Discharge curves for a Ni-Cd secondary battery monitored by LabVIEW

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We present an experimental project aimed at understanding how batteries work by analyzing discharge curves for a secondary battery. Our proposed experiment uses simple electronic components and takes advantage of the outstanding features provided by the commercial software LabVIEW in order to acquire, plot and save data on a disk in conjunction with an analog-digital board and a personal computer. We report discharge curves (E vs t), power, charge stored and energy delivered by a commercial secondary Ni-Cd battery as a function of time, using two different discharging methods: constant-load resistance and constant-current.

Keywords: Battery; Cd-Ni; LabVIEW.

Presentamos un proyecto experimental con el fin de mostrar el principio básico de operación de las baterías recargables analizando las curvas de descarga de una batería secundaria comercial. El experimento propuesto consiste en elementos electrónicos simples y se apoya en uso de las herramientas del software comercial LabVIEW para capturar, graficar y salvar los datos de corriente y voltaje. En este trabajo se reportan las curvas de descarga (E vs t), capacidad de carga, potencia y energía suministrada por una batería comercial secundaria de Ni-Cd en función del tiempo. Para medir estos parámetros, utilizamos dos métodos diferentes de descarga: resistencia de carga constante y corriente constante.

Descriptores: Batería; CD-Ni; LabVIEW.

PACS: 82.47

1. Introduction

Batteries supply the energy necessary for operateing several electronic devices that are essential commodities in our lives: toys, watches, calculators, cellular phones, laptop computers and pacemakers, to name only a few examples. A battery is a means of energy storage that transforms chemical energy, saved as chemical reactants, into electrical energy through electrochemical reactions of oxidation and reduction. When reaction products at the battery can be converted into reactants by applying a potential difference with an external power supply, and used again, these batteries are called secondary. Some examples of this group include: lead-acid battery, Ni-Cd or Ni-metal hydride cells. On the other hand, when the chemical products at the battery cannot be converted into reactants, and the battery is used only once, those batteries are called primary and some representative members for this group are: Leclanche, Zn-MnO_2-alkaline and some lithium batteries [1,2].

Although batteries have been present in our lives since childhood, some of the technical jargon and chemical transformations that take place inside a battery in producing electricity are unknown not only to common users but also to some technical students. Recently Smith *et al.* [3] published an article about discharging curves for different primary batteries through a constant resistor. They demonstrated how the potential delivered by a battery depends on time. Furthermore, these authors determined the theoretical and prac-

tical capacity of three different primary cells by weighing the reactive material inside the batteries taking into account the stoichiometry of the cell reactions and using Faraday's law.

We present here discharging curves for a Ni-Cd secondary battery obtained by using the commercial software LabVIEW and simple electronic circuits. Homemade programs written in language "G" in the environment provided by LabVIEW allow us to acquire, display and save experimental data easily on a disk. This particular software helps students to focus mainly on data analysis without distracting too much attention in the setting up of the experiment [4].

Experimental data collected include potential, E, and current, I, delivered by a battery as a function of time obtained for a constant resistance and current load. A routine inside our virtual instrument integrates the current passing through the circuit to obtain the capacity, *e.g.*, total amount of charge delivered by the battery during its discharge cycle in coulombs (C) or amperes-hour (A-h). Other parameters determined are power and energy delivered by the battery.

The aim of these experiments is to demonstrate that current and voltage supplied by a secondary battery during the complete course of the discharge are time-dependent. Some systems, *e.g.* fuel cells or hybrid batteries, come closer to an ideal behavior, with a constant I and E as a function of time [1]. Nevertheless, most of the secondary batteries, such as lead-acid and Ni-Cd do not behave ideally. Our experiments are oriented to freshman electrochemistry and physics students.

2. Overview of the experiment

2.1. Materials and equipment

For these experiments we use two commercial rechargeable AA, 900 mA-h, 1.2 V, Ni-Cd batteries from Huanyu Co., a battery charger, a 2.2 V light bulb with a holder, five resistors (11, 100, 150 Ω variable resistor, 470 Ω), two transistors model C1 740 RS, two switches, one diode, wires and alligators, a protoboard, a digital multimeter, a connector box model SCB-68 from National Instruments, a personal computer (PC) equipped with an analog-digital board model AT-MIO-16XE-50 from National Instruments and commercial software LabVIEW version 5.1 from the same company.

