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.

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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.

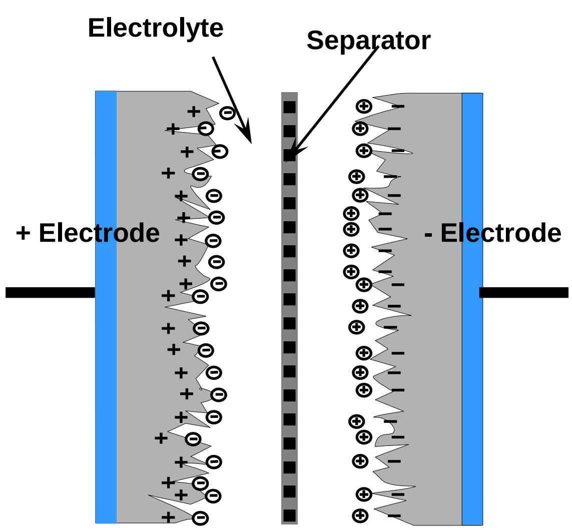

Figure 1: Ultracapacitor charge separation

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.

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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.

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.

Transportation – Diesel engine starting, train tilting, security door opening, tram power supply, voltage drop compensation, regenerative braking, hybrid electric drive.

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

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

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

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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.

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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 (VR). Since ultracapacitors are low voltage devices, this rated voltage is generally less than the application voltage required. Knowing the maximum application voltage (Vmax) 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 (Vmin), an approximate system capacitance can be calculated.

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

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

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

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where n = # series connected capacitors.

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

$$C = Csys \bullet n$$

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:

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

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 or one of our distribution partners for assistance in sizing the application properly.

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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

Specification	UoM	Description
Capacitance	F (Farads)	a measurement of energy storage in joules. C = qV
Voltage	V DC (Volts, Direct Current)	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 the rated voltage.
Surge Voltage	V DC (Volts, Direct Current)	Maximum voltage that the ultracapacitor can operate at for a few seconds without irreversible damage or cell opening
Internal Resistance, DC		the resistance corresponding to all the resistive components within the ultracapacitor, Rtot. 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. Rtot is compromised of resistive components attributed to contact, electrode, electrolyte, and other material resistances.

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Specification	UoM	Description
Internal resistance, 100hz or 1khz		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 (Isc)		momentary current possible in device if ultracapacitor is short circuited. Intended as a cautionary statement and not intended for ultracapacitor use or sizing purpose.
Leakage Current (Ic)		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 25C.
Maximum Continuous Current		continuous or IRMS current that can fed in the ultracapacitor without increasing the device's temperature beyond the supported range. This is mostly relevant for cycling applications.
Maximum Peak Current		one time, peak current that can be fed to ultracapacitor without significantly affecting its lifetime This is mostly relevant for UPS, power back up applications where there is sufficient time between current spikes.
Maximum Operating		represents the maximum voltage that can be safely implemented by UL810a

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Specification	UoM	Description
Voltage (and isolation voltage)		standard when building a string of modules or ultracapacitor. The Isolation Voltage is the level of voltage applied on every Maxwell Technologies' unit during its high pot test.
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		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		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		measurement of an instantaneous power from full rated voltage according to V2/4R where R = ac resistance. This value does not represent the sustainable power. The volumetric density is computed as V2/(4R x dm3) whereas the gravimetric density is equal to V2/(4R x Weight).
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

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Specification	UoM	Description
		ultracapacitor if held at rated voltage and 25 oC 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 25oC.

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.

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

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	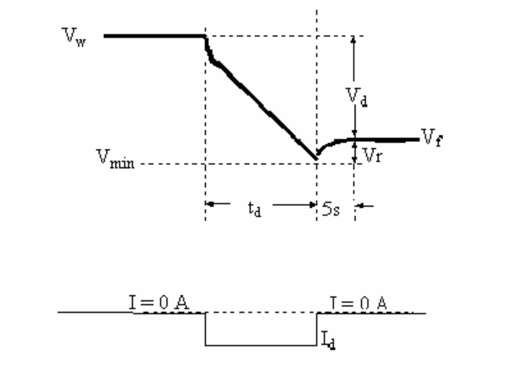 Figure 2: Testing profile
Leakage Current	Due to the extremely large surface area of the electrode the time constant of the last 0.5% of the electrode area is extremely long due to the pore size and geometry. The longer the ultracapacitor is held on charge the lower the leakage current of the device. 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.

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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 oC.

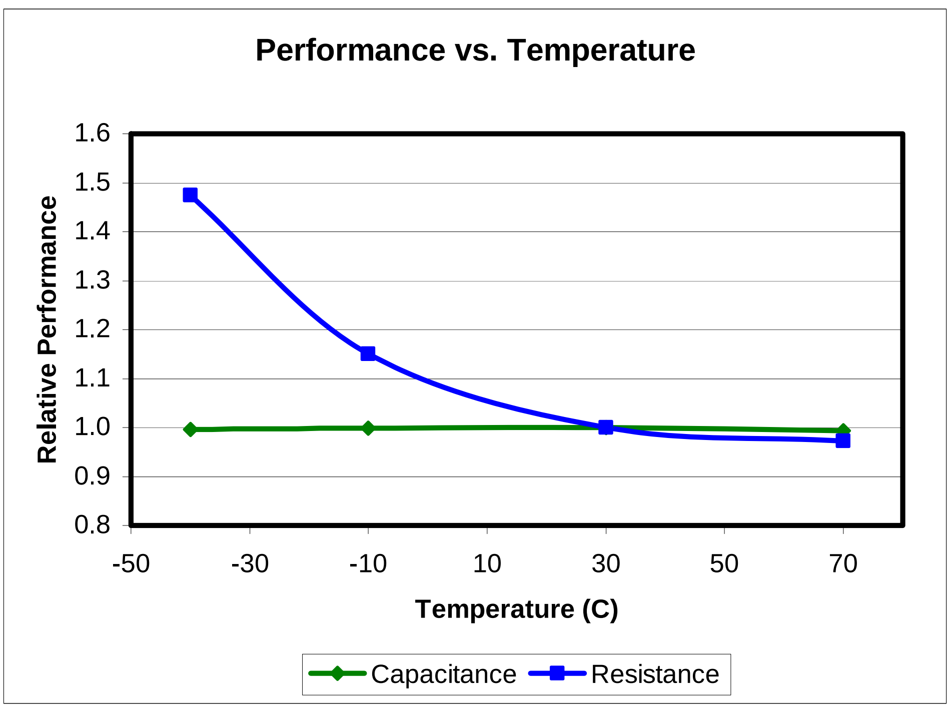

Figure 3: Relative ultracapacitor performance over operating temperature range

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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.

