	48.70				147.30×312.90×139.00	$2,986	
RG-400E/13			13	24			16.6	18.80		9.5742	32.59				205.10×248.30×188.00	$1,743	
RG-412-1			15	24			21.5	16.74		15.5781	23.11				292.10×300.90×177.30	$3,305	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-380E/60LS	Concorde	Lead Acid	48	24			44.5	25.89		16.8893	68.21				264.30×245.40×260.40	$3,923	[26]
RG-390E/25			25	24			24	25.00		11.4974	52.19				265.0×193.0×224.80	$2,296	
RG-390E/25L			25	24			24.9	24.10								$2,892	
RG-390E/25S			25	24			24	25.00		11.4974	52.19				265.0×193.0×224.80	$2,360	
RG-390E/25LS			25	24			25.9	23.17		11.5876	51.78				266.2×194.6×224.70	$2,728	
RG-390E			28	24			28.1	23.91		11.4974	58.45				265.00×193.00×224.80	$2,085	
RG-390E/L			28	24			28.1	23.91		14.9059	45.08				266.20×249.20×224.70	$3,087	
RG-390E/LS			28	24			29	23.17		14.9059	45.08				266.20×249.20×224.70	$3,413	
RG-390ES			28	24			28.1	23.91		12.9510	51.89				265.00×217.40×224.80	$2,518	
RG-365A			38	24						20.0267	45.54				207.20×362.00×267.00		
RG-365E			38	24						20.0267	45.54				207.20×362.00×267.00		
RG-385			13	24			15.4	20.26		6.4065	48.70				147.30×312.90×139.00	$2,986	
RG-400E/13			13	24			16.6	18.80		9.5742	32.59				205.10×248.30×188.00	$1,743	
RG-412-1			15	24			21.5	16.74		15.5781	23.11				292.10×300.90×177.30	$3,305	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-412-2	Concorde	Lead Acid	15	24			21.5	16.74		15.5781	23.11				292.10×300.90×177.30	$4,999	[26]
RG-441			24	44			39	27.08		18.4016	57.39				439.00×167.00×252.00	$5,691	
RG-442			24	44			39	27.08		18.4016	57.39				439.00×167.00×252.00	$6,352	
RG-443			11	24			12.2	21.64		7.6294	34.60				255.20×193.00×154.90	$2,478	
RG-445C			18	24			19.5	22.15		10.0843	42.84				316.00×197.60×161.50	$4,288	
RG-445E			18	24			19.5	22.15		9.3535	46.19				293.10×197.60×161.50	$4,302	
RG-900			22	24						14.8325	35.60				263.00×253.70×222.30		
RG-41				24			31.8	0.00		69.2190					406.4×406.4×419.1	$3,862	
RG-45			12	24			15.4	18.70		7.2447	39.75				305.00×122.40×194.70	$1,732	
RG-46			12	24			15.4	18.70		6.5509	43.96				312.90×160.80×130.20	$1,732	
RG-47			17	24			19.5	20.92		9.0715	44.98				331.90×122.40×223.30	$1,807	
RG-49			17	24			19.1	21.36		8.4899	48.06				344.10×189.50×130.20	$1,875	
RG-91			22	24			24.9	21.20		15.2453	34.63				508.00×135.10×222.30	$2,773	
RG12LSA			11	12			5.9	22.37								$208.95	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-119	Concorde	Lead Acid	22	24						11.9969	44.01				259.00×240.00×193.00		[26]
RG-132			6	24			6.6	21.82								$2,547	
RG-203			12	24			15	19.20		7.5977	37.91				286.70×147.80×179.30	$2,500	
RG-206			17	24			19.1	21.36		8.7435	46.66				286.20×147.80×206.70	$2,208	
RG-214			44	24						26.0431	40.55				430.90×295.40×204.60		
RG-222			17	24			19.5	20.92		8.8461	46.12				296.80×160.50×185.70	$2,470	
RG-224			24	24			23.1	24.94								$2,785	
RG-343			11	24			12.3	21.46		7.7896	33.89				272.70×161.20×177.20	$2,832	
RG-350			17	24			18.6	21.94		8.4914	48.05				308.20×133.10×207.00	$2,338	
RG-355			17	24			18.8	21.70		9.2030	44.33				365.10×123.20×204.60	$2,287	
RG-365B			38	24						22.8316	39.94				207.20×412.70×267.00		
RG-407			27	24			29.9	21.67		16.8078	38.55				294.10×300.00×190.50	$3,810	
RG-500			17	24			19.1	21.36		109.968	3.71				174.30×328.60×192.00	$2,897	
RG-600-1			17	24			19.1	21.36		10.4479	39.05				328.60×165.60×192.00	$3,227	

Table A2 Battery for aerospace application (continued)

Product series	Company	Materials	Normal capacity (Ah)	Normal voltage (V)	Continuous Discharge Current (A)	Mass specific Energy (Wh/kg)	Mass (kg)	Calculated mass specific energy (Wh/kg)	Calculated volume specific energy (Wh/l)	Volume (l)	Calculated volume specific energy (Wh/l)	Operating Discharge temp (℃)	Storage temp (℃)	Cycle life at 25 ℃ (cycles)	Dimensions L×W×H (mm)	Price (each)	Ref
RG-600-2	Concorde	Lead Acid	17	24			19.1	21.36		10.4479	39.05				328.60×165.60×192.00	$3,257	[26]
RG-25			22	12			10.3	25.63		4.4574	59.23				131.60×195.90×172.90	$198.75	
RG-25XC			24	12			10.7	26.92		4.4574	64.61				131.60×195.90×172.90	$229.95	
RG-35A			29	12			13.4	25.97		5.6564	61.52				131.30×248.30×173.50	$249.95	
RG-35AXC			33	12			14.5	27.31		5.6564	70.01				131.30×248.30×173.50	$268.95	
RG24- 9			8.5	24			10	20.40		6.1646	33.09				185.70×219.70×151.10	$398	
RG24-10			8.5	24			10	20.40		4.9688	41.06				184.80×186.20×144.40	$398	
RG24-11			11	24			12	22.00		6.1646	42.83				185.70×219.70×151.10	$443	
RG24-11M			11	24			12	22.00		6.9683	37.89				185.70×219.70×170.80	$471	
RG24-12			11	24			12	22.00		4.9688	53.13				184.80×186.20×144.40		
RG24-15			13.6	24			13.4	24.36		6.1646	52.95				185.70×219.70×151.10	$598	
RG24-15M			13.6	24			13.4	24.36		6.9683	46.84				185.70×219.70×170.80	$498	
RG24-16			13.6	24			13.4	24.36		4.9688	65.69				184.80×186.20×144.40	$498	
RG24-17			13.6	24			7.7	42.39		17.8455	18.29				279.4×228.6×279.4	$876	

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