ULTRACAPACITOR
Product Guide

Maxwell TECHNOLOGIES

BOOSTCAP ULTRACAPACITORS

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1 Description of Double Layer Capacitors

1.1 Theory

Electrochemical double layer capacitors (EDLCs) are similarly known as supercapacitors or ultracapacitors. An ultracapacitor stores energy electrostatically by polarizing an electrolytic solution. Though it is an electrochemical device there are no chemical reactions involved in its energy storage mechanism. This mechanism is highly reversible, allowing the ultracapacitor to be charged and discharged hundreds of thousands to even millions of times.

An ultracapacitor can be viewed as two non-reactive porous plates suspended within an electrolyte with an applied voltage across the plates. The applied potential on the positive plate attracts the negative ions in the electrolyte, while the potential on the negative plate attracts the positive ions. This effectively creates two layers of capacitive storage, one where the charges are separated at the positive plate, and another at the negative plate.

Conventional electrolytic capacitors storage area is derived from thin plates of flat, conductive material. High capacitance is achieved by winding great lengths of material. Further increases are possible through texturing on its surface, increasing its surface area. A conventional capacitor separates its charged plates with a dielectric material: plastic, paper or ceramic films. The thinner the dielectric the more area can be created within a specified volume. The limitations of the thickness of the dielectric define the surface area achievable.

An ultracapacitor derives its area from a porous carbon-based electrode material. The porous structure of this material allows its surface area to approach 2000 square meters per gram, much greater than can be accomplished using flat or textured films and plates. An ultracapacitors charge separation distance is determined by the size of the ions in the electrolyte, which are attracted to the charged electrode. This charge separation (less than 10 angstroms) is much smaller than can be accomplished using conventional dielectric materials.

The combination of enormous surface area and extremely small charge separation gives the ultracapacitor its outstanding capacitance relative to conventional capacitors.

1.2 Construction

The specifics of ultracapacitor construction are dependent on the application and use of the ultracapacitor. The materials may differ slightly from manufacturer or due to specific application needs. The commonality among all ultracapacitors is that they consist of a positive electrode, a negative electrode, a separator between these two electrodes, and an electrolyte filling the porosities of the two electrodes and separator.

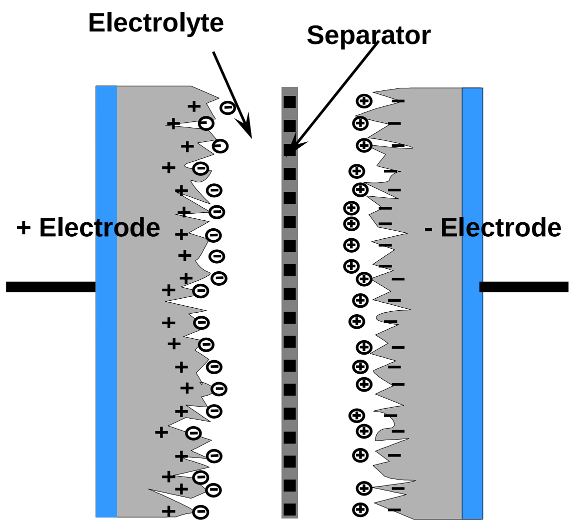

Figure 1: Ultracapacitor charge separation

The assembly of the ultracapacitors can vary from product to product. This is due in part to the geometry of the ultracapacitor packaging. For products having a prismatic or square packaging arrangement, the internal construction is based upon a stacking assembly arrangement with internal collector paddles extruding from each electrode stack. These current collector paddles are then welded to the terminals to enable a current path outside the capacitor.

For products with round or cylindrical packaging, the electrodes are wound into a jellyroll configuration. The electrodes have foil extensions that are then welded to the terminals to enable a current path outside the capacitor.

2 Typical Applications

Maxwell Boostcap® ultracapacitors products are offered in a full range of sizes. This enables utilization of ultracapacitors in a variety of industries for many power requirement needs. These applications span from milliamps current or milliwatt power to several hundred amps current or several hundred kilowatts power needs. Industries employing ultracapacitors have included: consumer electronics, traction, automotive, and industrial. Examples within each industry are numerous.

Consumer – digital cameras, lap top computers, PDA's, GPS, hand held devices, toys, flashlights, solar accent lighting, and restaurant paging devices.

Traction – Diesel engine starting, train tilting, security door opening, tram power supply, voltage drop compensation.

Automotive – 42 V vehicle supply networks, power steering, electromagnetic valve controls, starter generators, electrical door opening, regenerative braking, hybrid electric drive, active seat belt restraints.

Industrial – uninterrupted power supply (UPS), wind mill pitch systems, power transient buffering, automated meter reading (AMR), elevator micro-controller power backup, security doors, forklifts, cranes, and telecommunications.

Consideration for the various industries listed, and for many others, is typically attributed to the specific needs of the application the ultracapacitor technology can satisfy. Applications ideally suited for ultracapacitors include pulse power, bridge power, main power and memory backup.

2.1 Pulse Power

Ultracapacitors are ideally suited for pulse power applications. As mentioned in the theory section, due to the fact the energy storage is not a chemical reaction, the charge/discharge behavior of the capacitors is efficient.

Since ultracapacitors have low internal impedance they are capable of delivering high currents and are often times placed in parallel with batteries to load level the batteries, extending battery life. The ultracapacitor buffers the battery from seeing the high peak currents experienced in the application. This methodology is employed for devices such as digital cameras, hybrid drive systems and regenerative braking (for energy recapture).

2.2 Bridge Power

Ultracapacitors are utilized as temporary energy sources in many applications where immediate power availability may be difficult. This includes UPS systems utilizing generators, fuel cells or flywheels as the main power backup. All of these systems require short start up times enabling momentary power interruptions. Ultracapacitor systems are sized to provide the appropriate amount of ride through time until the primary backup power source becomes available.

2.3 Main Power

For applications requiring power for only short periods of time or is acceptable to allow short charging time before use, ultracapacitors can be used as the primary power source. Examples of this utilization include toys, emergency flashlights, restaurant paging devices, solar charged accent lighting, and emergency door power.

2.4 Memory Backup

When an application has an available power source to keep the ultracapacitors trickle charged they may be suited for memory backup, system shutdown operations, or event notification. The ultracapacitors can be maintained at its full charged state and act as a power reserve to perform critical functions in the event of power loss. This may include AMR for reporting power outage, micro-controllers and board memory.

3 Determining the correct Ultracapacitor for the application

Determination of the proper capacitor and number of capacitors is dependant on the intended application. For sizing the system correctly a number of factors should be known. These factors include the maximum and minimum operating voltage of the application, the average current or power, the peak current or power, the operating environment temperature, the run time required for the application, and the required life of the application. All of these issues will be covered in detail in the "Performance Characteristics" section of this guide. For now, a general approach is described.

Each of the products has a rated voltage (V_R). Since ultracapacitors are low voltage devices, this rated voltage is generally less than the application voltage required. Knowing the maximum application voltage (V_{max}) will determine how many capacitor cells are required to be series connected. The number of series connected cells is determined by:

$$\text{\# series cells} = \frac{V_{\max}}{V_R}$$

Next, by knowing the average current (I) in amps, the required run time (dt) in seconds and the minimum working voltage (V_{min}), an approximate system capacitance can be calculated.

$$C_{sys} = I \bullet \frac{dt}{dV} = I \bullet \frac{dt}{(V_{\max} - V_{\min})}$$

The total system capacitance is comprised of the capacitance of all the series connected capacitors for achieving V_{max}. For capacitors connected in series the capacitance of the individual cells is determined by:

$$\frac{1}{Csys} = \frac{1}{C1} + \frac{1}{C2} + \ldots + \frac{1}{Cn} \qquad [3]$$

where n = # series connected capacitors.

For C1=C2=…=Cn and rearranging equation 3, the cell capacitance (C) is determined by:

$$C = C_{sys} \bullet n$$

This capacitance value can then be compared to the product data sheets to determine the appropriate capacitor for the application. If the capacitance calculated is not achievable by a single capacitor it will be necessary to place one or more capacitors in parallel to obtain the necessary energy. For capacitors connected in parallel the capacitance is determined by:

$$C = C1 + C2 + \ldots + C_n$$

Therefore, take the calculated capacitance and divide by the capacitance available from the data sheet and round up to the next whole number. This will be the number of capacitors required in parallel.

There are many other items to consider for properly sizing the application. This includes the internal resistance of the capacitor to account for the instantaneous voltage drop associated with an applied current, the ambient operating temperature which affects the internal resistance and the capacitor life, and the life of the application. The ultracapacitor performance requirement at end of life of the application is necessary to ensure proper initial sizing of the system. Additional tools, application notes and white papers are available at our website to aid in the sizing process. It is recommended to contact Maxwell Technologies for assistance in sizing the application properly.

