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Experimental Analysis of Batteries under Continuous and Intermittent Operations

S. Castillo, N. K. Samala, K. Manwaring, B. Izadi and D. Radhakrishnan
Department of Electrical and Computer Engineering
State University of New York
New Paltz, NY 12561
samala49@newpaltz.edu, {bai, damu}@engr.newpaltz.edu

Abstract

Battery lifetime extension is a primary design objective for portable systems. This paper investigates how non-ideal properties of a battery impacts its lifespan. More specifically the paper analyzes experimental discharge characteristics of Alkaline, Nickel Cadmium, Nickel Metal Hydride and Lithium Ion batteries for both continuous and intermittent operation. Our experimental results revealed that, the lifespan of the alkaline battery increased by intermittent operation by 28% compared with continuous operation. The lifespan of the rechargeable batteries (Nickel-Cadmium, Nickel-Metal Hydride and Lithium Ion) however, either were not affected or were reduced by intermittent operation.

Keywords: Batteries, Intermittent operation, Continuous operation, Discharge characteristics, Lifespan.

1. Introduction

There is a high demand for long running batteries due to ever-increasing applications in mobile communications and portable equipment. Battery powered electronic systems, and integrated circuits within them, account for a large and rapidly growing revenue segment of the semiconductor industries. Unfortunately the projected improvements in the capacity of the batteries are much slower than what is needed to support the increasing complexity, functionality and performance of the systems they power. Figure 1 illustrates the widening battery gap between trends in processor power consumption [1] and improvements in battery capacity [2]. Bridging this gap is a challenge that system designers must face for the foreseeable future. Hence, low power has emerged as a major design consideration for the VLSI designer in recent years.

To reduce the power usage, some researchers have examined low power design techniques [3, 4] to minimize the average power consumption. This is either done by reducing the average current of the circuit while maintaining the supply voltage, or by scaling the supply

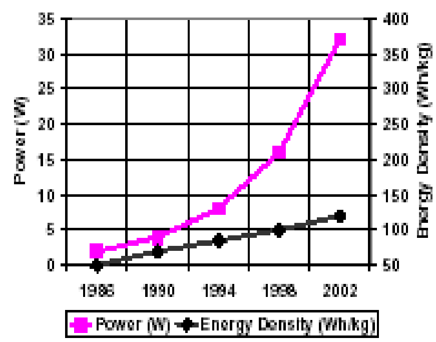


Figure 1. A widening "battery gap"

voltage statically or dynamically. Other researchers have focus on system level approaches that manage power usage in battery-operated, mobile applications [5, 6]. Often these schemes are based on a battery model [3, 4] that assumes the battery subsystem as an ideal source of energy, which stores and delivers a fixed amount of energy at a constant output voltage. In reality, however, it may not be possible to utilize the full stored energy of a battery since most electronic devices cease to operate once the supply voltage drops below a threshold voltage.

To get prolonged operation from most battery operated devices they must either be designed to minimize their power drain from the battery or find ways to improve the battery characteristics. The implications of non-ideal battery discharge phenomena has been analyzed by several researchers [5, 6, 7]. Martin [6] showed how the non-linear dependency of the battery capacity from discharge current should be taken into account when setting the frequency of operation of a battery powered motherboard. Pedram et al. [7] analyzed the supply voltage and speed setting for maximizing the lifetime performance product. Wu et al. [8] proposed a dual battery power management policy that switches between a low discharge rate (high-capacity) cell and a high discharge rate (lower capacity) cell depending on the load current absorbed by the system. Most of these approaches are applied at the design time.

In this paper, we report on our experimental evaluation of non-ideal characteristics of Alkaline, Nickel Cadmium, Nickel Metal Hydride and Lithium batteries under continuous and intermittent operations. The rest of the paper is organized as follows: Section 2 provides a brief background of the battery types and characteristics. Sections 3 and 4 present our experimental setup and simulation results for both continuous and intermittent operations. Finally, concluding remarks are given in Section 5.

