Welcome to Battery University!

Battery University™ is a free educational website that offers hands-on battery information to engineers, educators, media, students and battery users alike. The tutorials evaluate the advantages and limitations of battery chemistries, advise on best battery choice and suggest ways to extend battery life.

The material is based on "Batteries in a Portable World – A Handbook on Rechargeable Batteries for Non-Engineers" (3rd edition). The 328-page book is available to purchase on-line. Battery University™ is sponsored by Cadex Electronics Inc., a manufacturer of advanced battery chargers and test devices.

Isidor Buchmann
CEO and Founder, Cadex Electronics Inc.

How does Internal Resistance affect Performance?

With the move from analog to digital, new demands are placed on the battery. Unlike analog portable devices that draw a steady current, the digital equipment loads the battery with short, heavy current spikes.

One of the urgent requirements of a battery for digital applications is low internal resistance. Measured in milliohms, the internal resistance is the gatekeeper that, to a large extent, determines the runtime. The lower the resistance, the less restriction the battery encounters in delivering the needed power spikes. A high mW reading can trigger an early 'low battery' indication on a seemingly good battery because the available energy cannot be delivered in the required manner and remains in the battery

Figure 1 demonstrates the voltage signature and corresponding runtime of a battery with low, medium and high internal resistance when connected to a digital load. Similar to a soft ball that easily deforms when squeezed, the voltage of a battery with high internal resistance modulates the supply voltage and leaves dips, reflecting the load pulses. These pulses push the voltage towards the end-of-discharge line, resulting in a premature cut-off. As seen in the chart, the internal resistance governs much of the runtime.

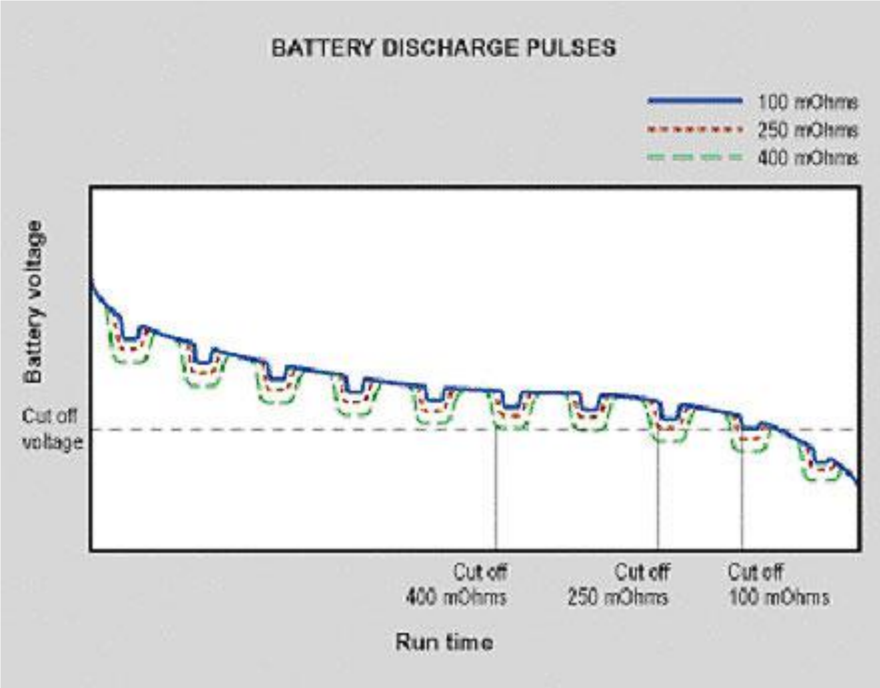

Figure 1: *Discharge curve on a pulsed load with diverse internal resistance. This chart demonstrates the runtime of 3 batteries with same capacities but different internal resistance levels.*

Talk-time as a function of internal resistance

As part of ongoing research to measure the runtime of batteries with various internal resistance levels, Cadex Electronics examined several cell phone batteries that had been in service for a while. All batteries were similar in size and generated good capacity readings when checked with a battery analyzer under a steady discharge load. The nickel-cadmium pack produced a capacity of 113%, nickel-metal-hydride checked in at 107% and the lithium-ion provided 94%. The internal resistance varied widely and measured a low 155 mOhm for nickel-cadmium, a high 778 mOhm for nickel-metal-hydride and a moderate 320 mOhm for lithium-ion. These internal resistance readings are typical of aging batteries with these chemistries.