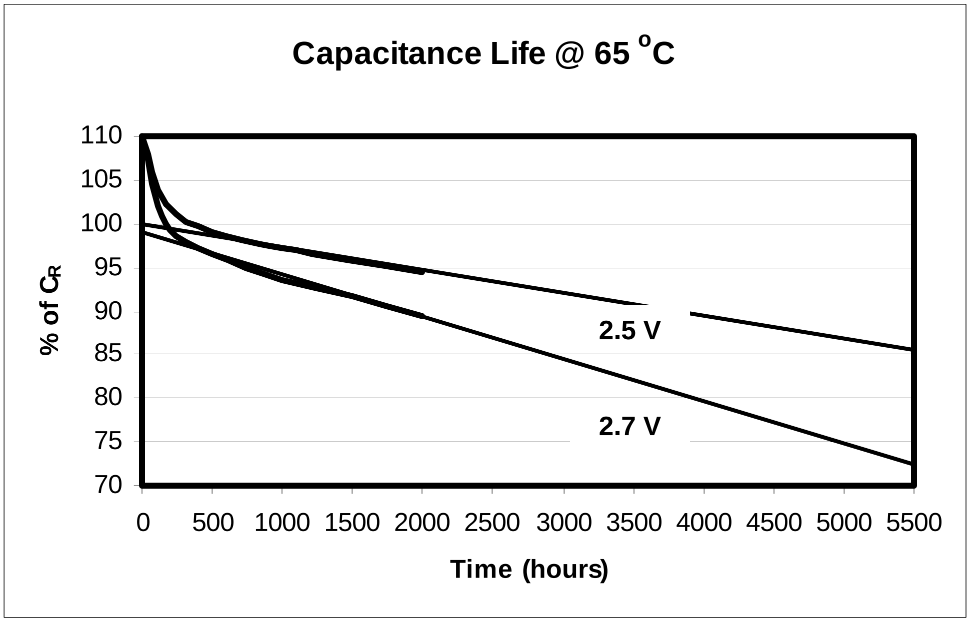

Figure 4: MC Cell Capacitance degradation at 2.7 V and 2.5 V at 65oC

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 oC, 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 oC

11,000 hrs @ 55 oC

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22,000 hrs @ 45 oC

44,000 hrs @ 35 oC

88,000 hrs @ 25 oC

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

5,500 hrs @ 65 oC

11,000 hrs @ 55 oC

22,000 hrs @ 45 oC

44,000 hrs @ 35 oC

88,000 hrs @ 25 oC

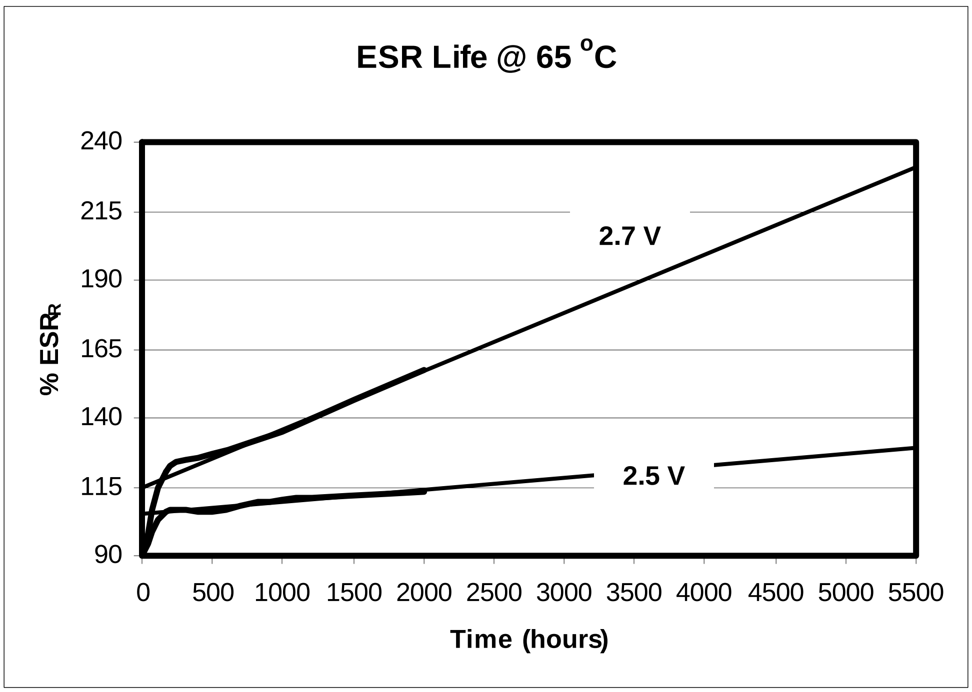

Figure 5: MC Cell Resistance degradation at 2.7 V and 2.5 V at 65oC

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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 oC, 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 oC
11,000 hrs	@ 55 oC
22,000 hrs	@ 45 oC
44,000 hrs	@ 35 oC
88,000 hrs	@ 25 oC

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

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

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

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is initially 70% reducing to approximately 50% at the product ages. The data provided is a combination of data points and extrapolation for the MC product.

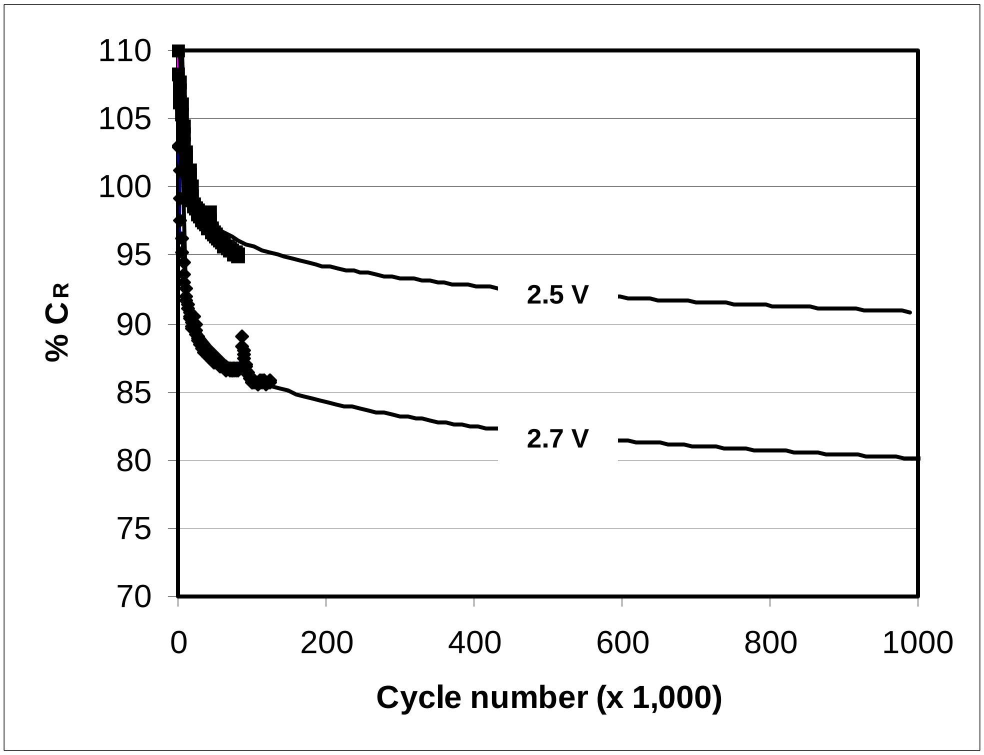

Figure 6: Capacitance change vs. Continuous cycling

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

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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.