2.2. Experiment setup

Two different electric circuits were constructed on a protoboard in order to discharge a battery at both constant load resistance (11Ω) and current (53 mA). Figures 1a and 1b show electronic diagrams of the circuits used in these experiments. For the first experiment, we monitor the potential drop at the battery terminals (E_{battery}) as a function of time. Current that
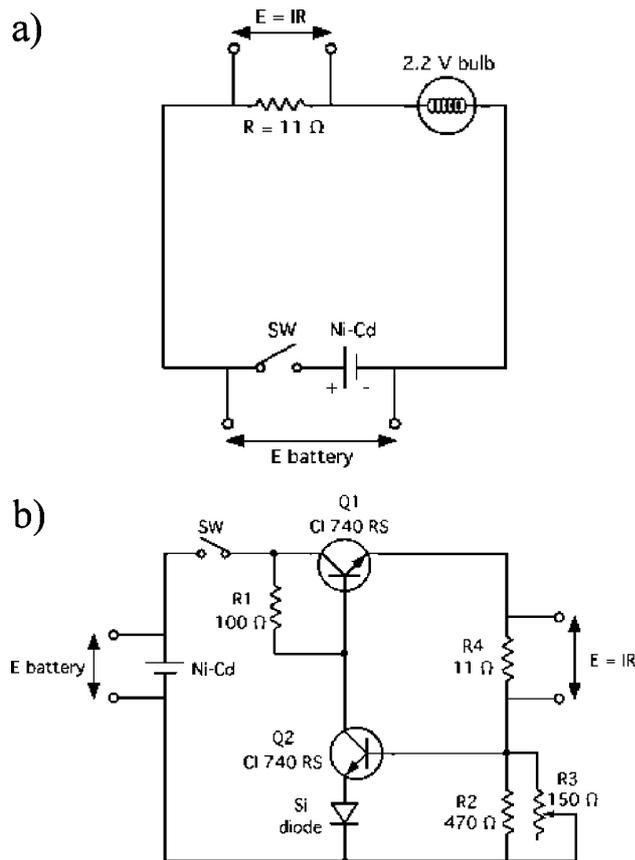
passes through the circuit is obtained by measuring the voltage drop across a known resistance and then applying Ohm's law. By using this strategy, we avoid sending current directly into the A/D card, which could damage it. During battery discharge, the bulb in the circuit lights up slightly, consuming current and alerting experimenters that current is flowing. In the second experiment, an electronic circuit constructed with two transistors is used, which makes it possible to drain a constant current from the battery [5]. All experiments are carried out by discharging only one commercial AA Ni-Cd battery (with a nominal capacity of 900 mA-h), because batteries frequently present different internal resistance, which that may induce undesirable side effects when they are discharged together. The voltage signals measured at the battery terminals and across a known resistance are sent to two different input channels of the SCB-68 box connector and then to an A/D board installed in the PC for automatic data acquisition.

We use the program LabVIEW, which provides an easy-to-use graphic environment with several built-in functions such as graphics, connectors, logic components, time constants and data acquisition icons [6]. Programs written in LabVIEW are usually known as virtual instruments (VI), because, in a way, they resemble somehow a functioning real instrument. All VI's have two different panels: the first one, called the front panel, serves as a communication interface between the user and the PC. It allows us to introduce information or modify experimental conditions. The second one is known as a block diagram, and provides an adequate environment for programming using icons and connectors [6].

Our VI front panel is designed to introduce some parameters, such as, total experimental time, number of sampled data points, resistor value used to calculate the current and number of channels used for data collection, and file name. The front panel includes several graphs to display how potential, current, power and battery charge vary as a function of time (see Fig. 2).