4 Specifications

Product datasheets are available for each product. These datasheets are accessible at the Maxwell Technologies website, www.maxwell.com. This section will provide a definition for the specifications and the methods of measuring said conditions.

4.1 Specification Description

Capacitance – a measurement of energy storage in joules. C = qV

Voltage – the voltage provided in the specification is the maximum operating voltage for a single capacitor. The rated voltage is the voltage in which the performance data is measured. It is possible for the capacitors to experience voltages in excess of the rated voltage. The impact is dependent on the time and temperature during this exposure. At no time should the capacitor be subjected to voltages in excess of 10% of the rated voltage.

Internal Resistance, DC – the resistance corresponding to all the resistive components within the ultracapacitor, R_{tot}. This measurement is taken after 5 seconds. Since the time constant of the ultracapacitors is approximately 1 second, it takes approximately 5 time constants or 5 seconds to effectively remove 99.7% of the stored energy. R_{tot} is compromised of resistive components attributed to contact, electrode, electrolyte, and other material resistances.

Internal resistance, 100 hz or 1 khz – is a measure of the high frequency resistance component and is mainly attributed to contact resistance. Because of the time constant of the ultracapacitors, operation at this frequency is highly inefficient. This measurement is provided because it is simple to measure and correlates easily with the DC resistance.

Thermal Resistance – rather than a rated current the thermal resistance may be used to determine the heat generation within the product at any given current load and duty cycle. The calculation is based on free convection and would be considered worst case. Forced convection would improve the thermal resistance.

Short Circuit Current – momentary current possible in device if ultracapacitor is short circuited. Intended as a cautionary statement and not intended for ultracapacitor use.

Leakage Current – stable parasitic current expected when capacitor is held indefinitely on charge at the rated voltage. This value is voltage and temperature dependent. Data sheet measurement is at rated voltage and 25 ^{o}C.

Operating Temperature Range – represents the operating temperature range of the ultracapacitor and may not reflect the ambient temperature.

Storage Temperature Range – represents the safe storage temperature without affecting ultracapacitor performance when no voltage is applied to the ultracapacitor.

Endurance, Capacitance – the maximum capacitance change expected if the ultracapacitor is held at rated voltage for the specified time and temperature which is intended to be the upper operational limits.

Endurance, Resistance - the maximum resistance change expected if the ultracapacitor is held at rated voltage for the specified time and temperature which is intended to be the upper operational limits.

Maximum Energy – the maximum energy available for new ultracapacitor when discharged from maximum working voltage to zero volts (note: for discharge to half voltage the energy is approximately 75% of maximum)

Peak Power Density – measurement of an instantaneous power from full rated voltage according to $V^2/4R$ where R = ac resistance. This value does not represent the sustainable power.

Power, Pd – gravimetric power density calculated between the ranges of a 20% to 40% voltage drop from the rated voltage.

Life Time – expected performance change for the ultracapacitor if held at rated voltage and 25 ^{o}C for 10 years.

Cycle Life – expected performance change after cycling 500k or 1M times (as specified on the data sheet) from rated voltage to half voltage. Cycling performed at a duty cycle resulting in no heating of the ultracapacitor with the ultracapacitor maintained at 25^{o}C.

4.2 Measurement Conditions

The methods utilized for obtaining the data specified on the data sheets are outlined. Alternative methods are possible but may result in slightly different results.

4.2.1 Capacitance

Capacitance is measured during discharge of the ultracapacitor with a constant current source from its rated voltage to half its rated voltage. Referring to figure 2, capacitance is calculated from the following:

$$C = \frac{I_d \bullet t_d}{V_w - V_f}$$

4.2.2 Resistance

Referring again to figure 2 the dc resistance, or ESR, is calculated from the following:

$$ESR = \frac{V_f - V_{\min}}{I_d}$$

The resistance measurement considers all resistive components over approximately five time constants of the product and is inclusive of all resistive elements. The actual resistance measured would be lower if measured over a shorter duration than the 5 seconds indicated.

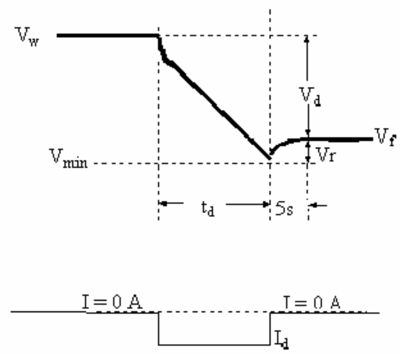

Figure 2: Testing profile

4.2.3 Leakage Current

Due to the extremely large surface area of the electrode the time constant of the last 0.5% of the electrode area is extremely long due to the pore size and geometry. The longer the ultracapacitor is held on charge the lower the leakage current of the device. The reported leakage current is a measurement of the charging current after holding the device at rated voltage for 72 hours continuous at room temperature. The measured leakage current will be influenced by the temperature during the measurement, the voltage in which the device is measured and the age of the product.

5 Performance Characteristics

This section describes the behavior of ultracapacitors under operating conditions such as temperature, dc charging, cycling and frequency. The data is represented in product specific format where applicable.

5.1 Temperature Effects, Initial Performance

The performance of Maxwell Technologies ultracapacitors is very stable over a wide operating temperature due to the chemistry and physical make up of the products. This behavior is common between all of the products lines due to the similar chemistry and construction. The following plot in figure 3 illustrates the relative capacitance and resistance change as a function of temperature between the operating temperature ranges of –40 to 65 ^{o}C.

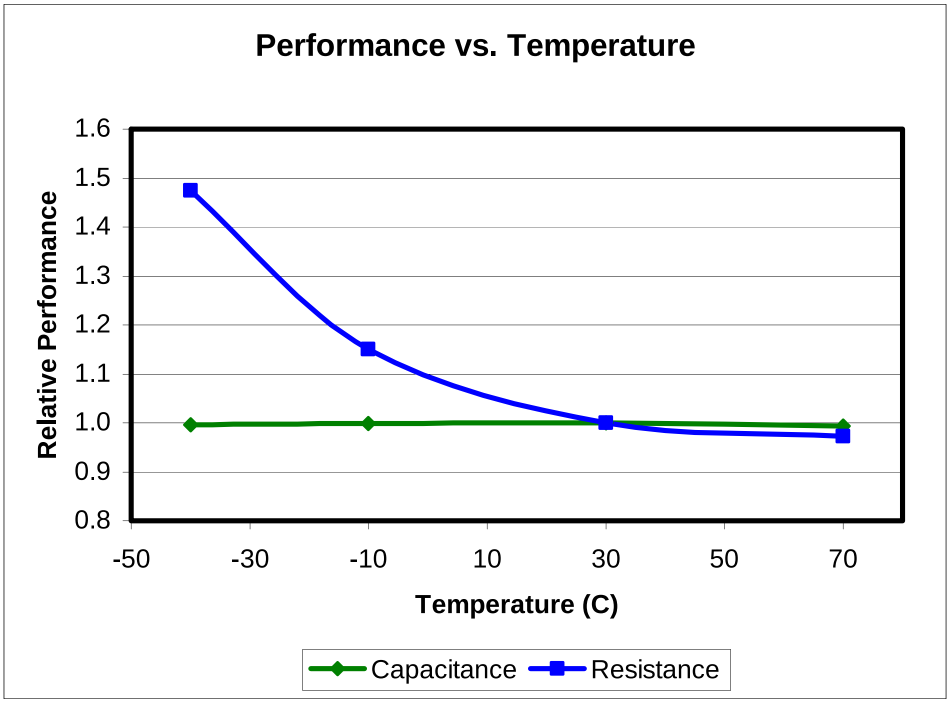

Figure 3: Relative ultracapacitor performance over operating temperature range

5.2 Voltage and Temperature Effects on Life

A common utilization of the ultracapacitors such as UPS applications is to maintain the ultracapacitors at working voltage until needed for the application. The following figures illustrate the influence of voltage on performance of the products when held at rated voltage and a lower voltage at its maximum rated environmental temperature. More detailed information related to product life is contained in the design section 7.3 of this manual.