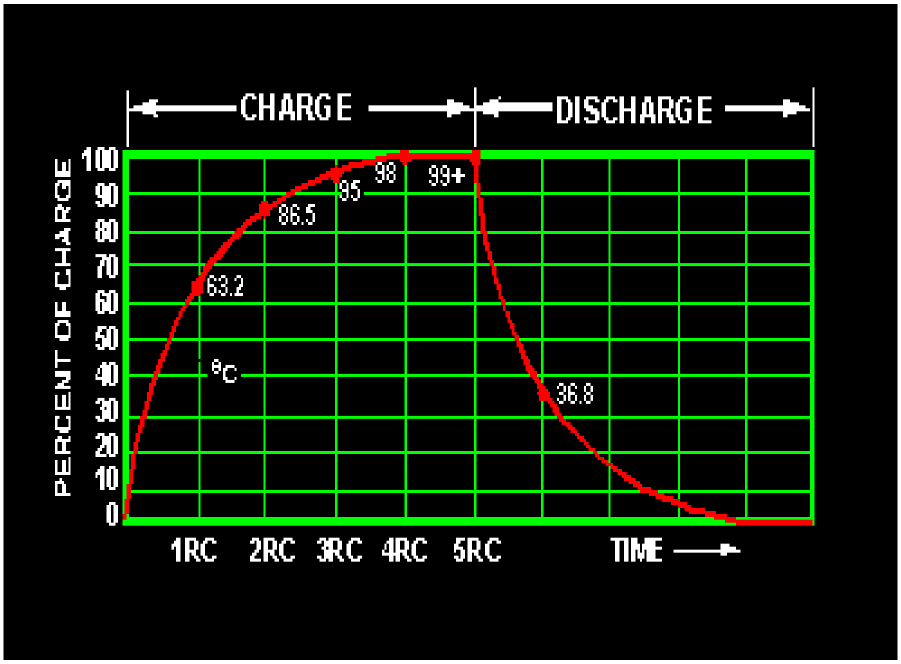

Figure 7: RC time constant relationship

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.

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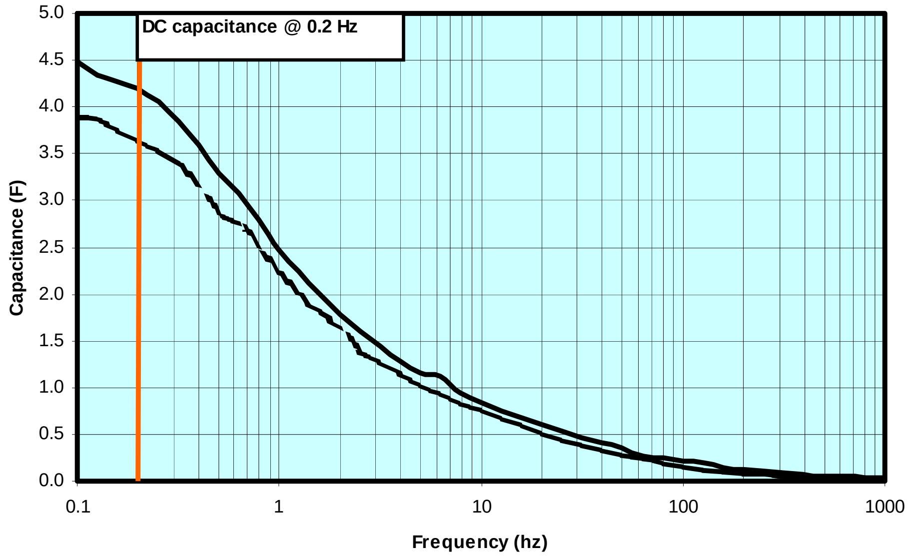

Figure 8: PC5 Capacitance vs. Frequency Response, 95% Confidence

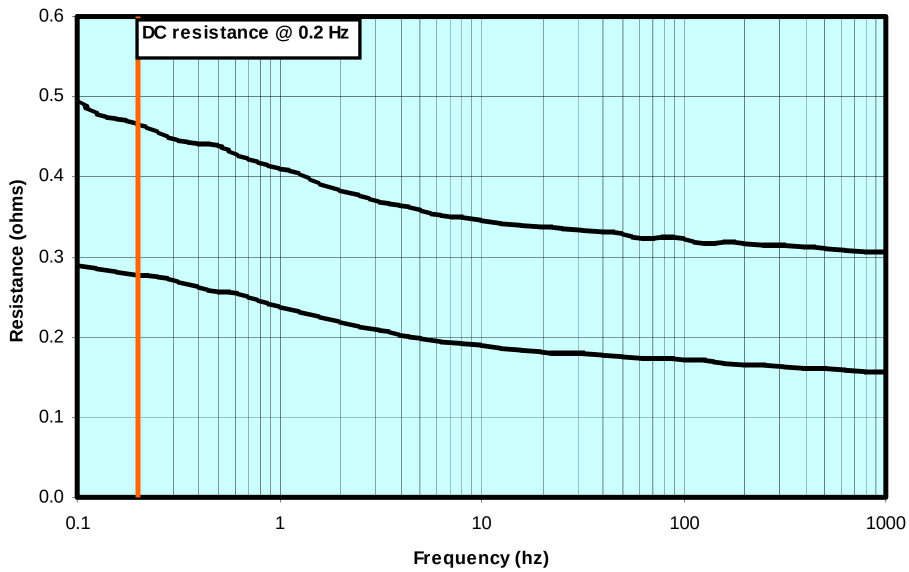

Figure 9: PC5 Resistance vs. Frequency Response, 95% Confidence

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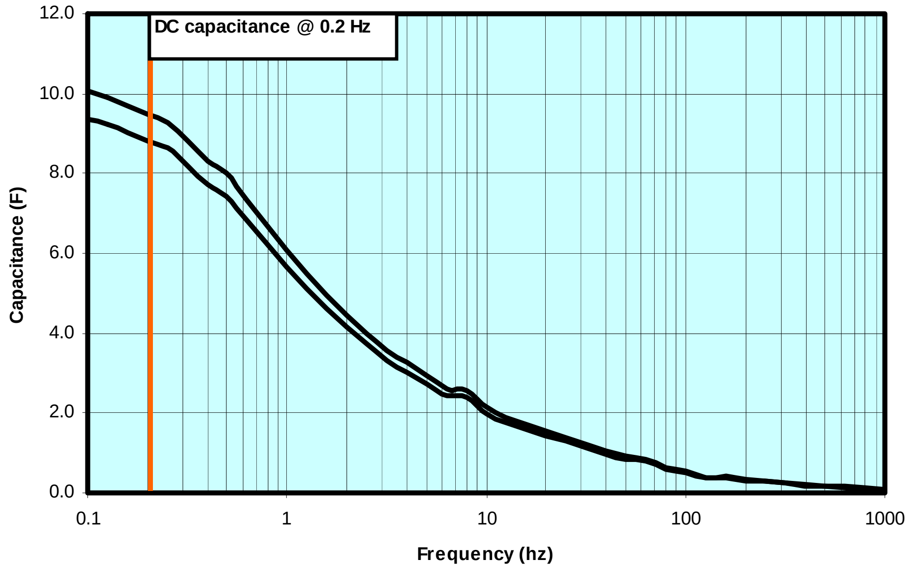