Let's now check how the test batteries perform on a cell phone. The maximum pulse current of a GSM (Global System for Mobile Communications) cell phones is 2.5 amperes. This represents a large current from a relatively small battery of about 800 milliampere (mAh) hours. A current pulse of 2.4 amperes from an 800 mAh battery, for example, correspond to a C-rate of 3C. This is three times the current rating of the battery. Such high current pulses can only be delivered if the internal battery resistance is low.

Figures 2, 3 and 4 reveal the talk time of the three batteries under a simulated GSM current of 1C, 2C and 3C. One can see a direct relationship between the battery's internal resistance and the talk time. nickel-cadmium performed best under the circumstances and provided a talk time of 120 minutes at a 3C discharge (orange line). nickel-metal-hydride performed only at 1C (blue line) and failed at 3C. lithium-ion allowed a moderate 50 minutes talk time at 3C.

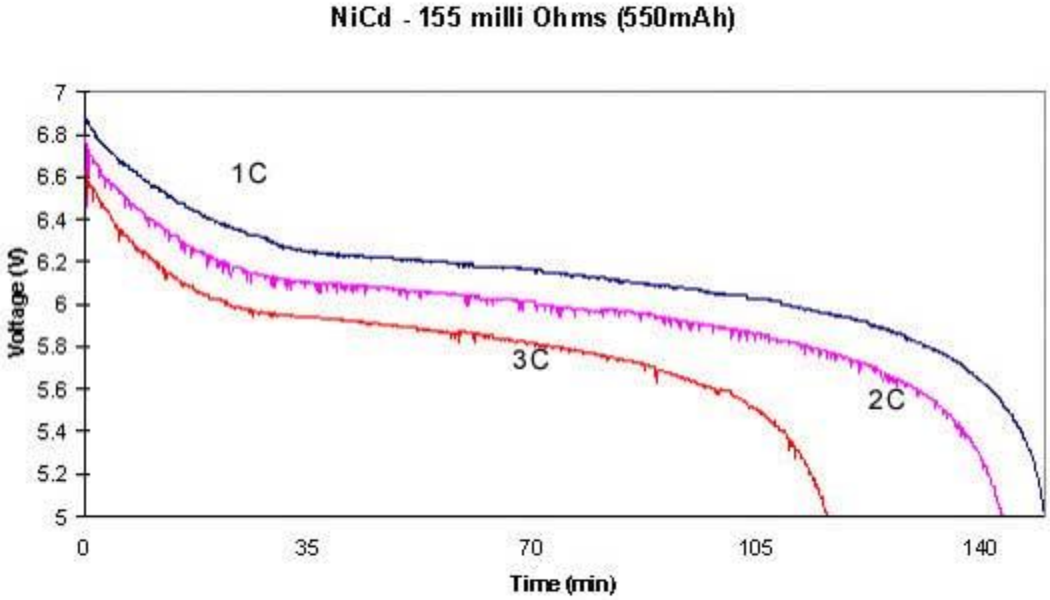

Figure 2: *Discharge and resulting talk-time of nickel-cadmium at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 113%, the internal resistance is a low 155 mOhm.*