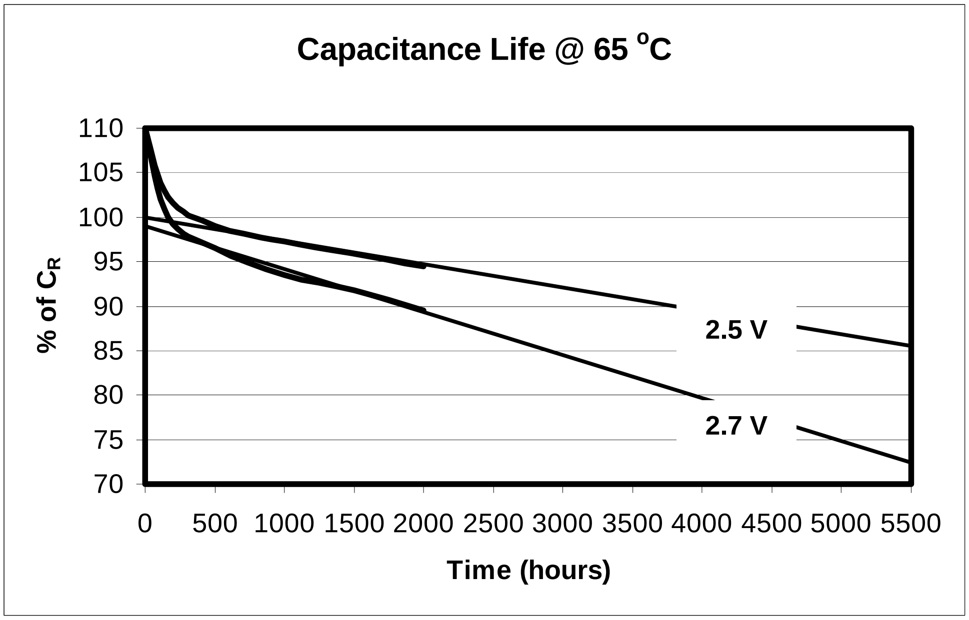

Figure 4: BCAP2600 Capacitance degradation at 2.7 V and 2.5 V at 65°C

Figure 4 represents the expected capacitance degradation relative to the product specification. The plot, along with the fact that the influence of temperature has a doubling effect for every 10 °C, can be used to predict the expected performance change for a variety of conditions. From this plot it is expected that a:

30% reduction in rated capacitance may occur for an ultracapacitor held at 2.7 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

15% reduction in rated capacitance may occur for an ultracapacitor held at 2.5 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

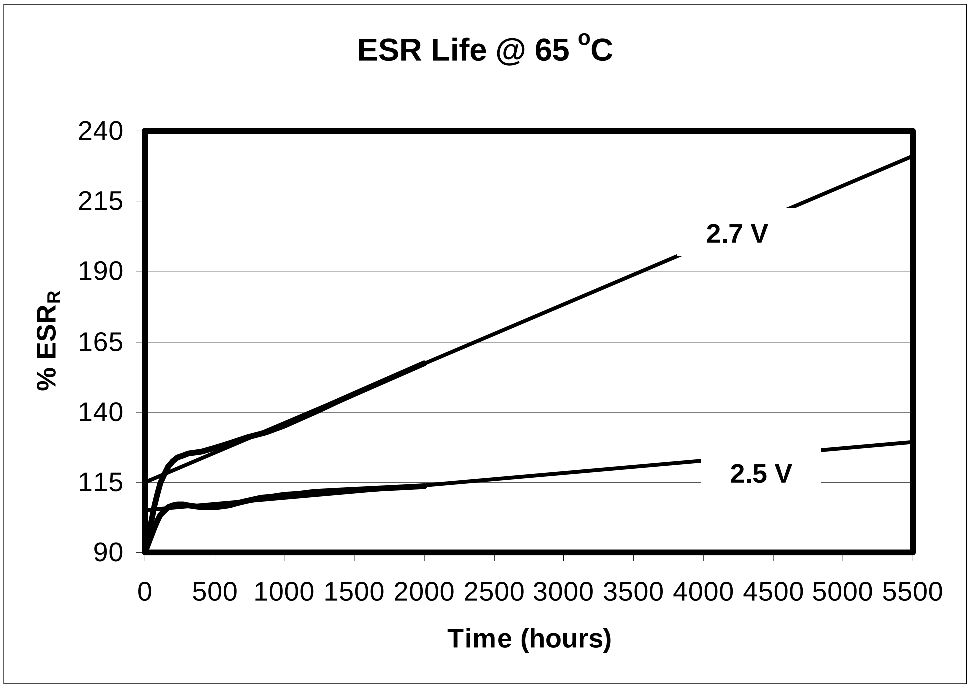

Figure 5: BCAP2600 Resistance degradation at 2.7 V and 2.5 V at 65°C

Figure 5 represents the expected resistance degradation relative to the product specification. The plot, along with the fact that the influence of temperature has a doubling effect for every 10 °C, can be used to predict the expected performance change for a variety of conditions. From this plot it is expected that a:

140% increase in rated resistance may occur for an ultracapacitor held at 2.7 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

40% increase in rated resistance may occur for an ultracapacitor held at 2.5 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

5.3 Cycling

Cycle testing is performed on the products to determine the degradation of ultracapacitor performance over cycling events. The cycle testing is performed at ambient temperature with no forced convective cooling. The cycles are performed at a continuous current as indicated on the data sheet from the rated voltage to half rated voltage. A 15 second rest is allowed between each charge/discharge cycle. The resulting duty cycle for this test is initially 70% reducing to approximately 50% at the product ages. The data provided is a combination of data points and extrapolation for the BCAP2600 product.

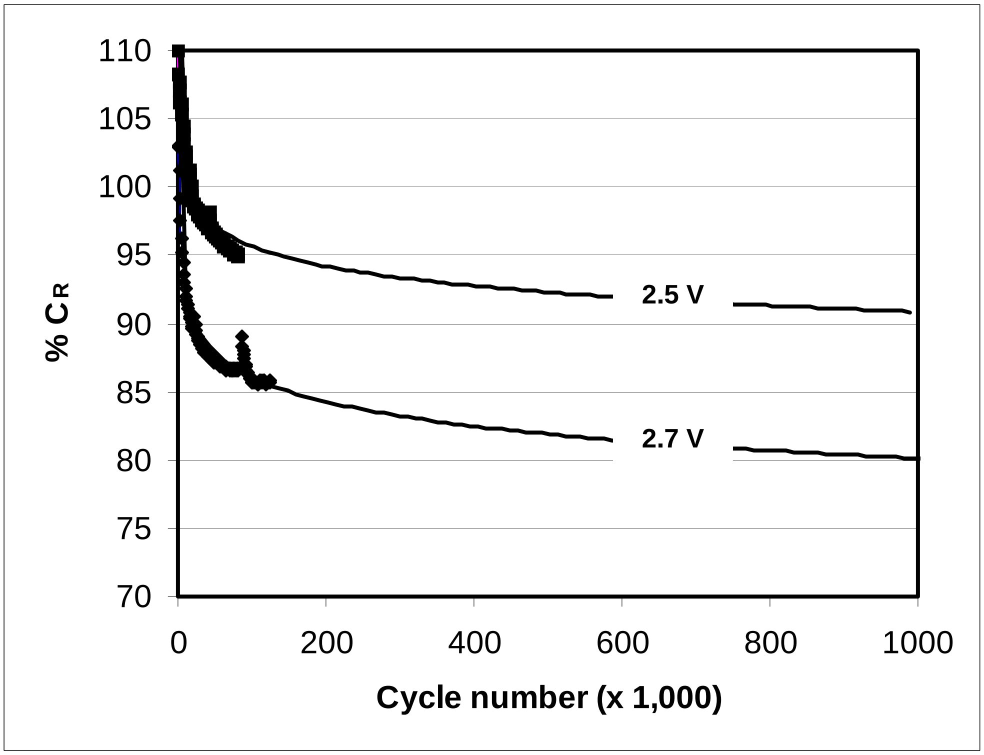

Figure 6: Capacitance change vs. continuos cycling

From Figure 6 it is seen that under the conditions described the product is expected to provide in excess of 1 million duty cycles with an approximate 20% reduction in rated capacitance. Notice in the 2.7 V cycle data the capacitance recovery during a stoppage in testing. This characteristic is normal when the ultracapacitor is allowed to rest. For most applications a rest period is allowed thus the figure illustrates a worst-case application. Similar life improvements illustrated previously for DC charging are evident for lower voltage cycling.

5.4 Frequency Response

Ultracapacitors have a typical time constant of approximately one second. One time constant reflects the time necessary to charge a capacitor 63.2% of full charge or discharge to 36.8% of full charge. This relationship is illustrated in the following figure.

