2. Features of small li-ion rechargeable batteries

2-1 Key features of small li-ion rechargeable batteries

Small li-ion rechargeable batteries have higher capacity and less leakage current than electric double-layer capacitors. Compared with standard lithium-ion rechargeable batteries, they have higher-speed charging and discharging, longer life, and better safety. The SLB batteries are capable of high-power discharge, which is extremely difficult to achieve with standard lithium-ion rechargeable batteries. They can be discharged over longer periods of time, which is not possible with electric double-layer capacitors.

2-2 Comparison with electric double-layer capacitors

Small li-ion rechargeable batteries contain nearly 50 times as much energy as its electric double-layer capacitors of the same size. Our small li-ion rechargeable batteries can be used in place of electric double-layer capacitors to power devices for longer periods of time.

* The following data are not guaranteed values.

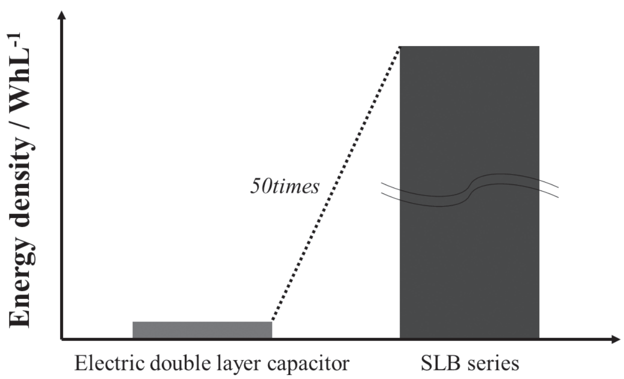

Figure 2-1. Comparison of volume energy densities of NICHICON's electric double-layer capacitors and its small li-ion rechargeable batteries

Materials in small li-ion rechargeable batteries" store and release electrical energy through the electrochemical reactions of lithium ions in the electrode active materials and the electrolyte. In the charged state, the self-discharge of the battery is low, as the electrode active materials are chemically stable by the charged voltage. The anode active material, lithium titanate, has excellent thermal stability, and resists self-discharge at high-temperature. Figure 2-2 shows the self-discharge behavior of a fully charged ϕ3x7L; 0.35mAh products at different ambient temperatures.

After being charged to 2.7V and stored at 60°C for 30

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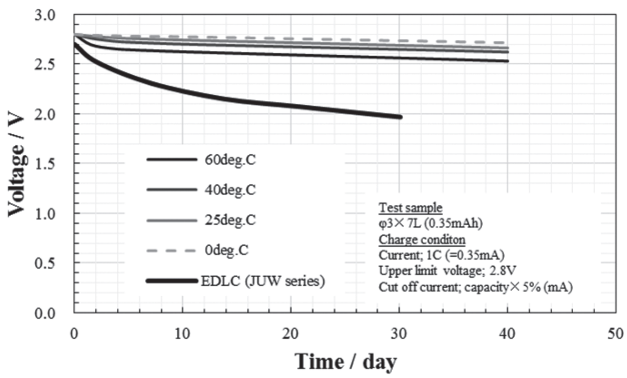

Figure 2-2. Changes in voltage on the ϕ3x7L; 0.35mAh when stored fully charged at different temperatures

days, NICHICON's electric double-layer capacitors drop in voltage to 1.97V. By contrast, after being charged to 2.8V, Small li-ion rechargeable batteries (ϕ3x7L) drop in voltage to 2.6V, indicating the leakage current is small.

Because this product demonstrates little self-discharge, they can be used for a long period of time without charging. This allows them to be used in conjunction with energy-harvesting technology, improving efficiency as they can store energy for a long period of time after being charged.

2-3 Comparison with general lithium-ion rechargeable batteries

2-3-1 Ultra-fast charge/discharge function

Small li-ion rechargeable batteries are superior to standard lithium-ion rechargeable batteries in their charge/discharge characteristics. Standard lithium-ion rechargeable batteries typically take about 1 hour to charge, while product can be charged and discharged at up to 20C (20 times the current value needed for charging in one hour; for the ϕ3x7L; 1C=0.35mA, 20C=7mA). Figure 2-3 shows the charging time and charging rate for different C rates on the ϕ3x7L. If charged at 20C, the battery could be charged to 80% of a full charge in around three minutes.

The ability to charge the batteries rapidly optimizes their use in devices that require short charging times and when charging is interrupted or forgotten.