Figure 10: PC10 Capacitance vs. Frequency Response, 95% Confidence

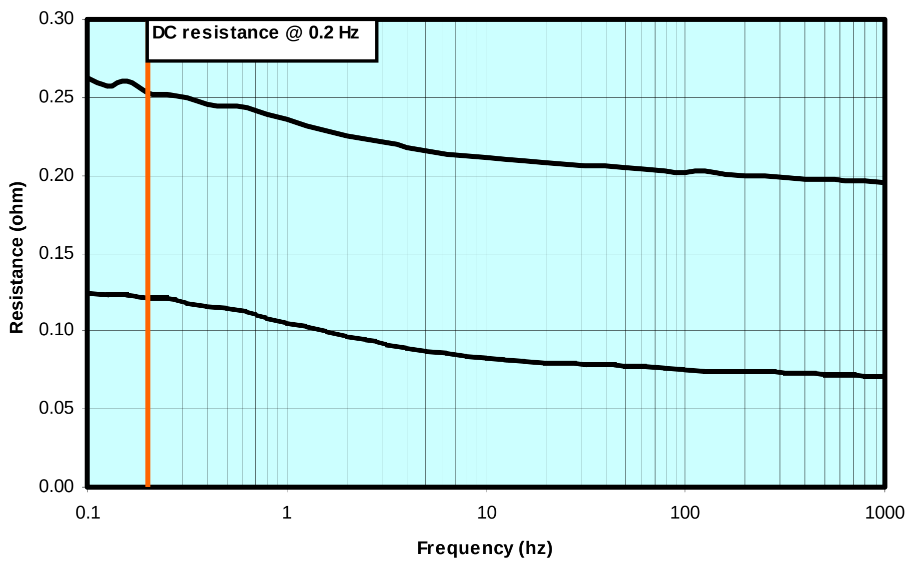

Figure 11: PC10 Resistance vs. Frequency Response, 95% Confidence

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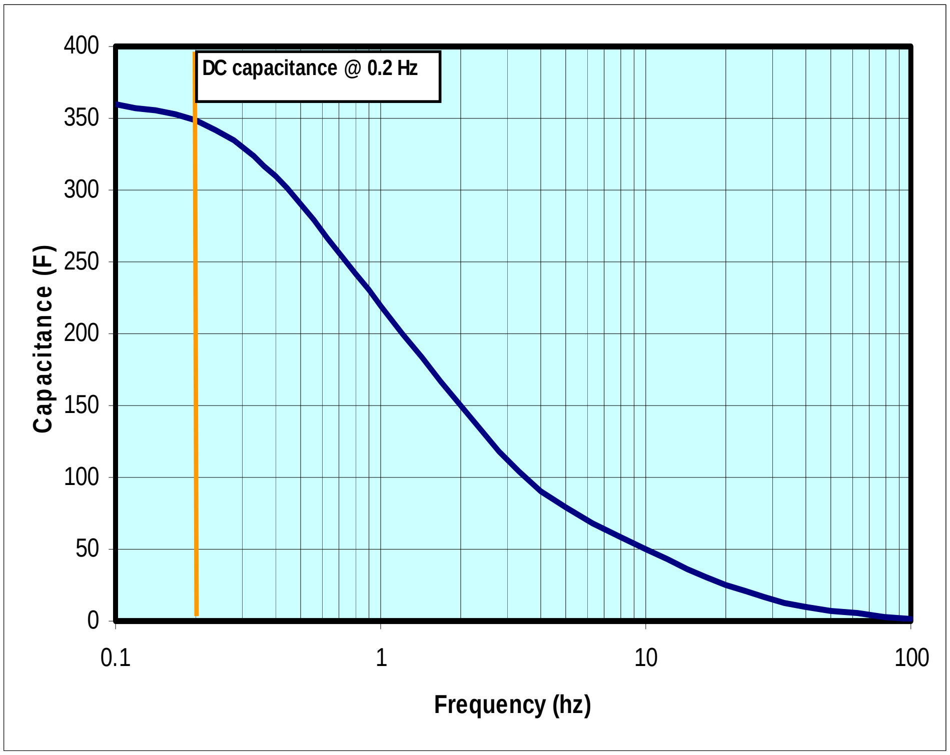

Figure 12: BCAP0350 Capacitance Frequency Response

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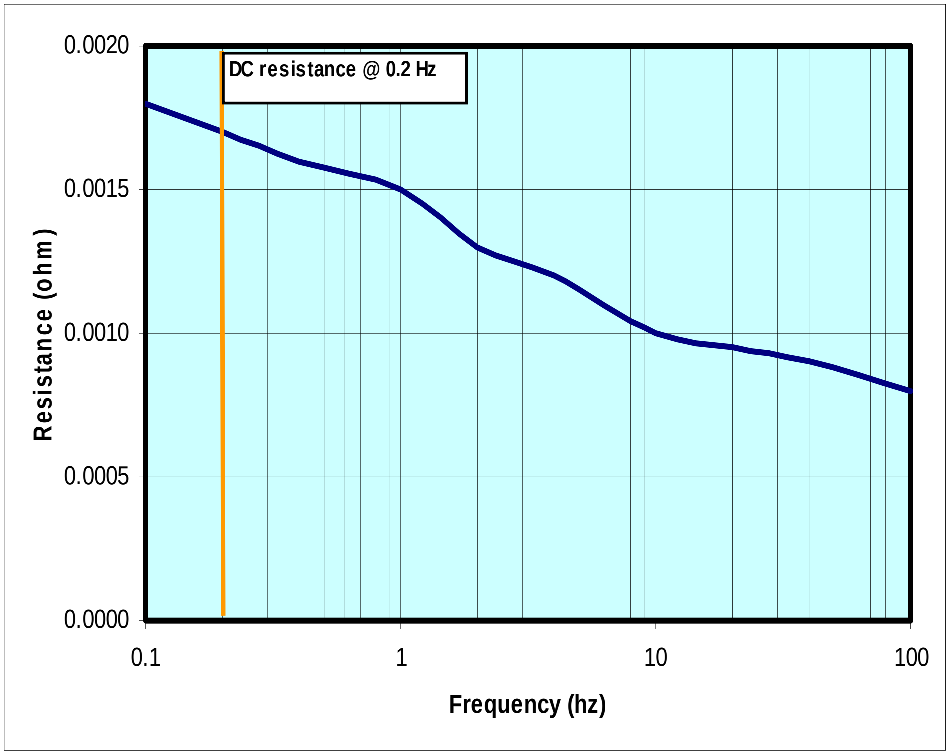

Figure 13: BCAP0350 Resistance Frequency Response

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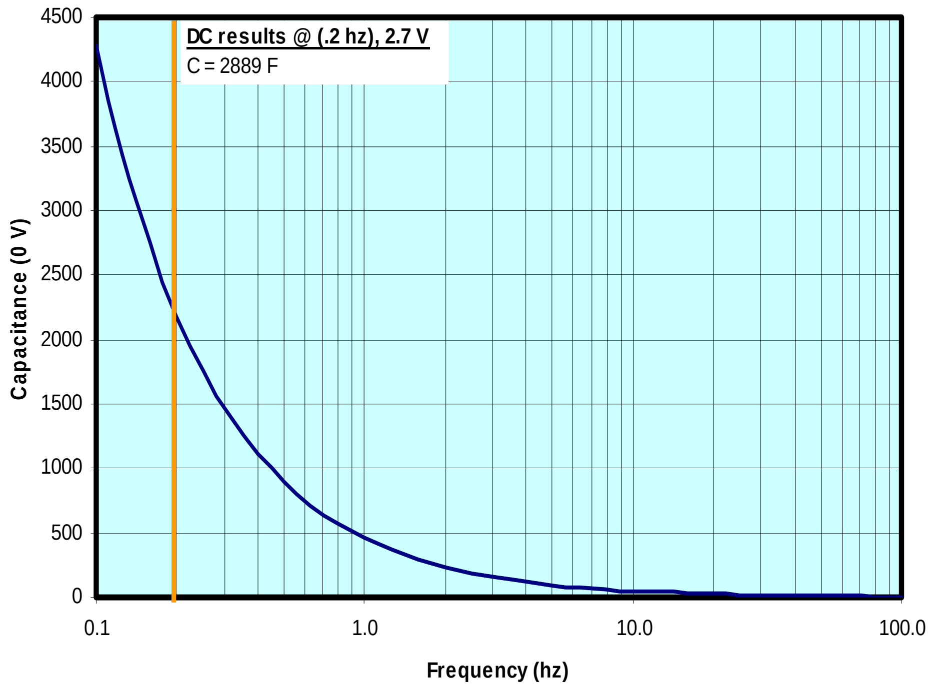