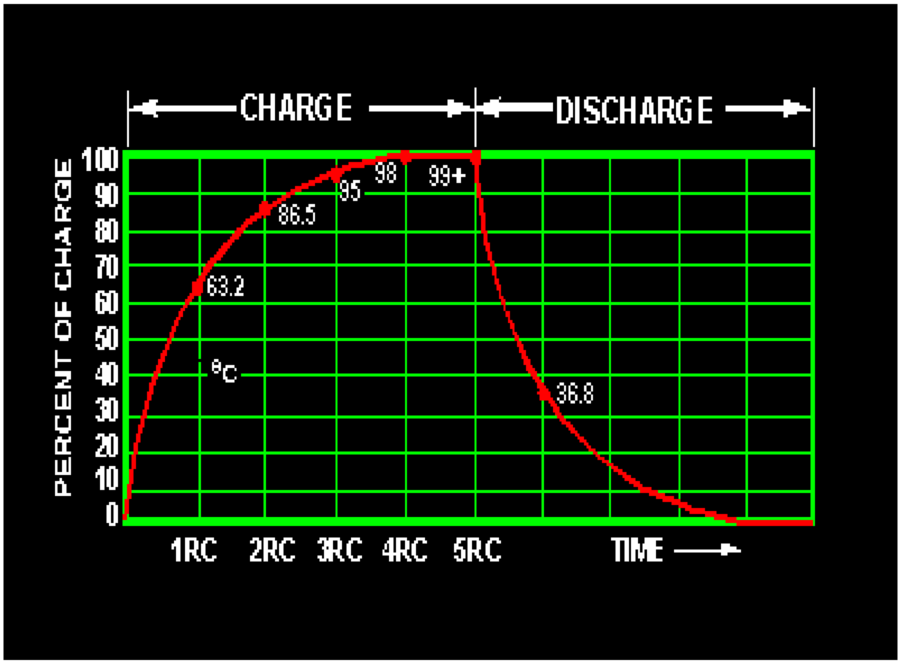

Figure 7: RC time constant relationship

The time constant of an ultracapacitor is much higher than that of an electrolytic capacitor. Therefore, it is not possible to expose ultracapacitors to a continuous ripple current as overheating may result. The ultracapacitor can respond to short pulse power demands, but due to the time constant the efficiency or available energy is reduced. The following figures illustrate the performance of the ultracapacitors at various frequencies. The drop off in capacitance is associated with response time necessary for the charged ions within the pores of the electrode to shuttle between positive and negative during charge and discharge. The drop in resistance is representative of the response time of the different resistive elements within the ultracapacitor. At low frequency all resistive elements are present where at high frequency only quick response elements such as contact resistance are present.

The test is typically conducted with no applied voltage. For this reason the capacitance appears to be much lower than what is stated at rated voltage as capacitance has a slight dependence on voltage.