2. Battery Types and Characteristics

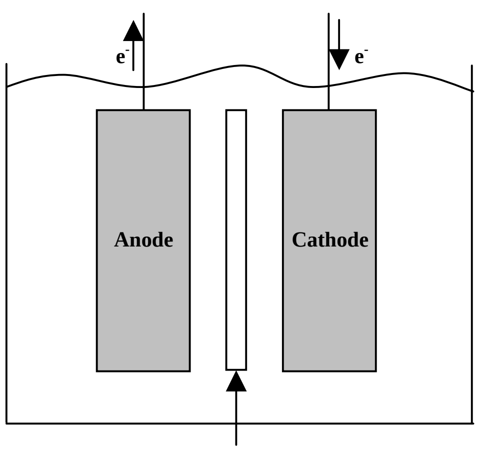


Figure 2. Basic Structure of a Battery

A battery consists of an anode, a cathode and an electrolyte, as shown in Figure 2. The electrolyte separates the two electrodes and provides a mechanism for the transfer of charge between them. During battery discharge, oxidation at the anode results in the generation of the electrons, which flow through the external circuit. Moreover, positively charged ions, by diffusion, move through the electrolyte towards the cathode. Reduction reaction occurs at available reaction sites in the cathode, generating negatively charged ions, which combines with the positive ions to generate an insoluble compound that gets deposited on the cathode. Sites where the compound is deposited gets inactive, making them unavailable for further use. As discharge proceeds, more and more reactions sites are made unavailable, eventually leading to a state of complete discharge.

The materials that make up a battery are normally part of the name of the battery, such as "Alkaline", "Lithium", "Ni-Cd (Nickel-Cadmium)". Some of the battery technologies that have been developed over the last two decades for portable devices are as follows:

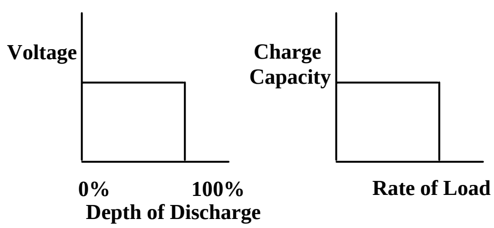
- **Alkaline:** This cell design gets its name from its use of alkaline aqueous solutions as electrolytes. Alkaline cells have many acknowledged advantages over zinc-carbon, including a higher energy density, longer shelf life, superior leakage resistance. Its lower internal resistance, allows it to operate at high discharge rates over a wider temperature range.

- **Nickel Cadmium:** This is a mature technology and has been successfully used for several decades to develop rechargeable batteries for portable electronic devices. Its advantages include low cost, and high discharge rates. While Ni-Cd technology has been losing ground in recent years owing to its low energy density and toxicity, it is still used in low cost applications like portable radios and CD/Tape players.

- **Nickel Metal-Hydride:** These batteries have been in wide spread use in recent years for powering laptop computers. They have roughly twice the energy density of Ni-Cd batteries. However, they have shorter life cycle. Moreover, they are inefficient at high rates of discharge and are expensive.

- **Lithium Ion:** This is the fastest growing battery technology today. It has significant higher energy density and twice the life cycle of a Ni-MH battery. Lithium Ion batteries are more sensitive to characteristics of the discharge current. They are more expensive than Ni-MH batteries and can be unsafe when improperly used. However, longer lifetimes have made them the most popular battery choice for notebooks, PDAs and cellular phones.

From the system designer's point of view, a battery cell is characterized by its nominal open circuit voltage (V_{oc}) and its cutoff voltage (V_{cut}). The cutoff voltage is the voltage at which most electronic devices consider the cell to be discharged. The battery lifetime is expressed as seconds elapsed until a fully charged cell reaches its cutoff voltage.



(a) Constant Voltage (b) Constant Capacity

Figure 3. Characteristics of an Ideal Battery

Figure 3 depicts the characteristics of an ideal battery, which has constant voltage throughout a discharge. The voltage drops instantly to zero when the battery is fully discharged as shown in Figure 3(a). Figure 3(b) represents a constant capacity for all load values. In practice, however, the voltage decreases with time and the battery is considered exhausted when its output voltage falls below V_{cut}. In this paper, we set V_{cut} as 80% of the nominal voltage. Two additional factors that differentiate real battery model from ideal battery model are rate capacity effects and charge recovery effects. Rate capacity effects are due to dependency between the actual capacity of a battery and the magnitude of the discharge current. Charge recovery effects are due to recovery of charge during the idle period. This characteristic is also referred as the relaxation phenomenon and is based on the concentration of the active species, which are charged ions such as Li^+ for Lithium Ion insertion cell. These active species are uniformly distributed at electrode-electrolyte interface at zero current. During discharge, the active species are consumed at the cathode-electrolyte interface and are replaced by new active species that move from electrolyte solution to cathode through diffusion. However, as the intensity of the current increases, the concentration of active species decreases at the cathode and increases at the anode. Hence, diffusion phenomenon is unable to compensate for the depletion of active materials near the cathode. As a result, the concentration of active species reduces near the cathode, decreasing the cell voltage. However, if the cell is allowed to idle in between discharges, concentration gradient decreases because of diffusion, and charge recovery takes place at the electrode. As a result, the energy delivered by the cell, and hence the lifetime, increases. The objective of this research has been to experimentally evaluate this phenomenon for different types of batteries.