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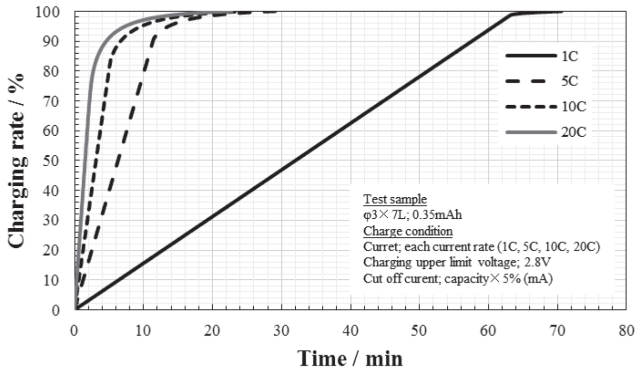

Figure 2-3. Relationship between charging time and charging rate of ϕ3x7L at different charging current rates

Figure 2-4 shows discharging time versus remaining capacity for the ϕ3x7L at different C rates. If discharged at a current value of 20C, the maximum guaranteed discharging current value, the battery could be discharged completely in approximately 3 minutes. Due to the extremely large discharge current given the product's size, the battery is well suited for use in devices that require high power and a small size.

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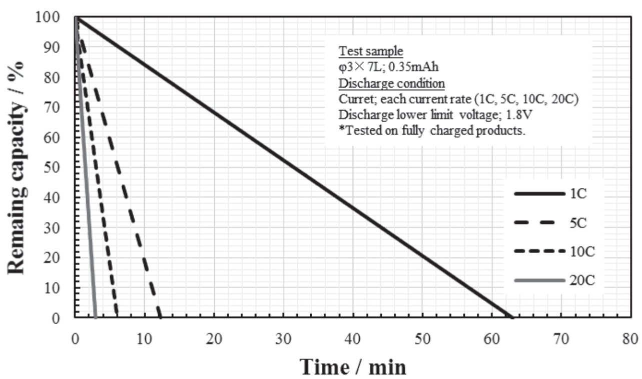

Figure 2-4. Relationship between discharging time and remaining capacity of ϕ3x7L at different discharging current rates

2-3-2 Low-temperature characteristics

Small li-ion rechargeable batteries have excellent low-temperature characteristics. Standard lithium-ion rechargeable batteries charging at temperatures significantly below 0°C becomes difficult, because lithium ions are less likely to be adsorbed by the anode (graphite) and tend to condense as lithium metal. Also, if the temperature is extremely low, dendrites form when lithium metal condenses, which can penetrate through the separator between the cathode and anode, causing an internal short circuit. If an internal short circuit occurs, an extremely high current passes through the short-circuit area, generating heat. Next the anode and electrolyte react causing decomposition within the electrolyte followed by the cathode and electrolyte reacting. Sparks from the short circuit and the release of oxygen due to the collapse of the cathode's crystal structure can result in an oxygen combustion reaction. Various exothermic reactions occur one after another resulting in thermal runaway and fire. The SLB use of lithium titanate for the anode, does not suffer thermal runaway due to its low resistance and can be charged and discharged at extremely low temperatures (-30°C).

Figure 2-5 shows charging curves for the ϕ3x7L being charged at 1C for various ambient temperatures. Figure 2-6 shows the discharging curves. At low temperatures, the reaction resistance increases for the electrolyte within the device and between the electrode and electrolyte, necessitating a higher voltage to initiate the charge (discharge), and capacity decreases. At -30°C, charge capacity decreases to around 52% of the level at room temperature, and discharge capacity falls to around 46%. Standard lithium-ion rechargeable batteries have higher resistances, so operation at extremely low temperatures can result in overcharge/over-discharge voltages. Thermal runaway can result in ruptures or fires, so in many cases temperature management in cells that contain thermistors within battery packs is designed to prevent low-temperature operation. The SLB, however, can be used in cold climates and remain safe to use.

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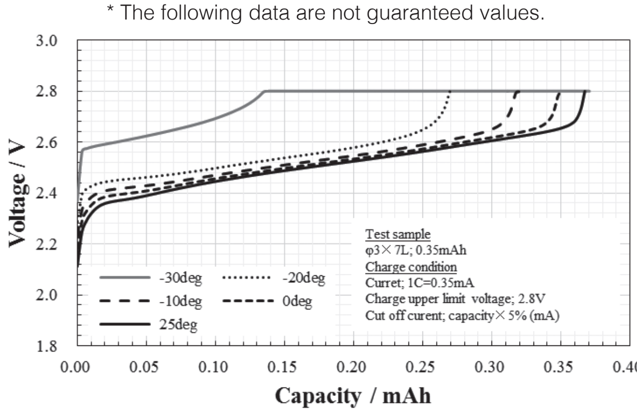

Figure 2-5. Charging curves for ϕ3x7 at a current value of 1C for different ambient temperatures

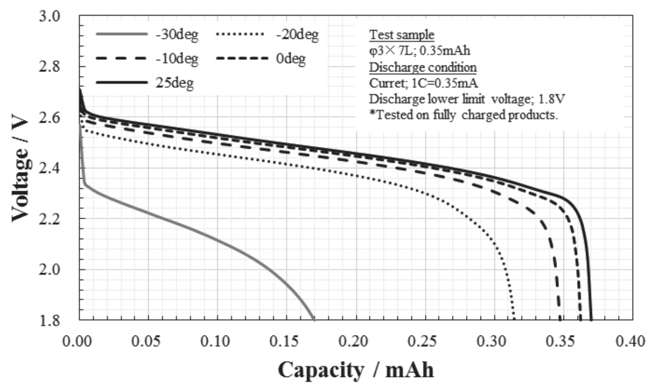

Figure 2-6. Discharging curves for ϕ3x7L at a current value of 1C for different ambient temperatures