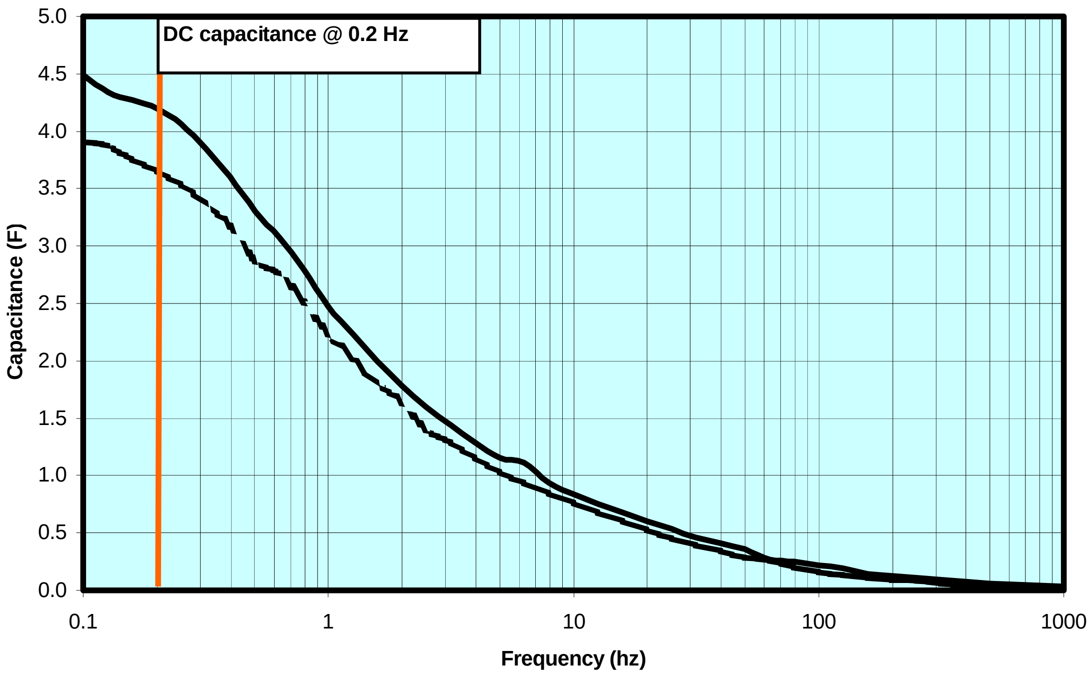

Figure 8: PC5 Capacitance vs. Frequency Response, 95% Confidence

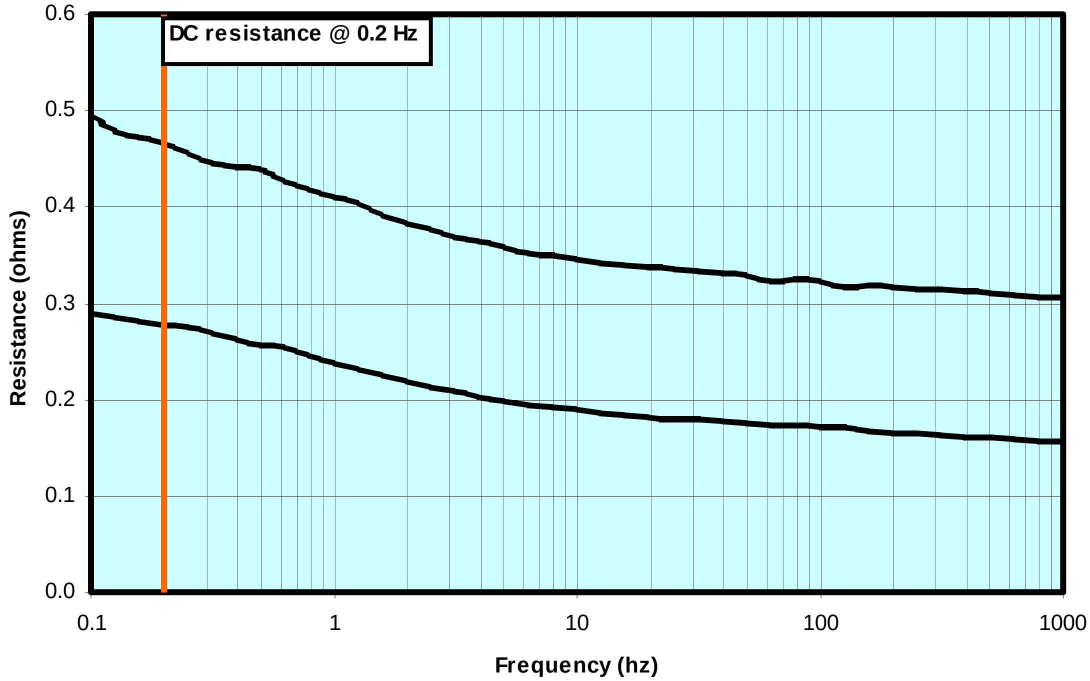

Figure 9: PC5 Resistance vs. Frequency Response, 95% Confidence

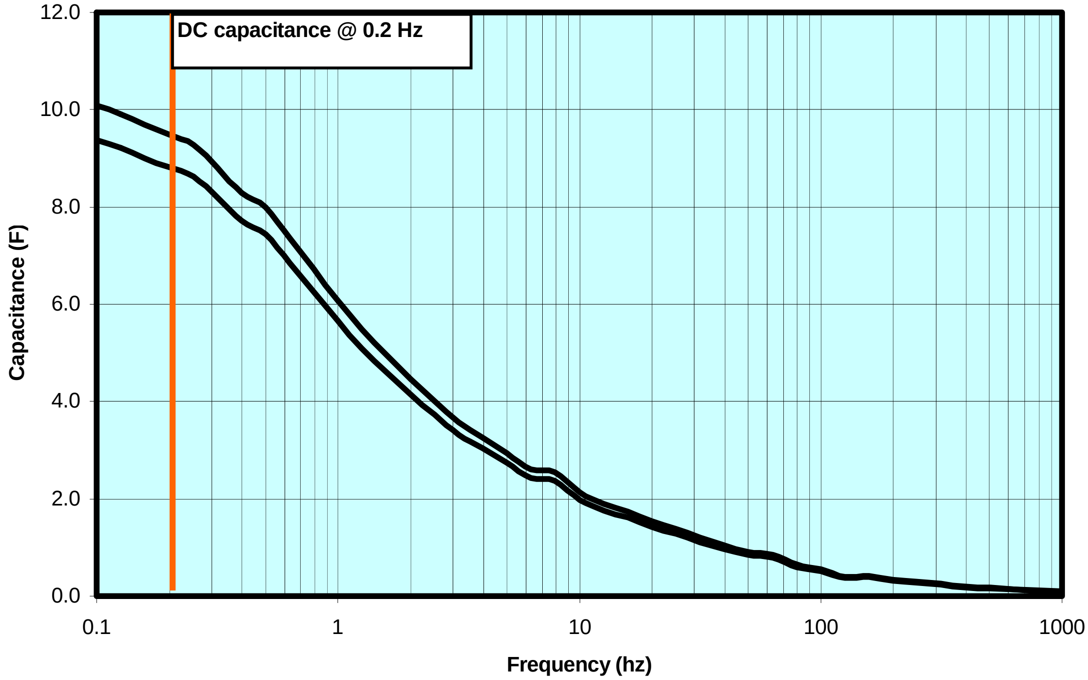

Figure 10: PC10 Capacitance vs. Frequency Response, 95% Confidence

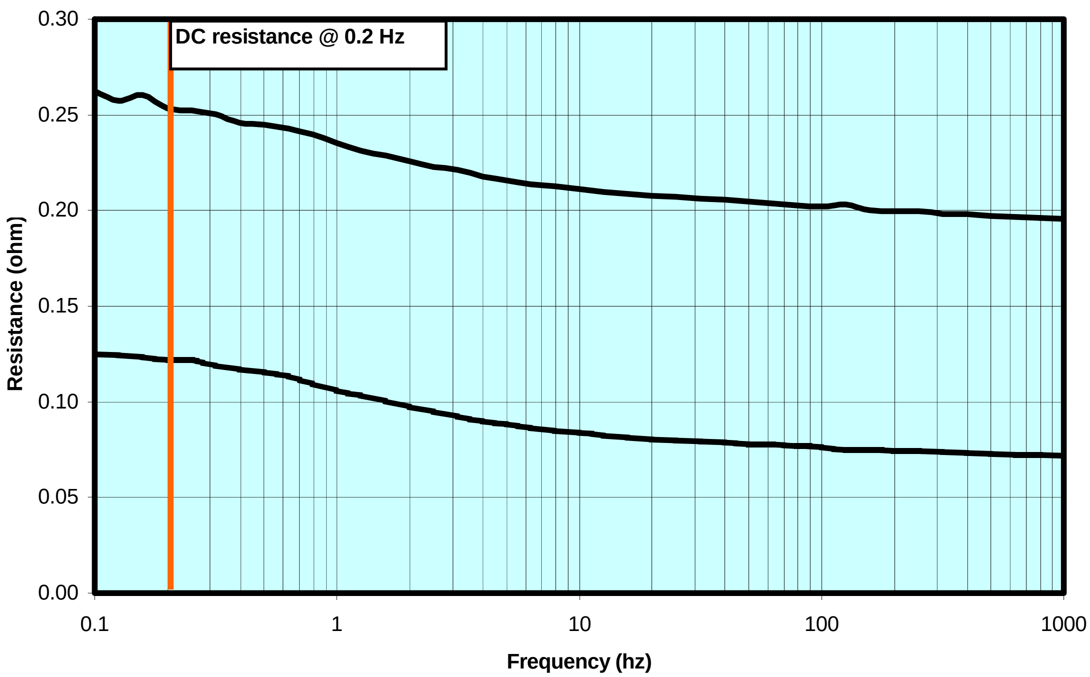

Figure 11: PC10 Resistance vs. Frequency Response, 95% Confidence

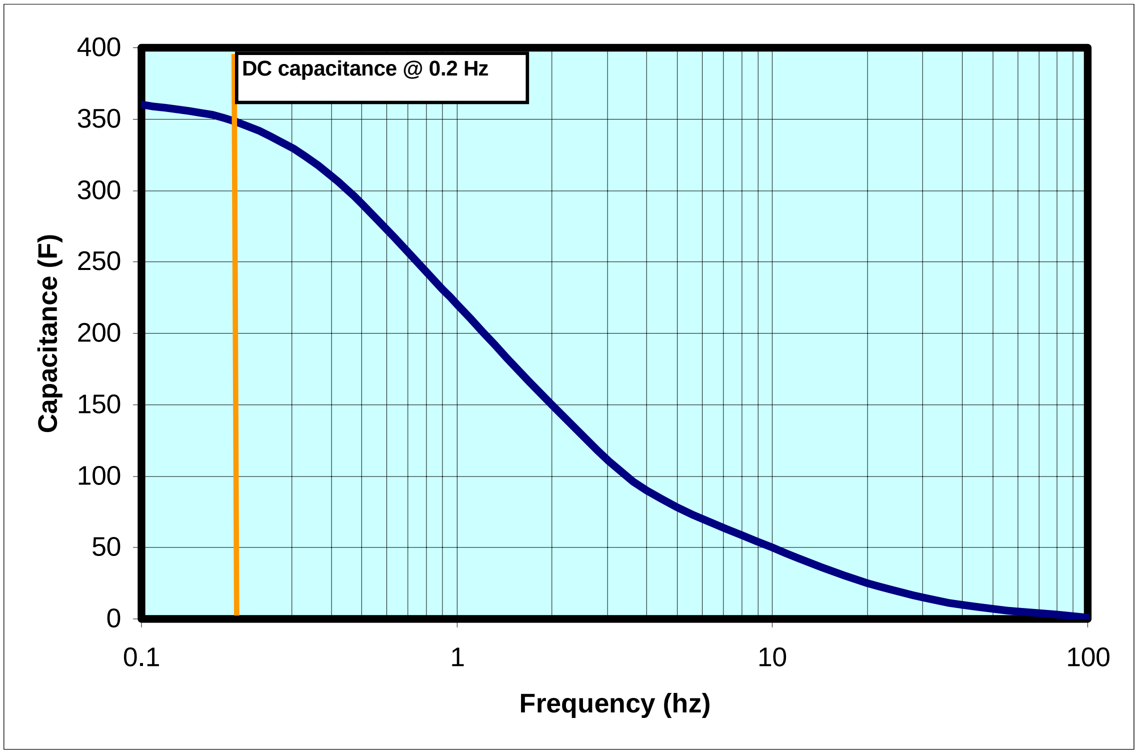

Figure 12: BCAP0350-E Capacitance Frequency Response

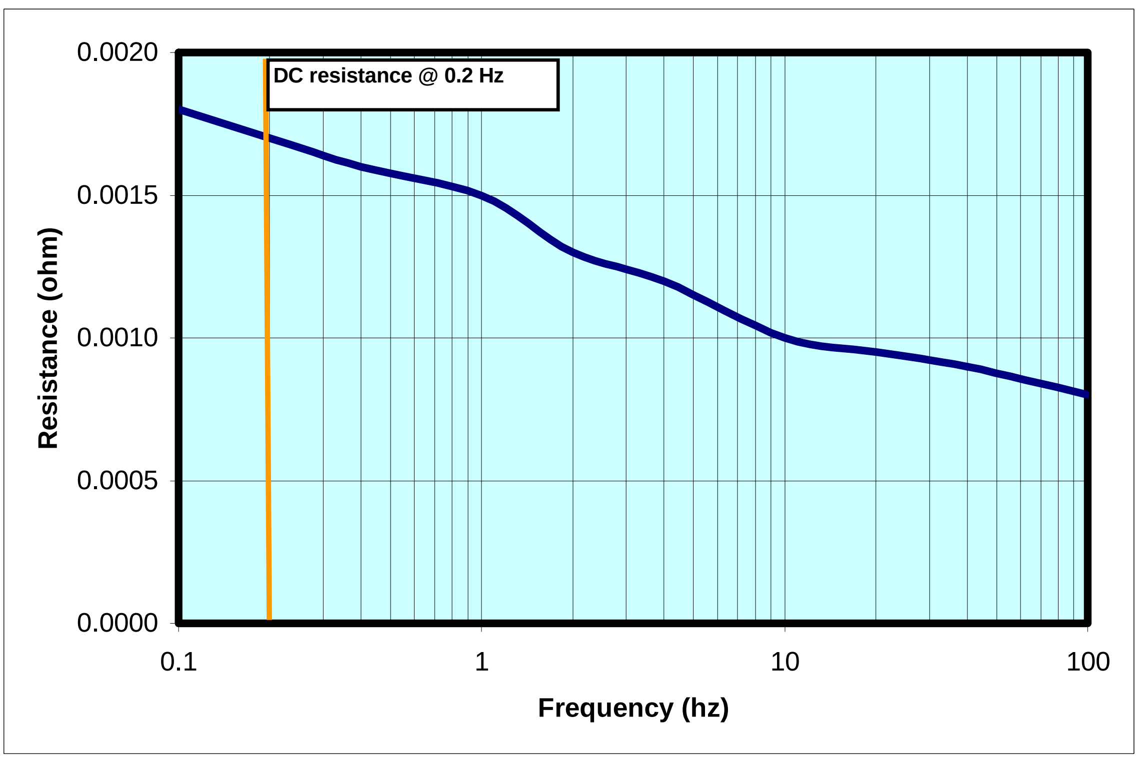

Figure 13: BCAP0350-E Resistance Frequency Response

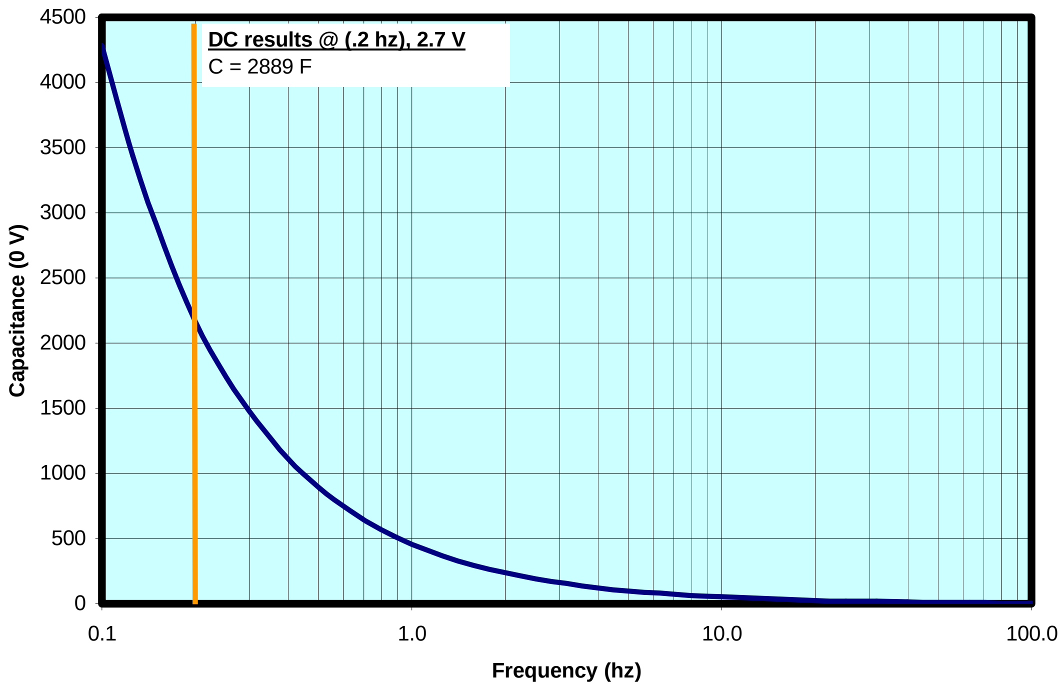

Figure 14: BCAP2600-E Capacitance Frequency Response

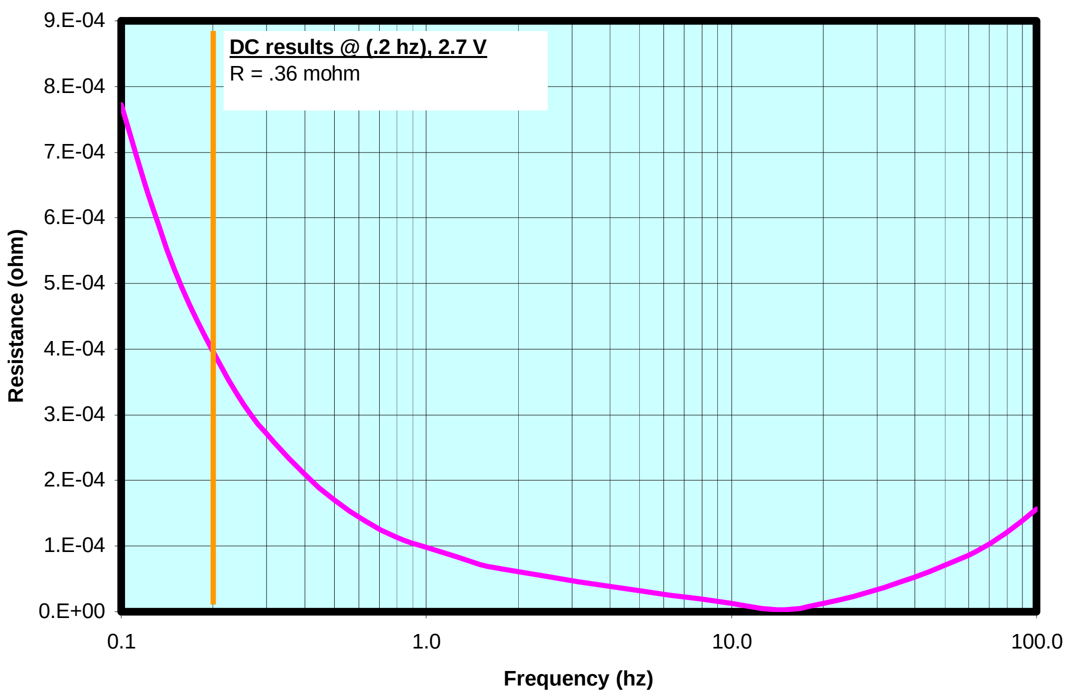

Figure 15: BCAP2600-E Resistance Frequency Response

6 Packaging

Products are packaged in a variety of methods dependent on the product type. All components are shipped discharged or with a shorting strap if required. If a shorting strap is attached, remove before use.

6.1 Typical Packaging

PC5 and PC10 products are typically placed in a tray for shipping. Trays are then vacuum sealed to protect the solderable leads until product is ready for use. Product should be used within six months of opening vacuum seal to prevent the solderable leads from oxidizing. Vacuum sealed bags are then placed in cardboard boxes.

PC5-5 products are typically placed in a tray for shipping. Trays are vacuum sealed although product is not solderable is not susceptible to oxidation. Vacuum sealed bags are then placed in cardboard boxes.

All other products, capacitors and modules, are shipped in cardboard boxes. Each capacitor is individually isolated within the cardboard box by dividers. Modules are packaged individually in a cardboard box.

6.2 Shipping Regulatory Information

The following provides information relating to International shipping standards and regulations as they pertain to ultracapacitors.

According to the U.S. Department of Transportation, Maxwell ultracapacitors containing less than 1.5 grams of acetonitrile in a sealed steel container are in a quantity and form that does not pose a hazard in transportation, and are not subject to the Hazardous Materials Regulations (HMR) 49 CFR Parts 171-180.

Maxwell Boostcap® products which are **not** subject to the HMR are all models and versions of **PC5, PC10,** and **PC5-5** (being an assembly of two PC5 units).