3. Battery Characteristics Under Continuous Operation

Table 1 lists the batteries that we used in our experiments. Figure 4 illustrates the setup that we used to control the discharging of the battery as well as to make the necessary battery characteristic measurements. We used a Vernier LabPro as a data collection interface between the voltage sensor and the PC. The device allows the PC to monitor up to four analog sensors and two digital sensors.

Figure 5 shows the discharge characteristics of an Alkaline battery for different V_{cut} and also indicates fairly linear characteristic across different loads. Accordingly, a 1Ω and 10Ω resistor would yield 5 and 125 hours of service, respectively. Hence, we started our experiment with a 1Ω resistor per Figure 4. The LabPro program was setup to record the battery characteristic every 5 seconds. Figure 6 shows our experimental results for continuous operation of an Alkaline battery with a 1Ω load.

Table 1. Specifications of four different batteries

Type	Voltage	Capacity
D size Non Rechargeable Alkaline	1.5v	1800mAh
D size Rechargeable Nickel Cadmium	1.2v	2000mAh
D size Rechargeable Nickel Metal Hydride	1.2v	4500mAh
Rechargeable Lithium Ion cell phone battery	3.7v	1400mAh

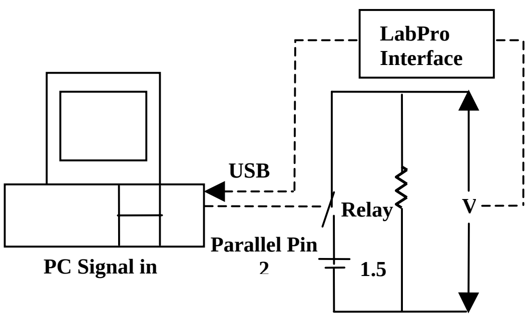


Figure 4. Battery Lifetime Measurement Setup for Continuous Operation

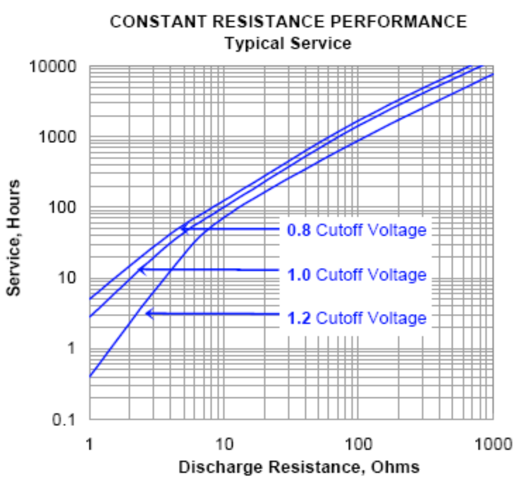
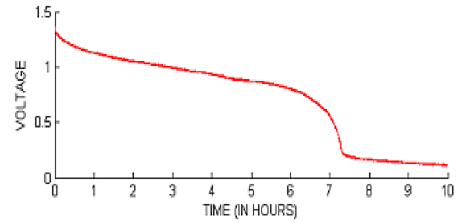
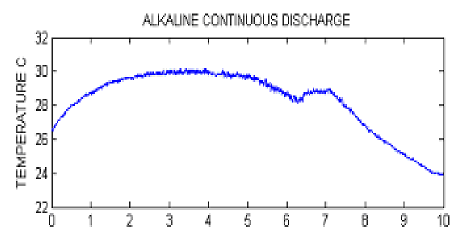