Figure 14: BCAP2600 Capacitance Frequency Response

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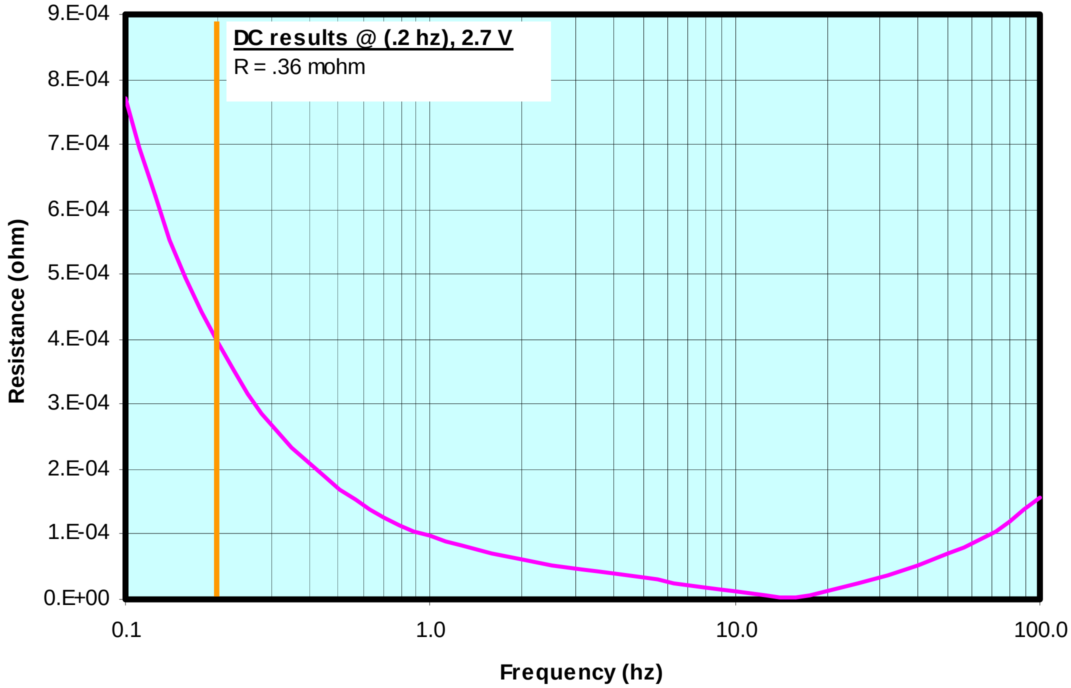

Figure 15: BCAP2600 Resistance Frequency Response

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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 Quantities

PC5 products are placed in a tray for shipping. Each tray contains 80 capacitors. Five trays are stacked on top of each other. This stack is placed in a laminated bag and vacuum sealed. The packaging will 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.

PC5-5 products are placed in a tray for shipping. Each tray contains 40 capacitors. 10 trays are stacked on top of each other. This stack is placed in a laminated bag and vacuum sealed. The product is not solderable is not susceptible to oxidation.

PC10 products are placed in a tube for shipping. Each tube contains 50 capacitors. 10 tubes are placed in a laminated bag and vacuum sealed. Product should be used within six months of opening vacuum seal to prevent the soldered leads from oxidizing.

Typical BCAP0350 product shipments are in a cardboard box. Each box containing 250 pieces.

BCAP650 to BCAP3000 cells are shipped in quantities of 30 in a cardboard box. Product stands on end during shipment.

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.

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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).

An MSDS for Acetonitril, a Product Information Sheet and a shipping guidelines document are available to aid in determining regional or local classification and disposal requirements.

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.

6.3 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.

6.3.1 Specific Packaging Requirements

Excepted quantities

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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.

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.

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 acetonitril 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

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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.

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 acetonitril 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.

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7 Design Considerations

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:

$$E = ½ C V2$$

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.

7.1.1 Safety considerations about the voltage and current

Cells should never be operated beyond the specified rated voltage for that particular device. As of this writing that voltage is 2.7V for the MC family and 2.5V for the BC and PC families. Failure to respect this upper voltage limit will result in minimally a shortening of the ultracapacitor lifetime and in extreme cases, a voltage induced failure of the part resulting in venting

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of the gasses that build up in the cell as a result of the overvoltge condition. The level of the impact of the over voltage condition on the operation of the cell is dependent to the magnitude and time at which the particular cell is operated in that over voltage condition. It is always safe to assume that any over voltage is bad for the cell operating characteristics and lifetime.

The continuous DC currrent density which are recommended maximums for long life reliable operation of the cells of all types is 50mA per farad. The cells will operate effectively at currents higher than these recommended values however potential damage can occur to the cells depending on the magnitude over this value of current density and duration/duty cycle of the high current pulses in the application. Maxwell Technologies is ready to discuss your applications with respect to high currents and together we can determine if the high current you need to use will result in damage or excessive degradation to the cells.

7.1.2 Safety considerations about high voltage circuit and electrical Isolation

It is very common for ultracapacitor to be utilized in high voltage applications and this generally requires a series string of cells or cell modules to be assembled. Building up such a string of cells or modules requires careful consideration of the creepage and clearance requirements of these strings. Consult the manufacturers data sheet on the isolation resistance of the modules in the string for guidance on how much clearance is required between modules or other grounding structures. In the case of building up a module from loose cells be sure to consider the operating voltage of the module in its series string final configuration and be certain to design the module with necessary creepage and clearance as well as proper isolation materials. Hi Pot testing should always be conducted on individual modules and on series module strings in order to accurately assess the safety of the isolation of the string. In the case where isolation is not sufficient at the module level or creepage and clearance is not availabel at the system level, the maximum operating voltage of the series string should be adjusted down to a safe level on consideration of these characteristics. In general an application voltage above 50V is considered a potential danger to human body.

7.2 Ambient Temperature

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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.

7.2.1 Safety considerations about temperature

Maxwell Ultracapacitors operate effectively between the cell body temperatures of -40C and +65C. Operating the cells at higher body temperature than 65C will result in unwanted abuse of the cell and severe degradation in operating characteristics as well as lifetime. The magnitude of this degradation is proportional to how high the temperature is beyond the upper limit as well as how long the cells stay there. Typical affects include rapid capacitance degradation and ESR increase as well as possible excessive gas generation ultimately resulting in pressure related venting of the cell.

The temperatures above apply to the body temperature of the cell. It is recommended that the temperature of the body of the cell is monitored in the application in order to be sure its temperature is not exceeding safe levels. The temperature sensing device can be safely attached to either the positive or negative terminal of the cell and an accurate and representative temperature can be monitored. These are particularly convenient places to monitor temperature as they are not covered with anything like labels or shrink wrap and therefore are directly accessible to accurate temperature measurement. It is not recommended to sense temperature anywhere else on the cell for safety reasons. However, if it is desired to place a sensing element on the mid section of the cell, then the temperature reading must be adjusted for the influence of the label and/or the shrink wrap that covers the cell. If the shrink wrap of the cell is removed to accommodate a sensing device, cell warranty considerations could be influenced in the event of a failure due to the fact that the cell body in all families is a live terminal and exposing it can result in short circuits in the event of contact or close proximity with other conductors.