2-3-3 Overcharge resistance

Small li-ion rechargeable batteries are more resistant to overcharging than standard lithium-ion rechargeable batteries. Product characteristics for this battery indicate its maximum rated voltage at 2.8V, but no significant capacity degradation was observed in charge/discharge cycle tests involving repeated charging to more than 2.8V. Figure 2-7 shows the results of a charge/discharge cycle test conducted on the ϕ3x7L, where the battery is repeatedly charged to 3.3V at a current value of 10C and discharged to 1.8V, indicating the retention rate for 1C discharge capacity based on the number of cycles. Even when repeatedly overcharged to 3.3V for 1,500 cycles, the retention rate was 98% of initial capacity.

These results suggest that even when operating in conditions where the charging voltage is not controlled no sudden degradation in the product's characteristics occurs.

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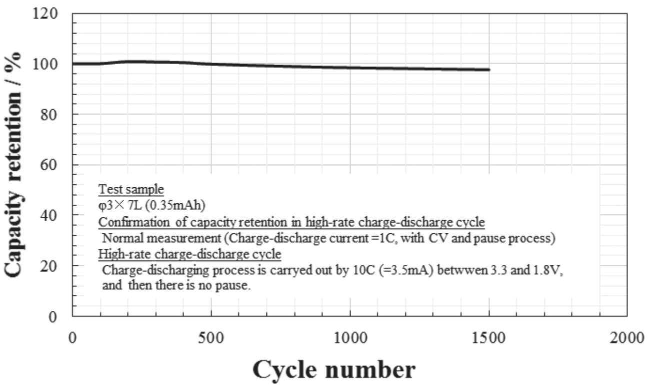

Figure 2-7. Capacity retention rate versus number of charge/discharge cycles when ϕ3x7L charged to 3.3V

2-3-4 Over-discharge resistance

Small li-ion rechargeable batteries are more resistant to over-discharging than standard lithium-ion rechargeable batteries. Product characteristics for this battery indicate its rated minimum voltage at 1.8V, but when subjected to a fully discharged cycle test where the battery is short-circuited for a long period of time, it could again be charged and discharged.

For example, the SLB could be used in temperature sensors for clean-energy applications. If used in energy harvesting of solar power, it could remain uncharged for a long period of time. Figure 2-8 indicates changes in discharge capacity if the ϕ3x7L is attached to a resistor (15Ω) and stored at different ambient temperatures. No significant decline in capacity was observed at different temperatures even when stored fully charged for 1,000 hours.

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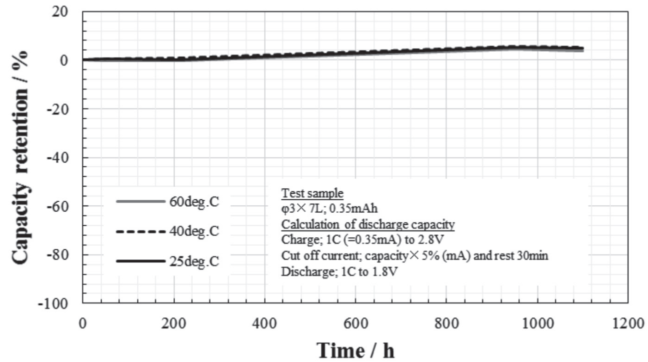

Figure 2-8. Rate of change in discharge capacity when stored fully charged at different ambient temperatures

Figure 2-9 shows the rate of change in discharge capacity for the ϕ3x7L following charge/discharge cycles between 2.8V to 0V at different ambient temperatures. Although the decrease in capacity was more significant than in a test where the battery was stored fully discharged, after 1,800 cycles the battery's capacity decreased by approximately 30% at 60°C and by 22% at 40°C, indicating the product would not suddenly fail.

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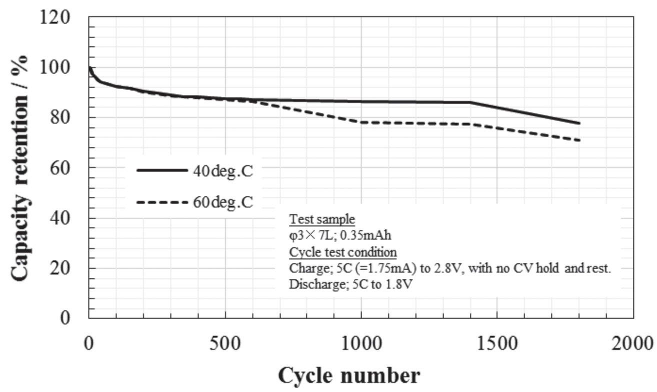

Figure 2-9. Rate of change in discharge capacity at different ambient temperatures following a full discharge cycle to 0V