Figure 5. Data sheet for Alkaline Batteries

Figure 6(a) confirms the manufacture data per Figure 5. The result also illustrates that after about six hours, the battery begins to deteriorate. We next monitored the battery temperature, during this period, to investigate the effect of heat, as a possible cause of this deterioration. Figure 6(b) indicates that, after an initial warm-



(a) Continuous discharge for Alkaline Battery



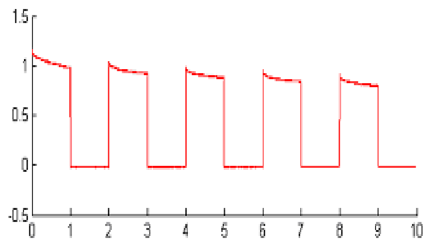
(b) Temperature Curve for Continuous Discharge

Figure 6. Voltage and Temperature Characteristics of an Alkaline Battery

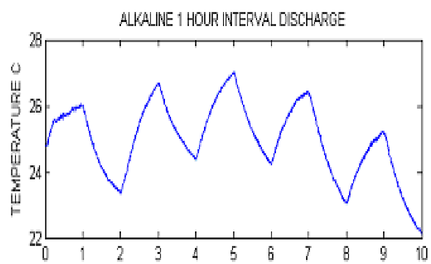
up, the temperature is fairly stable during the lifetime of the battery. During the deterioration period (between six and seven hours of usage), the temperature increases slightly. After this period, the battery for all practical purpose is considered exhausted. We attained similar results for the continuous operation of other batteries.

4. Battery Characteristics Under Intermittent Operation

We used the set up in Figure 4 for the intermittent operation as well. We used a Matlab program to control the relay via the parallel port. Figure 7 illustrates the voltage and temperature measurements of the Alkaline battery under intermittent operation by turning the relay in Figure 4 on and off every fifteen minutes. Figure 7(a) verifies that, after each rest period, the starting voltage is slightly higher than the voltage prior to the same rest period. The overall temperature characteristics of continuous and intermittent operations are similar. However, the overall temperature under intermittent operation is slightly lower due to regular cooling off periods.



(a) Voltage



(b) Temperature

Figure 7. Voltage and Temperature Characteristics Under Intermittent Operation

We next compared the Alkaline battery's voltage characteristics under continuous and intermittent operations. Note that the graphs of the intermittent operations are manipulated by removing segments of Figure 7(a) that correspond to the periods where the battery is idle. We also examined the effect of different rest periods on the battery characteristics by setting the time intervals to turn the relay on and off to thirty minutes. Figure 8 illustrates the result for Alkaline battery under continuous and intermittent operations. To compare the graphs, we define the time a battery takes to discharge to its cutoff voltage as the cutoff time (t_{cut}). According to Figure 8, t_{cut} for continuous operation is 1.8 hours. Under intermittent operations, t_{cut} is 2.5 hours and 2 hours with fifteen and thirty minutes of rest, respectively. Our data confirms the relaxation phenomena in the Alkaline battery. Moreover, it reveals that a longer rest period, results in a higher $t_{cut.}$ We next repeated our experiments for Nickel Cadmium battery. Figure 9 illustrates the graphical results of our experiments. Accordingly, t_{cut} for continuous operation is 1.67 hours.

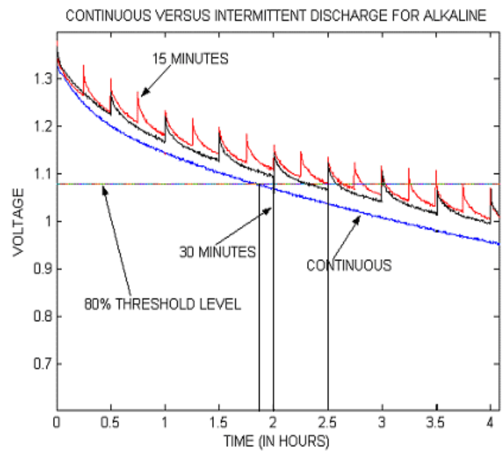


Figure 8. Continuous versus Intermittent Discharge for Alkaline Battery

Under intermittent operation t_{cut} is 1.46 hours for both fifteen and thirty minutes of rest. The result indicates that the relaxation phenomena does not hold in this particular battery and longer rest period has no positive effect on the overall t_{cut}. The result is particularly surprising since the intermittent operation resulted in a worse performance compared to continuous operation. We are currently investigating this characteristic further in Nickel Cadmium battery.