Dangerous Goods are defined as those goods which meet the criteria of one or more of nine UN hazard classes and, where applicable, to one of three UN packing groups according to the provisions of section 3 of the IATA Dangerous Goods Regulations. The nine classes relate to the type of hazard whereas the packing groups relate to the applicable degree of danger within the class.

Maxwell Technologies has determined that, though ultracapacitors are neither explicitly permitted nor exempt from Dangerous Goods Regulations, it is prudent to classify these products as UN1648, Acetonitrile, until such time as a specific classification is established.

6.2.1 General Packaging Requirements

IATA regulations define specific packaging and labeling requirements for international air transportation. Requirements vary based on the hazard and applicable degree of danger. In general, there are four (4) levels of packaging requirements described for air transportation; excepted quantity, limited quantity, passenger aircraft, and cargo aircraft.

U.S. Department of Transportation (DOT), UNECE ADR, and IMDG requirements for ground and maritime shipments may differ from IATA regulations. As of the release date of this document, to the best of our knowledge, in no case is the road or maritime requirements more stringent than the IATA regulations. Therefore, packaging and shipping under IATA regulations satisfies these other requirements.

In the U.S., ultracapacitors that will be shipped via domestic ground transportation to an endpoint within the U.S. may be packaged and labeled in conformance with either 49 CFR or IATA regulations.

6.2.2 Specific Packaging Requirements

6.2.2.1 Excepted Quantities

Very small quantities of dangerous goods may be transported under the “Dangerous

Goods in Excepted Quantities" provisions of the IATA regulations, or as "Small Quantity" provisions in U.S. 49 CFR. These provisions allow a shipper to avoid certain marking, labeling and documentation requirements. *See* IATA Section 2.7 and 49 CFR 173.4. These methods also involve less stringent packing requirements. The shipping containers need not meet the "General Packing Requirements" discussed above, or the UN specification packaging requirements. Instead, simple "drop tests" are to be performed by the shipper to determine if the packaging is adequate.