FIGURE 1. Circuit diagrams: a) the discharge circuit consists of a constant load resistance and it is used to calculate current and to monitor potential drop across the battery terminals; b) electronic circuit, constructed with two transistors, that amakes it possible to drain a constant current from the battery.
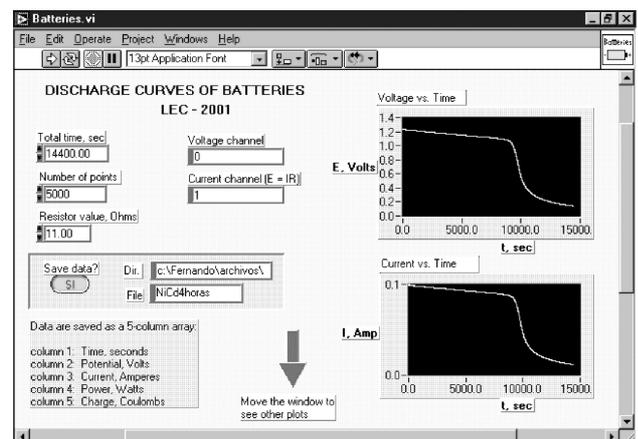
FIGURE 2. Front panel of the LabVIEW virtual instrument used as interface between the computer and the experimenter.
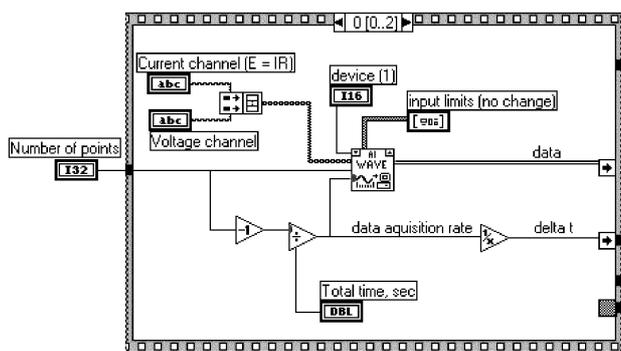
FIGURE 3. Fragment of virtual instrument's block diagram.

In Fig. 3, we show a section of the block diagram for this VI front panel. It uses a LabVIEW sequence structure to control the order of execution. First, an analog input subroutine acquires the specified number of data points at the desired rate from both current and voltage channels. Once the data acquisition task has taken place, a time vector is constructed up using a for loop structure, since the number of points and data acquisition rate are known. The last step before plotting them is to separate the data array into two different vectors, the voltage signal and the potential drop through the resistor. The current is then calculated using Ohm's law, and integrated using a customized cumulative integral subroutine (trapezoidal rule), in order to calculate the charge delivered by the battery. Another customized subroutine allows the experimenter to save data as a text-delimited file including time, $t(s)$, potential, $E(V)$, current, $I(A)$, power, $P(W)$ and charge, $Q(C)$ which can be easily processed with a spreadsheet or a scientific graphic software package.

A battery is opened using a handsaw to show students its interior. Most of the Ni-Cd rechargeable batteries are constructed as Swiss roll electrodes. A porous Ni sheet impregnated with nickel hydroxide is rolled together with a porous Cd sheet impregnated with cadmium hydroxide. The electrolyte is a solution of potassium hydroxide, and a thin porous polypropylene plastic membrane is used as a separator. Fig. 4 shows a schematic diagram of the interior components of a commercial Ni-Cd battery [2,7].

3. Results and discussion

Initially, students monitor and report open circuit potentials for batteries charged for different times using a digital multimeter. Table I summarizes some of the potentials measured for an AA, Ni-Cd commercial battery. Only batteries charged for times longer than 8 hours were capable of coming close to the potential that resembles the reversible cell potential (1.35 V) [7].

The electrode reaction taking place at the cathode (positive electrode) during the discharge of the battery is the reduction of nickel hydroxide (III) to produce Ni(II) hydroxide; and that at the anode (negative electrode) is the oxidation of Cd to produce cadmium hydroxide [7]. The arrangement
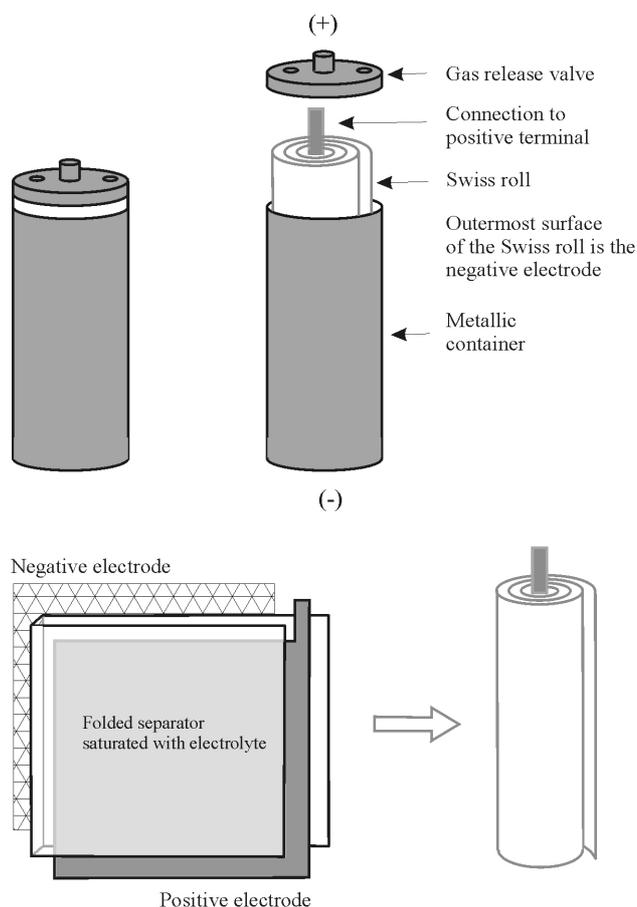
FIGURE 4. Schematics of electrode arrangement inside a Ni-Cd battery.