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It is of great benefit to control ambient temperature in order to avoid cell operating temperatures above 40C. Doing so will prolong the performance of the cell and its lifetime. Operating the ultracapacitors at temperatures up toward 65C, while reliable and safe, will result in shorter cycle and DC lifetimes than operating at temperatures below 40C. To optimize the lifetime of the device keeping temperatures low are a benefit. On the other end of the temperature scale, avoid operating at temperatures much below -40C the ultracapacitor will cease to function as the electrolyte in the device freezes and is unable to fulfill its intended function thereby hindering the device. Once the device is able to thaw out it will return to normal function but at that low temperature level operation is not possible.

In general monitoring ambient temperature and the temperature of the cells and reacting to stressful temperature conditions to remove the stress, is the best way to ensure long trouble free lifetime of the ultracapacitor cells. Likewise it is important to regard storage temperature requirements of the cells as cells will age when exposed to thermal stress even though the cell is not functioning at the time.

7.3 Humidity

The ultracapacitor cells are able to operate effectively at high levels of humidity. During operation no special precautions are required other than to prevent condensation and the collection of condensation that can interfere with the operation of any electrical device.

However storage humidity can have a negative effect on the PC product line. Those parts are shipped in vacuum packed containers in order to exclude moisture exposure to the parts when the parts are stored. The terminal pins of the cells are susceptible to oxidation and eventually corrosion due to high levels of humidity over prolonged periods of time. Once soldered in place or otherwise connected the terminal pins are no longer prone to these corrosive effects. So when storing the PC ultracapacitors take the necessary steps to retain the original packaging undisturbed. If an original vacuum pack is opened and a partial package is remaining after use it is required to reseal the packaging introducing a vacuum at the time of resealing to prevent the remaining parts from experiencing humidity exposure. Failure to regard this important storage requirement will result in oxidation of the pins and as a result, there will be a reduced solderability of the pins and possible damage to the terminal pins, if the oxidation is allowed to continue unchecked for an extended period of time. Maxwell takes no responsibility for the oxidized terminal

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pins from cells that were removed from the original packaging and then exposed to humidity over time.

Oxidized terminations can be cleaned using an abrasive emery cloth to lightly remove the oxide buildup. Care must be taken to remove only the oxidation and not to remove the tinning that is on the terminal pins that was applied at the factory. Removal of the tin layer will render the terminal pins difficult or impossible to solder.

Proper care of the PC cells with respect to protection from humidity when in storage is essential to avoid solderability problems when the cells are to be used.

7.4 Pressure

All Maxwell Ultracapacitor cells are able to tolerate low pressure operation as specified in IEC 60068-2-13 without any negative effects or impacts. Operating at high pressure is also tolerated well up to nominal pressures above atmospheric. If the application demands that the ultracapacitor operate in ambient pressures higher than 1 atm (gauge) please consult with Maxwell on guidance for this operation. None of the Maxwell family of cells has been characterized at pressures higher than this and special testing and characterization will need to be executed to be sure there are no negative impacts as a result of this operating mode.

7.5 Polarity / Reverse voltage

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. However, if the ultracapacitor has been conditioned for charge in a certain direction and then is changed, the life will be reduced due to this conditioning.

The consequences of connection of a Maxwell ultracapacitor does vary dependent upon the family of the capacitor however generally there are a few effects that will be shared between the devices and the behavior of the devices in a reverse voltage condition. Particularly in the MC lines the cell

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lifetime will be shortened considerably when the cell is connected with the positively marked terminal to the negative terminal of the charging source. This is the case in the BC cells as well although to a lesser degree. Finally in the PC cells, reversing the voltage may not show any ill effects on cell performance until the cell has been then further reconnected correctly after use in the reversed condition. At that point the cell will show degraded lifetime and performance characteristics. In general, attention must be paid to the proper polarity of the cells when connecting them to avoid these negative affects of lifetime and performance degradation.

7.6 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.

7.7 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:

C1 = 100 F and 0.011 ohms

C2 = 110 F and 0.012 ohms

C3 = 95 F and 0.010 ohms

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If each ultracapacitor is initially at 0 volts and the string of ultracapacitors is charged to 7.5 volts at a constant current then C3 will reach 2.5 volts before C2 or C1.

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

Thus if the string is not at 7.5 volts C3 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.

7.7.1 Active balancing and Voltage Management

Active balancing schemes are varied. Maxwell Technologies has adopted a voltage management methodology based on a voltage limitation scheme. This methodology will always attempt to sink the voltage of the ultracapacitors operating at a level above a given threshold. The maximum current during balancing varies by product. Refer to the voltage management application note for more information.

7.7.2 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.

7.8 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

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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.

7.8.1 Capacitor replacement

When one unit of an ultra capacitor string needs replacement, the following options are available:

Replacing the cell with a new one of the same type

The new cell will have a higher capacitance than the rest of the string. Although possible, this will lead to higher voltage on the other cells, and to the further acceleration of their aging process. This affect is further exacerbated if the cell is of a different kind than the other elements of the string. The following balancing schemes can improve the life of this “refurbished” string:

- Passive (resistive) balancing
- Active balancing where each cell is individually monitored and balanced.
- Selective balancing (in addition to the existing circuit), i.e. implement additional resistive elements in parallel with all the original cells, lowering these cell voltages in order to reach the original lifetime.

The application of one of these will enforce that the new cell is operated at a higher voltage while the older cells operate at a normal voltage and will limit the acceleration of the aging process.

Replacing the cell with a new one of the same type and lower the string operating voltage

This will ensure that all the remaining cells in the string will still operate at the original design voltage and thus deliver the desired life time.

Replacing the cell with a new one of a different type (i.e. mixing energy and power)

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Although mixing power and energy products within the same string is possible with the use of an appropriate balancing, Maxwell Technologies does not recommend nor support such implementations.

Replacing the cell with an "aged" equivalent in the string

Using a combination of higher temperature and voltage (no greater than 65 degrees C and 2.7V), it is possible to align the aging status of cell on a level close to the one of the string. This can be achieved by maintaining the individual cell under charge at the given voltage and temperature. It is recommended to decrease the initial capacitance by 5-7% at a minimum in order to pass beyond the early phase of a cell.

After completion of this process, the aged cell can be inserted in the string. It is still recommended to use a balancing circuit to maximize the lifetime of the string.

Replacing the entire string

While costlier, this option will not only guarantee that the cells are well balanced but also provide a net additional lifetime to the system. If the string is replaced by a string of another type of cells (example power vs. energy type), the impedance of the string will change and thus it is important to modify the charging and/or load circuit accordingly if maintaining the time constant is paramount to the application. As an example, an additional resistive element might be added in series with the string to maintain the original resistance of the circuit.

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8 Mechanical integration and 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.

8.1 Shrink Sleeve

Each cell has a shrink sleeve covering the body of the cell. This shrink sleeve serves an important function. The cells are constructed in such a way that the body of the cell is connected to one of the terminals and therefore carries a potential difference from the surrounding hardware. Therefore the shrink sleeve should not be removed from the cells for any reason. It is necessary for safe implementation of the cells. With such low resistance the ultracapacitors are capable of discharging all their energy very quickly and if a short circuit would occur between the exposed body of the cell and the surrounding chassis hardware for example, a dangerous situation can arise. Removal of the shrink sleeve is not a Maxwell supplied configuration for any cell and therefore removal of the sleeve without consultation by Maxwell prior to doing so will have warranty implications.