6.2.2.2 Limited Quantities

The "limited quantities" exemption is similar to the "excepted quantities" provisions in that both permit shipment of dangerous goods in small quantities under less stringent requirements than larger shipments of dangerous goods.

The advantages of shipping as a "limited quantity" include:

Although the packaging must meet the construction standards of UN specification packaging, it does not need to be tested and marked as such. The quantity limits are higher than the amounts for excepted quantities. The package performance tests are merely a drop test and a stacking test, both of which may be performed by the shipper rather than a certified testing company. Other than these few exceptions, the General Packing Requirements discussed above must be met.

France has a State variation to instruction Y305 that states: Dangerous goods may not be transported to, from or through the French territory under the provisions of Subsection 2.8 (Limited Quantities of Dangerous Goods) of these regulations. This requirement does not apply to over flight. *See* IATA Section 2.9.2 (FRG-02).

This State variation does not amount to an absolute ban on air transport of AN in Europe. Rather, it (i) applies only in France; (ii) applies only to dangerous goods transported under the limited quantities exemption; and (iii) does not apply to over flight. If Maxwell anticipates shipping ultracapacitors to or through France, then the shipment must meet the more stringent standards of packing instructions 305 or 307, discussed more fully below.

6.2.2.3 Passenger Aircraft limitations

If the "excepted quantities" provisions or the "limited quantities" exemption cannot be met, for the transportation of higher quantities of ultracapacitors by passenger or cargo aircraft, the packing instruction for the shipment of both "acetonitrile" is instruction "305" (again assuming packing group II applies -- flash point of less than 73º F). *See* Attachment C (IATA Packing Instruction 305). That instruction provides the following:

All of the General Packing Requirements, discussed above, must be met. The maximum amount of AN in any aluminum inner packaging (ultracapacitor) is 5.0 liters; the maximum amount in the outer packaging is also 5.0 liters. The aluminum casing of the ultracapacitor must meet IP3A packaging requirements (described in the limited quantities exemption discussion above). The outer packaging must meet UN specification packaging requirements and may be any of the types listed at the bottom of Attachment C, including fiberboard boxes stamped as "4G". Those packaging must meet the test requirements of Section 5.0.2, which are generally performed by the packaging manufacturer. *See* IATA Sections 5.3 (305) and 6.1.3.

6.2.2.4 Cargo Aircraft limitations

If the "excepted quantities" provisions or the "limited quantities" exemption cannot be met, for the transportation of higher quantities of ultracapacitors by cargo aircraft only (again assuming packing group II applies), the packing instruction for the shipment of both "acetonitrile" is instruction "307." *See* Attachment D (IATA Instruction 307). That instruction provides the following:

All of the General Packing Requirements, discussed above, must be met. The maximum amount of AN in any aluminum inner packaging (ultracapacitor) is 10.0 liters; the maximum amount in the outer packaging is 60.0 liters. The aluminum casing of the ultracapacitor must meet IP3A packaging requirements (described in the limited quantities exemption discussion above). The outer packaging must meet UN specification packaging requirements and may be any of the types listed at the bottom of Attachment D, including fiberboard boxes stamped as "4G". Those packaging must meet the test requirements of Section 5.0.2, which are generally performed by the packaging manufacturer. *See* IATA Sections 5.3 (307) and 6.1.3. This packaging may not be shipped on passenger aircraft.

For additional information regarding packaging and shipping of ultracapacitor products please contact Maxwell Technologies.

7 <u>Design Considerations</u>

This section offers additional considerations and descriptions for designing around specific needs.

7.1 Voltage

Ultracapacitors are capable of operating between its rated voltage and zero volts. The rated voltage is determined by the electrochemical stability of the dielectrics internal to the capacitor. Ultracapacitors manufactured by Maxwell Technologies utilize an organic electrolyte. An advantage of an organic electrolyte over an aqueous electrolyte is a much higher operating voltage. If a capacitor is operated above its rated voltage whether it is an aqueous of organic based electrolyte, the electrolyte will evolve gas. Once the voltage level is lowered below its rated voltage, gas evolution subsides. Thus, occasional spikes above the rated voltage will not immediately affect the capacitor. Depending on the frequency and duration of the voltage spikes the capacitor life will be reduced.

Efficient utilization of the available energy and power storage is achieved with the widest operating voltage range use. Most electronics have a minimum voltage threshold for utilization, limiting the effective utilization voltage of the capacitor although there is no limitation in the capacitor itself. Since the energy in the capacitor is proportional to the voltage squared according to the following equation:

$$E = \frac{1}{2} C V^2$$

It is possible to utilize approximately 75% of the available energy if the application utilizes from the rated voltage to ½ rated voltage of the capacitor.

7.2 Ambient Temperature

Another advantage of the organic based electrolyte is its low freezing point. This enables the ultracapacitors to be utilized over a wide range of temperatures. The advantages are especially noticeable at lower temperatures. The ultracapacitor performance is relatively unaffected by temperature. Since the charge storage is not a chemical reaction, the capacitance is very stable over the entire operating temperature range of the capacitors. The capacitor resistance is affected by the ion mobility within electrolyte. Thus as the temperature drops closer to the freezing point of the electrolyte, the ion mobility decreases resulting in higher resistance. A generic plot of the capacitance and resistance as a function of temperature is provided in Figure 3.

7.3 Life

Ultracapacitor life is predominantly affected by a combination of operating voltage and operating temperature. The ultracapacitor has an unlimited shelf life when stored in a discharged state. When referring to ultracapacitor life the data sheets reflect the change in performance, typically decrease in capacitance and increase in resistance. The life specified by industry standards is a 20% decrease in capacitance and/or 200% increase in resistance. The ultracapacitor does not experience a true end of life rather the performance continually degrades over the life of the use of the product. End of life will be when the ultracapacitor performance no longer maintains the application requirements. This may be different from that specified on the data sheets.

The typical degradation behavior of the ultracapacitor resembles that of an exponential decay. The majority of the performance change occurs during the initial use of the ultracapacitor and this performance change then levels off over time. The most dramatic effect of the life degradation is on the internal resistance of the device.

7.4 Polarity

Unlike many batteries the anode and cathode of an ultracapacitor are comprised of the same material. If the positive and negative terminal and casing are also comprised of similar materials, then theoretically the ultracapacitor has no true polarity.
For manufacturing and consistency purposes the terminals are marked with polarity. It is recommended practice to maintain the polarity although catastrophic failure will not occur if the ultracapacitor is reversed charged for some reason. If the ultracapacitor has been conditioned for charge in a certain direction and then is changed, the life can be reduced due to this conditioning.

For the PC5, PC10 and PC5-5 products the case is comprised of stainless steel. Due to the corrosion potential of stainless steel it is required to maintain the polarity indicated on the products. Reverse polarity on these products will cause accelerated life reduction.

7.5 Charging

Since the energy storage mechanism of the ultracapacitor is not a chemical reaction, charging/discharging of the ultracapacitors can occur at the same rate. Therefore, the rated current for the ultracapacitor applies for both charge and discharge. The efficiency of charge and discharge are in practical terms the same. A variety of methods are possible for charging of the ultracapacitors. This may be either through constant current or constant power charging via a dc source or through ac charging methods. A separate application note is available discussing different methodologies for ultracapacitor charging.

7.6 Series Connection

Since the individual ultracapacitor cell voltage is relatively limited compared to the majority of application requirements, it is necessary to series connect the ultracapacitors to achieve the voltage required. Because each ultracapacitor will have a slight tolerance in capacitance and resistance it is necessary to balance, or prevent, individual ultracapacitors from exceeding its rated voltage. Consider a string of 3 ultracapacitors with the following performance:

C_1 = 100 F and 0.011 ohms
C_2 = 110 F and 0.012 ohms
C_3 = 95 F and 0.010 ohms

If each ultracapacitor is initially at 0 volts and the string of ultracapacitors is charged to 7.5 volts at a constant current then C_3 will reach 2.5 volts before C_2 or C_1.

$$dt = \frac{C}{I} \bullet dV$$

Thus if the string is not at 7.5 volts C_3 will continue to charge above its rated voltage of 2.5 volts. In order to address this issue, balancing is required to maintain the ultracapacitors within its rated voltage. Balancing can be achieved through two different methods, active balancing or passive balancing.

7.6.1 Active Balancing

Active balancing schemes are varied. Maxwell Technologies has adopted a balancing methodology based on a linear voltage balancing scheme. This methodology will always attempt to balance two adjoining ultracapacitors based on the voltage mismatch between the two ultracapacitors. The maximum current during balancing varies by product. Refer to the product data sheet or product manual for more information.