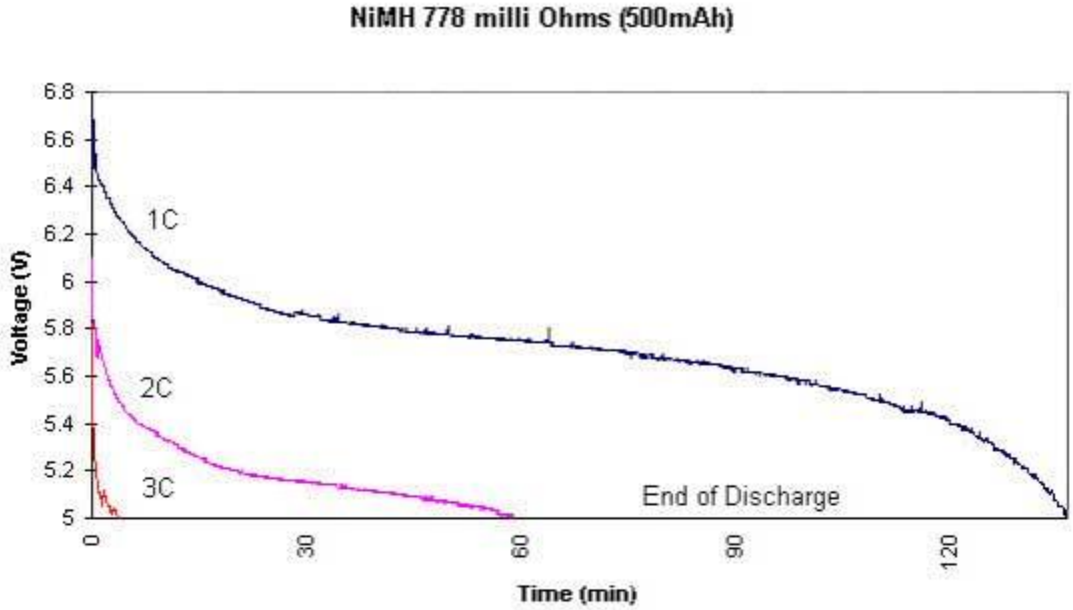

Figure 3: *Discharge and resulting talk-time of nickel-metal-hydride at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 107%, the internal resistance is a high 778 mOhm.*

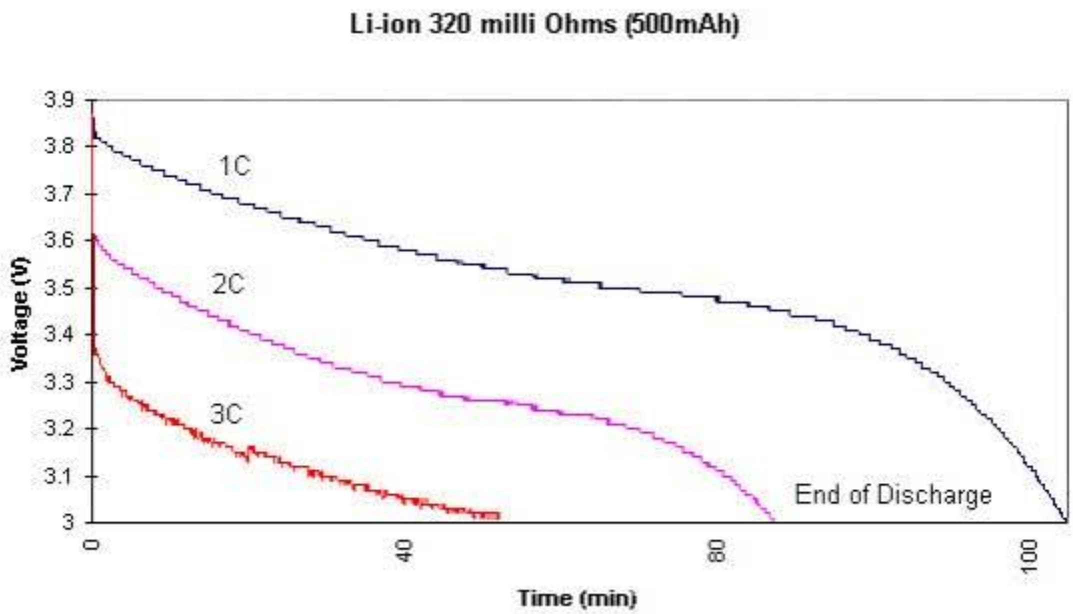

Figure 4: *Discharge and resulting talk-time of a lithium-ion battery at 1C, 2C and 3C under the GSM load schedule. The battery tested has a capacity of 94%, the internal resistance is 320 mOhm.*

Internal resistance as a function of state-of-charge

The internal resistance varies with the state-of-charge of the battery. The largest changes are noticeable on nickel-based batteries. In Figure 5, we observe the internal resistance of nickel-metal-hydride when empty, during charge, at full charge and after a 4-hour rest period.

The resistance levels are highest at low state-of-charge and immediately after charging. Contrary to popular belief, the best battery performance is not achieved immediately after a full charge but following a rest period of a few hours. During discharge, the internal battery resistance decreases, reaches the lowest point at half charge and starts creeping up again (dotted line).