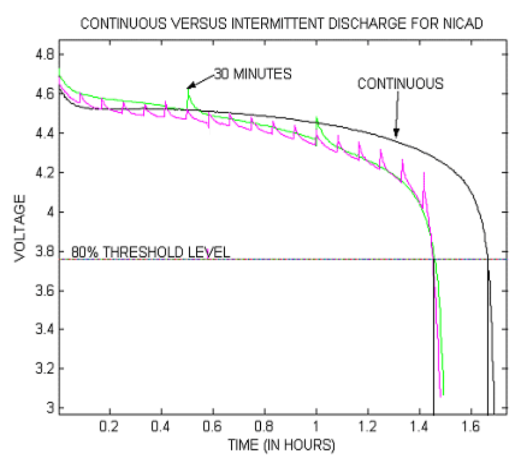


Figure 9. Continuous versus Intermittent Discharge for Nickel Cadmium Battery

Similar experiments were conducted on Nickel Metal Hydride battery and their results are shown in Figure 10. The result indicates that fifteen minutes intermittent operation yields similar result to that of the continuous operation. The result of thirty minutes intermittent operation is slightly worse. Again, the result indicates that the relaxation phenomenon does not properly hold in Nickel Metal Hydride battery.

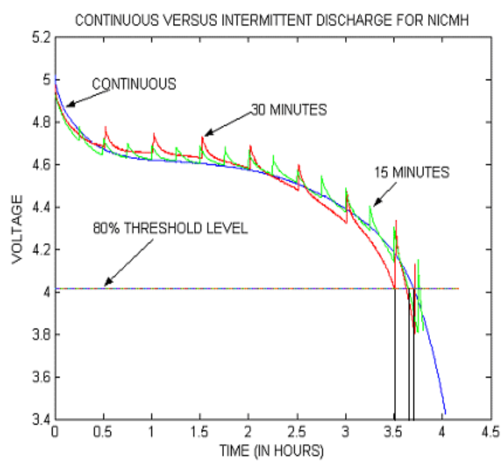


Figure 10. Continuous versus Intermittent Discharge for Nickel Metal Hydride battery.

Our last set of experiments were conducted for the Lithium Ion battery. The results, as indicated by Figure 11, reveals that the charge recovery does not have any effect on t_{cut} of the Lithium Ion battery.

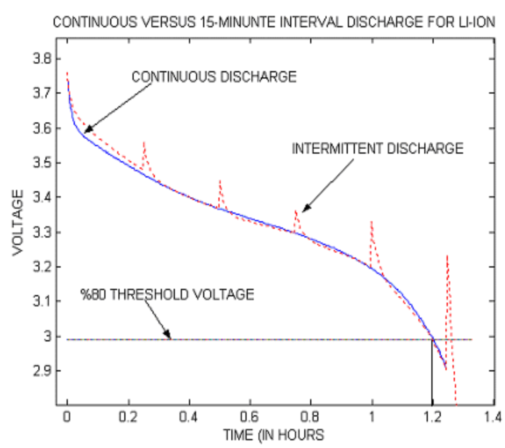


Figure 11. Continuous versus Intermittent Discharge for Lithium Ion Battery

Table 2 summaries our experimental results for different batteries under continuous and intermittent operations. Accordingly, intermittent operation is not viable technique to prolong rechargeable battery's life.

Table 2. t_{cut} for Different Batteries

Battery type	**Continuous**	**15 Minutes Intermittent**	**30 Minutes Intermittent**	**Maximum Difference**
Alkaline	1.82 hours	2.5 hours	2 hours	27.2%
NiCad	1.67 hours	1.46 hours	1.46 hours	-12.57 %
Ni MH	3.70 hours	3.65 hours	3.5 hours	-1.35%
Li-Ion	1.2 hours	1.2 hours	1.2 hours	0.0%

5. Conclusion

In this paper, we experimentally examined the relaxation characteristic of Alkaline, Nickel Cadmium, Nickel Metal Hydride and Lithium Ion batteries. Our experimental results revealed that the relaxation phenomenon only holds for non-rechargeable batteries. The intermittent operation of the rechargeable batteries either resulted in no improvement in overall battery lifespan or resulted in a shorter lifetime. We are currently investigating these behaviors.

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