8.2 Terminal Cleanliness

Ultracapacitors have very low equivalent series resistance and therefore are able to deliver high levels of power. This is what these devices are known for and generally what they are used for. Upon connecting terminals of cells together, cleanliness is important. Interconnection with dirty or oxidized cell terminals can result in poor efficiency of the system at a minimum. High resistance interconnects are prone to high temperatures as a function of the square of the current flowing through them and therefore can generate significant heat at the interconnect site not to mention the impacts on the performance characteristics of the system. Use care when handling ultracapacitors and to make sure that the terminals of the cells are clean before using. Remove any oxidation or other debris and dirt from the terminals using appropriate methods. Care should be taken not to alter the

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terminals in any way through the cleaning process so the selected cleaning method should have no influence on the terminal itself. If guidance is needed on treating a specific condition, contact Maxwell Applications Engineering and they will help you with your questions.

Most applications do not make use of single ultracapacitors but rather require them to be used in series or parallel strings to meet demands for energy and power. Below are the guidelines that are useful in making sure that the integration of the cells is done in such a way that the cells can be expected to provide long term reliability and good performance over lifetime. Since the cells are of marked difference in their size, construction, terminations and other characteristics it is appropriate to address the mounting considerations for each family separately. Therefore below, while there are some general guidelines for use of the cells in an integrated package, there is also a section devoted to each cell type with all mounting considerations for each one.

8.3 PC Series Ultracapacitor Mounting Considerations

8.3.1 Bending of the terminals

The PC cell line is designed with a very specialized glass to metal seal around the positive terminal pin in order to create a hermetic cell for in the device and to isolate the pin electrically from the cell body. When mounting or handling the PC cells use caution not to bend the terminal pins especially the positive pin. Bending moments applied to the pins can cause stress at the root of the pin (where it enters the cell) and the result can be a cracked glass seal. The consequence of such a condition is generally leakage of the electrolyte from the cell interior as well as degradation in part performance following that leakage. It is not always immediately evident that the glass seal is cracked when it is done. This may result in latent electrolyte leakage while the cell is in the application rather than exposing the crack existence directly by leaking when the cracking occurs. Maxwell Technologies provides the PC cells in a specifically bent pin configuration and uses a special tool and employs a specialized process developed to bend the pins without putting stress on that glass to metal seal. Please do not attempt to bend the pins of the PC products without first consulting Maxwell Technologies Inc. Maxwell Technologies may elect to void certain warranty provisions if pins are bent by customers without Maxwell consultation.

8.3.2 Soldering the Cells

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Soldering of the cells requires heat application and there is a level and duration of heat applied to the cell that will negatively affect its operating characteristics. Maxwell Technologies has published guidelines available on the Maxwell website (www.Maxwell.com) for cell soldering that characterize the thermal control required when soldering the cells. Please utilize these guidelines to ensure that the cells are not overheated during the soldering process.

8.4 BC Series Ultracapacitors Mounting Considerations

8.4.1 Bending of the tab terminals

The terminal tabs of the BC family of products are not intended to carry a moment load or to be bent in any way. Small deflections of the tabs are acceptable however should be avoided in order to be 100% safe regarding the tab integrity and strength. The terminals are fabricated of aluminum alloy and as such have poor fatigue characteristics as well as marginal stress resistance in bending. Bending of the tabs can result in cracking and failure at the bend point. In addition these bending moments are highest at the point where the terminal joins with the cell and translate into stress applied to the laser welded connection between the tab and the cell located at this point. This can result in detachment of the tab or leaking of the cell as the tab is "torn" from the cell breaking the laser welded connection points. Generally bending of the cell tabs should be avoided in all cases considering the BC family of cells.

8.4.2 Soldering the Cells

Soldering of the cells requires heat application and there is a level and duration of heat applied to the cell that will negatively affect its operating characteristics. Maxwell Technologies has published guidelines available on the Maxwell website (www.Maxwell.com) for cell soldering that characterize the thermal control required when soldering the cells. Please utilize these guidelines to ensure that the cells are not overheated during the soldering process.

8.4.3 Mechanical Impact on the Cells

The BC products are constructed of strength and weight optimized aluminum casing commonly referred to as the can. This can is pure

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aluminum and has the properties of pure aluminum. That is that the material is very malleable and can be formed without excessive force. Therefore if the BC products are subjected to high mechanical impulse as in the case of dropping the cell from a substantial height, it is possible that the cell can be dented or otherwise deformed as a result of the impact. Any cell sustaining an impact should be examined thoroughly both physically and electrically to be certain there has been no deformation in the form of denting or creasing or showing the signs of negative effects on the electrical properties of the cell. If in doubt, the cell should not be used. The consequence of using a dented cell can be electrolyte leakage, short circuit, high leakage current or a combination of those effects among others. The best practice is to discard a cell that has a deformation of the lid or the can.

8.4.4 Suspending the Cell from the terminals

The cells should be mounted as practically as possible such that dynamic application forces such as vibration accelerations or continuous motion accelerations and the static force of gravity are generally acting on the cell in a direction that is aligned along the axis of the welded tab terminals. In all cases, with the axially designed BC family it should be avoided that these dynamic forces are acting on the cell in the direction perpendicular to the axis of the terminal tabs. If mounting in this manner is a requirement of the application then the cell should be supported on the body of the cell rather than allowing the entire force applied to the cell to be carried by the tabs only. This can be accomplished by strapping, bonding with silicone or other adhesive or otherwise fixing the part to a substrate in which the substrate carries the load of the part that is transmitted through the adjunctive support. Failure to consider the dynamic loads placed on the cells during application may result in failure of the tabs through fatigue or strength failure resulting in system failure.

8.5 MC Series Ultracapacitors Mounting Considerations

8.5.1 Mechanically Supporting the Cells in Modules and Other Applications

When using the cells in a module or in other applications where the cell body is to be supported the following guidelines should be followed.

- Support the cell body over as much of the surface as is practical and possible

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- Support the cell body in at least two points along the length of the cell. Supporting in only one spot or location will result in the application of undesirable moments and forces on the cell terminals which are to be avoided.
- Mount the cell rigidly fixed in place such that potential displacement of the cell during application function is minimized. Do not mount the cell in such a way that enables it to freely move while being constrained by the terminals of the cell.
- Do not cover or otherwise conceal the vent of the cell by the mounting structure in such a way that it will constrain the ability of the vent to function when an over pressure condition is encountered in the cell. It is best to orient the cell to allow the vent to face free volume whereby deformation of the cell during a venting is not physically constrained. Consult with Maxwell Technologies Applications Engineering for guidance on this particular topic.
- Do not support the cell exclusively by the terminals. Regardless of cell orientation the body of the cell needs at least line to line support in more than one location in any application to ensure that the terminals are being protected from stress and potential failure modes.