TABLE I. Initial potentials measured for an AA, Ni-CD commercial battery.

Charging time, (h)	Initial potential, (V)
2	1.094
4	1.232
8	1.307

of both electrodes inside the battery components appears schematically represented in Fig. 4.

The cathodic reaction corresponds to

$$2\beta\text{-NiO(OH)} + 2H_2O + 2e^- = 2\beta\text{-Ni(OH)}_2 + 2OH^-$$
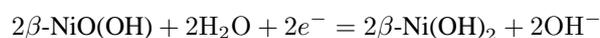
and the anodic reaction (during discharge) is

$$\text{Cd} + 2OH^- = \text{Cd(OH)}_2 + 2e^-$$
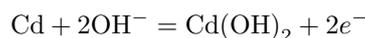
Once the open circuit potential for the battery is known, we obtain a series of discharge curves under different conditions. Figures 5a and 5b illustrate a set of experimental discharge curves obtained for a Ni-Cd battery acquired at both constant resistance and current load. The two sets of curves correspond to two different charging times. For each curve at
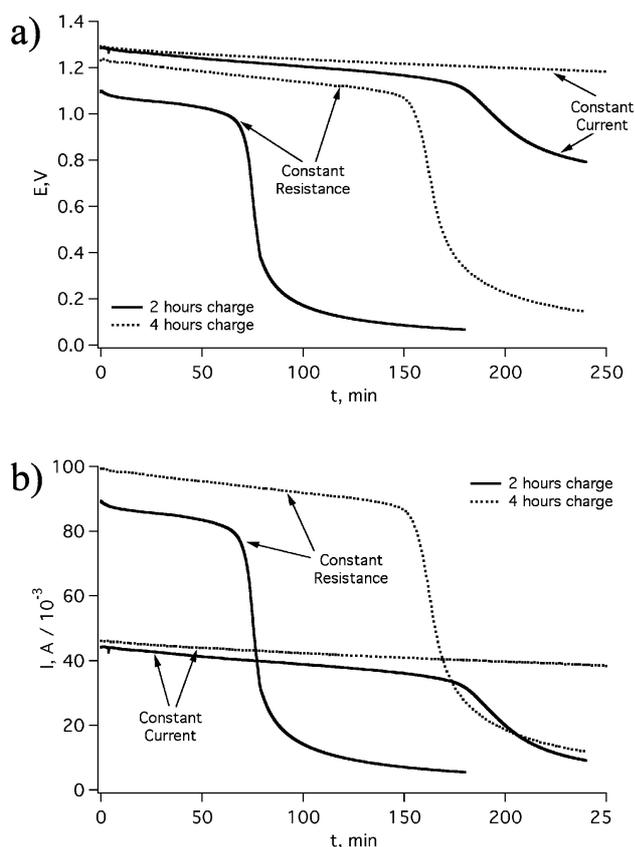
FIGURE 5. Discharge curves of a Ni-Cd battery: a) E vs. t and b) I vs. t.

constant resistance, we can identity two well defined regions. For instance, we can identify two regions in the discharge curve (E vs. t) for a battery charged for 2 hours and discharged at constant resistance, see Fig. 5a. Initially, there is a region which appears as a plateau between 0 and 75 min. In this region, the current response is mainly controlled by the ohmic potential drop across the electrolyte and battery separator [2,8,9]. Finally, at the end of the plateau, we can identify the cut off potential, which delimits the useful time for the battery and corresponds to the situation where reactants have been depleted at the battery [2]. Here, we stress to the students the fact that after this potential the battery can no longer supply energy enough to operate an external device, *e.g.* flashlight, radio or calculator.

For batteries being discharged at a constant current, the plateaus extended for longer periods of time than the ones obtained when batteries are discharged at a constant resistance, for the discharge rate used (50 mA). We only observed a complete discharge curve for batteries charged over times no longer than 2 hrs. Similar trends are observed for plots of E vs. t and I vs. t independently of the discharging method used (see Figs. 5a and 5b).