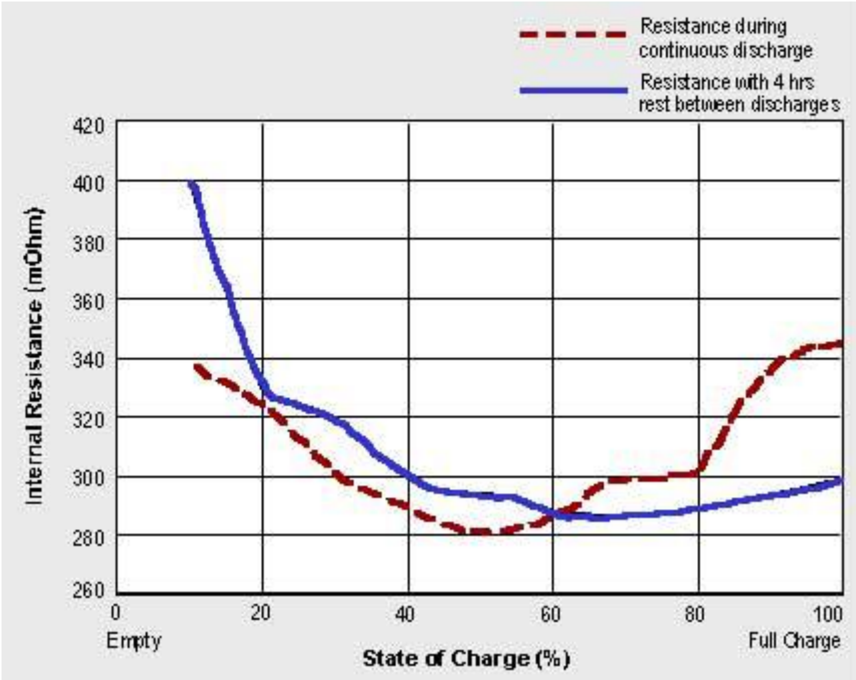

Figure 5: *Internal resistance in nickel-metal-hydride. Note the higher readings immediately after a full discharge and full charge. Resting a battery before use produces the best results.*
References: Shukla et al. 1998. Rodrigues et al. 1999.

The internal resistance of lithium-ion is fairly flat from empty to full charge. The battery decreases asymptotically from 270 mW at 0% to 250 mW at 70% state-of-charge. The largest changes occur between 0% and 30% SoC.

The resistance of lead acid goes up with discharge. This change is caused by the decrease of the specific gravity, a depletion of the electrolyte as it becomes more watery. The resistance increase is almost linear with the decrease of the specific gravity. A rest of a few hours will partially restore the battery as the sulphate ions can replenish themselves. The resistance change between full charge and discharge is about 40%. Cold temperature increases the internal resistance on all batteries and adds about 50% between +30°C and -18°C to lead acid batteries. Figure 6 reveals the increase of the internal resistance of a gelled lead acid battery used for wheelchairs.

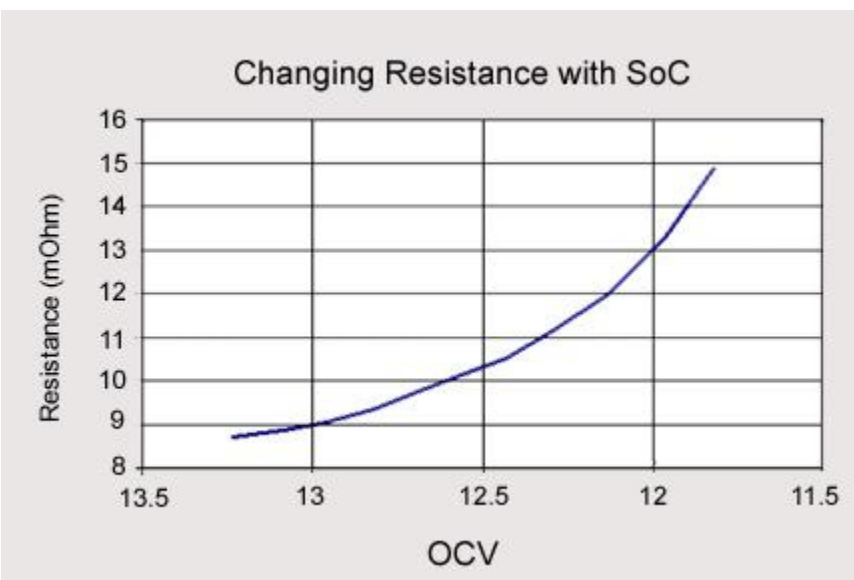

Figure 6: *Typical internal resistance readings of a lead acid wheelchair battery. The battery was discharged from full charge to 10.50V. The readings were taken at open circuit voltage (OCV).*
Cadex battery laboratories.