7.6.2 Passive Balancing

Passive balancing implies no variation in the voltage regulation as a function of the ultracapacitor condition. The most typical method of passive balancing utilizes resistors. The concept of resistive balancing employs resistors in parallel with the ultracapacitors.

7.7 Interconnecting Methods

A variety of interconnect methods are employed with the various product offerings. They range from buss bar interconnecting to soldering. In general the larger the cell capacitance the more critical the cell interconnects becomes. The larger capacitance devices have internal resistances on the order of a few hundred micro-ohms. A poor interconnection can have more resistance than the internal resistance of the device itself. Larger devices will generally be required to carry larger currents, thus necessitating reliable interconnects.

7.7.1 Buss bar considerations

All capacitor interconnects will be made through bus bar connections. This may be in the form of traces for surface mount devices, gauge wires or metal bars. It is necessary to consider the application current requirements and ensure the material thickness or wire gauge is properly sized for the intended use.

With the exception of products intended for solder mounting, the terminals are made of aluminum alloys. The application environment should be considered when selecting the buss bar material. The corrosion potential of dissimilar metals in combination of the environmental conditions is a prime consideration for a reliable interconnection over the life of the application.

7.7.2 Mechanical fastening

Several products are threaded to allow bolted buss bar interconnections. When fastening to these threaded interconnects attention should be made to the products torque recommendations. Over torque may cause the ultracapacitor terminal to slip resulting in damaged internal interconnections of the device. This could cause increased device internal resistance resulting in over heating of the device during use.

Thermal mismatch of the fastening bolt and aluminum threads of the terminal should be considered based on the application current requirements. When fastening wave, split or similar washers are recommended to compensate for thermal mismatch issues which may result in threads loosening over time.

Joint compounds to prevent oxidation between the terminal and bus bar are recommended. Preparation of the terminal and bus bar surface should be made according to the selected joint compounds recommendation

7.7.3 Welding

Reliable, low resistance connections are possible through laser welding. If this method is to be considered it is recommended to contact Maxwell Technologies for recommendations specific to the product considered.

Maxwell Technologies utilizes laser welding for some of its modular product offerings. Some products are designed specifically with this interconnection methodology in mind.

7.7.4 Soldering

Soldering is required for PC5, PC10 and BC series products. Additional application notes are available for recommendations for soldering of these products.

7.8 Ultracapacitor Efficiency

Unlike batteries, the ultracapacitor has the same efficiency during charge or discharge. This enables the ultracapacitor to be recharged quickly without current limiting as long as the current is within the rated current for the device.

The only efficiency losses associated with ultracapacitors are due to internal resistance of the device resulting in IR drop during cycling. For most uses the ultracapacitor efficiency is in excess of 98%. For high current or power pulsing the efficiency is reduced. Typical efficiency under high current pulses is still greater than 90%.

7.9 Thermal Properties

Many applications for ultracapacitors utilize the devices under high duty cycles. One of the factors attributing to performance reduction for the ultracapacitor is temperature as addressed in section 7.3. For minimum performance influence over the life of the application it is necessary to maintain the ultracapacitor core temperature within the rated temperature range of the device. The lower the temperature is maintained the better for life considerations.

Products are packaged in a variety of configurations and form factors. All products are provided with an electrically insulating shrink sleeving around the capacitor body. For this reason and since all current passes through the capacitor terminals, cooling at the capacitor ends or terminals is the most efficient means for cooling of the capacitor.

Depending on the duty cycle of the application cooling can be accomplished via heat sinks (conduction), air flow (convection) or a combination of the two. Consideration should be made for the duty cycle and resulting capacitor temperature as well as the anticipated ambient temperature the device will be operating under. The combination of the two should not exceed the operating temperature for the ultracapacitor.

Following is data that should be helpful for system design considerations for possible cooling requirements.

Capacitor heating data has been collected for various products. Data was collected at ambient with no forced convection. With the low impedance of the ultracapacitors the test results are sensitive to the interconnection integrity during testing.

Maxwell Technologies determines a thermal resistance, or R_{th} ($^{o}C/W$), for products based on free convective cooling. If active cooling is employed further improvements can be made, so the provided R_{th} should be considered a guideline.

Utilizing the provided R_{th} for the products an anticipated temperature rise can be predicted based on the application current and the duty cycle. This temperature rise can then be added to the ambient temperature to determine the maximum current and duty cycle for the devices for maintaining within the operational specification and the application life requirements. The temperature rise of the product can be predicted as follows:

$$\Delta T = I^2 R_{dc} R_{th} d_f$$

where I = current, R_{dc} = dc resistance or low frequency based on constant discharge (non pulsing), R_{th} = thermal resistance, and d_f = duty cycle fraction (0 to 1),. Alternatively for ac currents the high frequency resistance should be utilized for pulsing currents. The thermal resistance is provided for each product on the data sheet.

8 Safety Information

8.1 General Precautions

Individual capacitors are low voltage devices. They are capable of delivering extremely high currents especially in short circuit situations. Handling of capacitors should be done in an uncharged state. When designing a system with higher voltages standard safety practices should be followed for the voltage levels of consideration.

The packaging for the ultracapacitors is completely sealed. The devices do not contain re-sealable venting. Most devices contain a high pressure fuse enabling the packaging to open more controlled in the event of a catastrophic failure. Catastrophic failure for the ultracapacitors can occur in over voltage situations. As the devices are operated in excess of the rated voltage, electrolyte decomposition will occur. The higher the current the more accelerated this decomposition may occur. The typical failure sequence as the ultracapacitor is maintained well above its rated voltage with continued supplied current is a raise in temperature of the device up to 125 to 150 ^{o}C followed by an opening of the ultracapacitor package at the fuse. Products with a fuse are designed to open with an internal pressure of 12-15 bar.

If product is found to be leaking (identified by a white salt crystal formation on product) the capacitor should be removed from the system. A leaking capacitor will eventually increase in resistance or could cause long term corrosion of interconnects. Incidental contact with the salt residue is not harmful although should not be ingested. Take normal precautions after contact which includes washing hands. Refer to MSDS for more information.

In the event the packaging is compromised either by puncturing or crushing a very limited amount of electrolyte fluid will be released depending on the size of the ultracapacitor. The amount of fluid will generally be limited to a few milliliters maximum. An open or compromised package should be immediately removed from the system and placed in a well-ventilated area. The electrolyte has a high vapor pressure and quickly evaporates. The electrolyte is classified as flammable and should be handled with normal considerations for flammable materials. Full information regarding flammability rating and handling is available in the electrolyte MSDS.

8.2 Disposal

Ultracapacitors are composed of aluminum, carbon, paper and an organic electrolyte. Ultracapacitors contain no heavy metals or toxic materials. Municipalities differ in how materials are classified for disposal. An MSDS is available to aid in determining regional or local classification and disposal requirements. In general, packaging material is recyclable. The remaining materials can be incinerated at high temperatures.

8.3 Safety Recognition

Maxwell has taken steps to additionally recognize the ultracapacitor products for safe use in electronic devices by submitting ultracapacitors for Underwriter's Laboratory testing. Datasheets for each product reflect whether UL Recognition is granted for each product type and is also included on the product labeling.

Maxwell Technologies continues testing products to various regulatory standards. A separate matrix document is available with the most up to date testing and recognition all of the products have completed.

8.4 RoHS Compliance

Maxwell is committed to providing product satisfying Directive (2002/95/EC) limiting use of hazardous substances in electrical and electronic components. All products satisfying the directive are listed in separate documentation and are available upon request.

8.5 Standards Testing

Products have been tested to a variety of standards to validate safety and reliability. These test include shock, vibration, thermal cycling, thermal shock, and water resistance. A list of the products tested and the standard in which they are accepted is available in a separate document.

9 Quality

As a manufacturer of high reliability components and systems, Maxwell Technologies understands the impact of high reliability and quality of our products. This knowledge assures our ongoing commitment to manufacture products to meet the highest quality standards.

Maxwell Technologies and its employees are committed to continuously improving the processes by which we provide our products and services, so that our work meets requirements and is done right the first time.

Maxwell Technologies is an ISO 9001 certified company. Our European facility is certified to the ISO 14001 (environmental management standard) as well as ISO/TS 16949 (automotive). As part of a continuous improvement activity aimed at achieving higher levels of quality performance, Maxwell is working aggressively to meet the requirements of additional formal rigorous management system standards. Our plans include implementation of the ISO/TS 16949 standard within our US-based Boostcap® division. We are also working aggressively to achieve compliance with the ISO 14001 standard at our San Diego facility bringing the entire corporation into compliance with these environmental standards.

Customer satisfaction is a key indicator of quality and so we seek our current and prospective customers' inputs and involvement in improving our products and services.