One important battery parameter that can be calculated with the same set of data collected is the instantaneous power P delivered by the battery. It depends on the working rate

for a battery, normally; it is evaluated over short periods of time [2]. We find P as the product of the instantaneous current delivered by the battery and the instantaneous voltage given by the battery. Although the P vs. t plot is not shown in this report, it displays the same trends as those observed for E vs. t or I vs. t graphs plotted separately.

We ask students to integrate I vs. t discharge curves in order to obtain the practical capacity of the battery. By definition, it corresponds to the amount of charge saved in the battery as a function of the cutoff potential reached at a specific time and, as we mentioned before, this potential coincides with the end of the plateau in the discharge curve [1,2].

$$Q = \int_0^t I \, dt \tag{1}$$

As might be expected the amount of charge saved in the battery increases upon increasing charging times (see Fig. 6). All experiments were run using commercial Ni-Cd batteries with a nominal capacity of 900 mA-h, which is equivalent to 3240 C.

By comparing the experimental amount of charge stored by batteries charged for long periods of time (up to 8 hrs.), we always obtained a smaller value than the nominal capacity reported by the manufacturer. To further analyze the experimental data, we also compare the amount of charge supplied to the battery, for different charging times, with the amount of charge delivered by the battery during the discharging cycle. Table 2 summarizes these data. Both values are similar and appear as a percentage in the fourth column of Table II. It is evident that discharging efficiency increases with charging time. Differences can be explained in terms of heat losses during charging and discharging processes. For all batteries, we used a constant charging current equal to 78.5 mA.

Furthermore, we calculate the amount of work performed by the battery by integrating instantaneous power supplied by the battery. The following equation defines the amount of energy performed by the battery [1,2]:
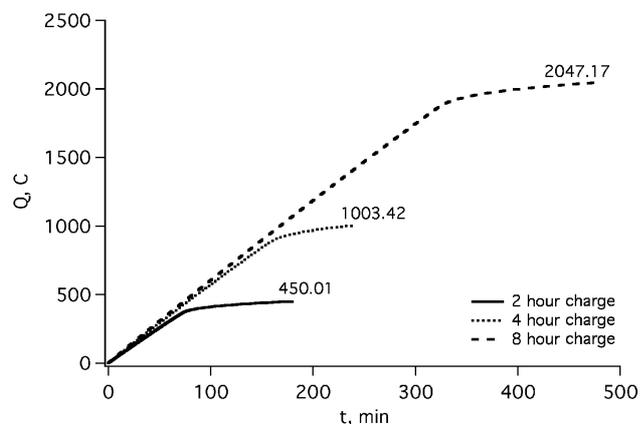
FIGURE 6. Capacity plots as a function of different charging time of a Ni-Cd battery.

TABLE II. Charge supplied and delivered by the battery.

Charging time, (h)	Q_{supplied}, (C)	$Q_{\text{discharged}}$, (C)	$\frac{Q_{\text{discharged}}}{Q_{\text{supplied}}} \times 100$	Energy $= \int_{0}^{t} P(t)dt$, (J)
2	565.2	450.01	79.61	401.36
4	1130.4	1003.42	88.77	1068.60
8	2260.8	2047.17	90.55	2318.67

$$\text{Energy} = \int_{0}^{t} Pdt. \qquad (2)$$

The energy delivered by the battery appears as the last column of Table II.

After performing these experiments, students are asked to write a report and to discuss and analyze the whole set of data obtained experimentally. In general terms, this work helps to familiarize students with the technical jargon and different parameters used to characterize batteries.

4. Conclusion

A simple experiment for acquiring and analyzing discharge curves for a secondary battery is presented. These experiments allow students to achieve a better understanding of how real batteries work under different discharge conditions. We show that LabVIEW software has become a valuable tool for performing this type of experiment, because it facilitates data acquisition, thus reducing experimental efforts and helping students to focus more on data analysis.

4.1. Safety concerns

Since the battery is made of nickel and cadmium, it is important that students wear a lab. coat and gloves if the professor decides to open a battery. Otherwise students can realize in the schematics and data provided in this report. If a battery is finally opened, nickel and cadmium electrodes should be disposed of adequately.

4.2. Supplemental Material

A copy of the virtual instrument in LabVIEW used to perform these tests is available to those interested upon request from the authors.

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