8.5.2 Bending Moment Applied to the Lid of the Cell

The MC cell has a "floating" lid design in which the sealing of the cell is dependent upon the normal force and deflection that the lid puts on the O-ring inside the cell providing the seal. This force and deflection is set at the factory upon assembly of the cells and influence on this setting should be avoided by mounting the cells in such a way as to minimize the possible application of bending forces on the lid of the cell. Bending moments applied to the lid can cause the lid to rock on the o-ring creating a differential compression across the o-ring and possibly resulting in leakage of the electrolyte from the cell. It is known that upon the application of bending moment to the lid of the cells that exceeds a specific level that the cell lid can be permanently displaced and not return to its factory set position. This can result in electrolyte leakage as a result of changing that lid position. Therefore application of bending moment to the lid of the MC cells should be avoided when designing and integrating the cells in order to protect the cells from the impact of lid movement and the expected increased potential for leakage of the electrolyte. Configurations of

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mounting should be avoided whereby dynamic or static forces apply bending moments to the negative terminal (lid) of the cell.

Bending moments can be applied to the cell in a number of ways dependent upon mounting design. It is a particularly risky practice to mount the cells end to end with rigid connections between the terminals of the cells or to mount them directly terminal to terminal. Mounting the cells in this fashion makes it very difficult to avoid these bending moments being described unless the cell body is fixed rigidly prior to interconnection and then the interconnect is established and is designed in such a way that it avoids application of bending moments on that lid. That is because the cell has tolerances in concentricity, orientation and size of the terminals that preclude perfect alignment of the cells when mounted terminal to terminal. Then relying on the alignment of those terminals to support the cells without moments is inappropriate. It is not recommended to mount cells in this fashion unless the mounting and interconnection accounts for all alignment and tolerances that lead to stress on the terminals and is designed to eliminate all the stress possibilities.

Likewise consideration must be given to the influence of interconnect cables on the cell lids. In high current applications stiff interconnect cables can apply bending moments unless proper strain relief techniques are utilized. Consider this when designing the interface of the cells to the system.

Failure to respect this requirement to avoid bending moments on the terminals of the cell may, at the discretion of Maxwell Technologies, result in compromise of warranty provisions in the event of cell failures due to leaking electrolyte or other failures as induced by the application of bending moments on the lid of the cell.

8.5.3 Torsion Applied to the Lid of the Cell

Given the floating lid design of the MC cells then torque applied to the lid of the cell during mounting can result in “spinning” of the lid and eventually breaking of the interconnect between the lid and the electrode internal to the cell or otherwise compromising of the seal. Therefore the application and mounting of the cell must be such that no torque is applied to the lid with the exception of terminal tightening torque in the case of applications that employ the cells with threaded terminals. And in the case of applying cells with threaded terminals, care must be taken to ensure that tightening torque does not ever exceed the recommended value as noted on the Maxwell specifications for the cell. Failure to respect this specification can

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result in lid spinning and severe failure of the cell immediately or later in the application. The cells must be fixed in such a way that no torque can be dynamically applied to the lid of the cell in the application.

8.5.4 Normal Forces Applied to the Lid of the Cell

Care should be taken in the application of the cell to avoid excessive axial forces either compressive or tensile to the positive or negative terminals of the cells. Again the floating lid design is susceptible to deformations under stress and therefore it is good practice to strive for a neutral force design where all forces applied to the cell are resolved between the body of the cell and the substrate to which it is mounted. The cell is most robust in this axial direction and therefore it is of much less concern than avoiding bending moments or torsion on the cell lid but care and good engineering should be employed to miminze this static or dynamic axial forces that may be applied to the cell during usage in mounting or in the application.

8.5.5 Mechanical Impact on the Cells

The MC products are constructed of a strength and weight optimized aluminum casing commonly referred to as the can. This can is pure aluminum and has the properties of pure aluminum. That is that the material is very malleable and can be formed without excessive force. Therefore if the MC products are subjected to high mechanical impulse as in the case of dropping the cell from a substantial height, it is possible that the cell can be dented or otherwise deformed as a result of the impact. Any cell sustaining an impact should be examined thoroughly both physically and electrically to be certain there has been no deformation in the form of denting or creasing or showing the signs of negative effects on the electrical properties of the cell. If in doubt, the cell should not be used. The consequence of using a dented cell can be electrolyte leakage, short circuit, high leakage current or a combination of those effects among others. The best practice is to discard a cell that has a deformation of the lid or the can.

8.5.6 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

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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.

8.5.7 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. Use a highly conductive aluminum-aluminum antioxidant. For example, Noalox® Anti-Oxidant Compound available from IDEAL is a viable choice. There are many other vendors that supply equivalent compounds.

8.5.8 Using Threaded Interconnects

Threaded terminals are avaiable on the MC line of ultracapacitors produced by Maxwell. It is important that proper precautions be applied when using threaded interconnects from cell to bus bar. Maxwell recommends the use of a conductive antioxidant on the threads which functions as a lubricant to facilitate threading of the nut or other fastener onto the threaded post to avoid galling and damage to the aluminum threaded terminals. Over the useage time of the cell, the antioxidant also functions to protect the thread from further oxidation which can result in high ESR interconnections and heating of the cell or loss of high power performance. There is a published guideline on the Maxwell website specifically describing the proper

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application of this antioxidant and use with threaded interconnects. Please consult that document when using the cells with the threaded terminals to make up connections that will have long lifetime reliability.

8.5.9 Welding Cell Interconnects

Maxwell provides cells with terminal configurations that are suitable for welding to bus bars or other structures/substrates. In all cases when welding cells together heating level, distribution and duration must be minimized. The following weld processes are recommended as methods to create interconnects:

- Laser Welding
- Resistance Welding
- Ultrasonic Welding

These three welding techniques all have the special characteristic that they can be executed with the minimum application or generation of heat given that they act in such a localized focused area. Maxwell Technologies Inc. has extensive experience with all three techniques and is available for consultation on the proper methods to employ these welding techniques. In all cases however, the customer is responsible for appropriate application of the welding to interconnect cells. If specific application support is requested Maxwell will support the request to the extent possible to enable good welding to be employed.

By contrast it expressly not recommended that TIG or MIG or other carbon arc welding technology be utilized to interconnect cells and bus bars. These welding techniques generate broad intense levels of heat at the weld zone and it has been shown in Maxwell testing that using these techniques are deleterious to the electrical performance of the cells. Therefore the use of these welding techniques is not supported by Maxwell. Choosing to utilize one of these methods will result in voiding of certain warranty provisions for the cells. Therefore these welding techniques should be avoided when welding bus bars to the cells or welding the cell to other structures.

8.6 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.

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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%.

8.7 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 Rth (oC/W), for products based on free convective cooling. If active cooling is employed further improvements can be made, so the provided Rth should be considered a guideline.

Utilizing the provided Rth for the products an anticipated temperature rise can be predicted based on the application current and the duty cycle. This

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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:

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

where D = duty cycle (0 to 1), I = current, Rdc = dc resistance or low frequency based on constant discharge (non pulsing). Alternatively for ac currents the high frequency resistance should be utilized for pulsing currents. Please refer to the product datasheet for the thermal resistance, Rth, constants determined for the products assuming free convection.

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9 Safety Information

9.1 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 oC 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 the acetonitril 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 provided in the acetontril MSDS.

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9.2 Disposal

Ultracapacitors are composed of aluminum, carbon, paper and an organic electrolyte. Ultracapacitors contain no heavy metals or toxic materials hazardous to the environment. Municipalities differ in how materials are classified for disposal. An MSDS for Acetonitril, a Product Information Sheet and a shipping guidelines document are 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.

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10 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 and ISO/TS 16949 (automotive) certified company. Our European facility is certified to the ISO 14001 (environmental management standard). 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.

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.

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Contact Information:

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. - Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

Refer to our website **www.maxwell.com** for full terms and conditions.