Rabbit Season – A Battery Based Laboratory Exercise for Engineering Students

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A laboratory investigation suitable for college freshmen is provided (see Appendix A). In this experiment, students investigated the performance of ordinary consumer batteries under specified discharge conditions. The discharge conditions were those described in a international standard for battery performance.[1,2] The experiment was intended to introduce students the importance and utility of international standards. Experimental conditions were based on these standards and on manufactures' claims (available from their websites at http://www.duracell.com and http://www.eveready.com). This investigation could easily be modified to illustrate other important engineering concepts.

The investigation also provided an opportunity to address ABET Criteria 3a (knowledge of mathematics, science and engineering), 3b (design and conduct of experiments; analysis and interpretation of data) and 3g (ability to communicate effectively).[3] The data acquired during the discharge period was statistically analyzed and formal written reports were required. The experiment has been used once in a freshmen biomedical design course at the Milwaukee School of Engineering (MSOE). Students reported that, while the experiments were quite time consuming (requiring about 1 hour per day for 8 days to obtain their data and another 4 to 8 hours to prepare their reports), they found them interesting and informative.

The experiment was interesting in a number of ways. It provided an opportunity for students to investigate electrical devices with which they are familiar (batteries). The title of this paper acknowledges the student familiarity with the well known advertising campaigns of the two major U.S. battery manufactures. This familiarity appeared to enhance student interest in the experiment. Initially, students expressed a desire to find out for themselves, "which brand of batteries is better." After completing the experiments, they had learned that even a relatively simple question such as this could be difficult to answer unequivocally.

As freshmen, student had not yet taken college level circuits or electronics courses. Most, however, did have some awareness of voltage (potential), current and resistance (Ohm Law) concepts from high school and college physics courses. These topics were reviewed prior to assigning the experiment. The students also performed a set of simple electrical circuits and measurements exercises to review their knowledge and familiarize them with the specific instrumentation in the laboratory in which they worked.

Students did not have any experience with the statistical hypothesis testing. A single lecture provided very simplified introduction to hypothesis testing in general and to the use of Excel™ statistical tools in particular. This introduction was limited to specific concepts needed by the students to interpret their results. Five groups of students performed the experiments. In spite of their brief introduction to statistics, three of these groups correctly performed and interpreted t-tests on their data.

Figures 1 and 2 show some results obtained by the students. Each group obtained data from 4 of each brand of battery and their data was pooled for analysis. Figure 1 shows the average voltages of each brand of battery as a function of time during discharge. The “saw tooth” appearance of this plot is the result of the standard discharge protocol that involved daily 1 hour discharge periods followed by an approximate 23 hour “recovery” periods. Students were instructed to place error bars on the plot as shown. Figure 2 shows the results of a t-test comparing the average life of each brand of battery. The test indicates a significant difference in the lives. Students were also asked to create and explain several other plots and to perform and interpret several other statistical tests.

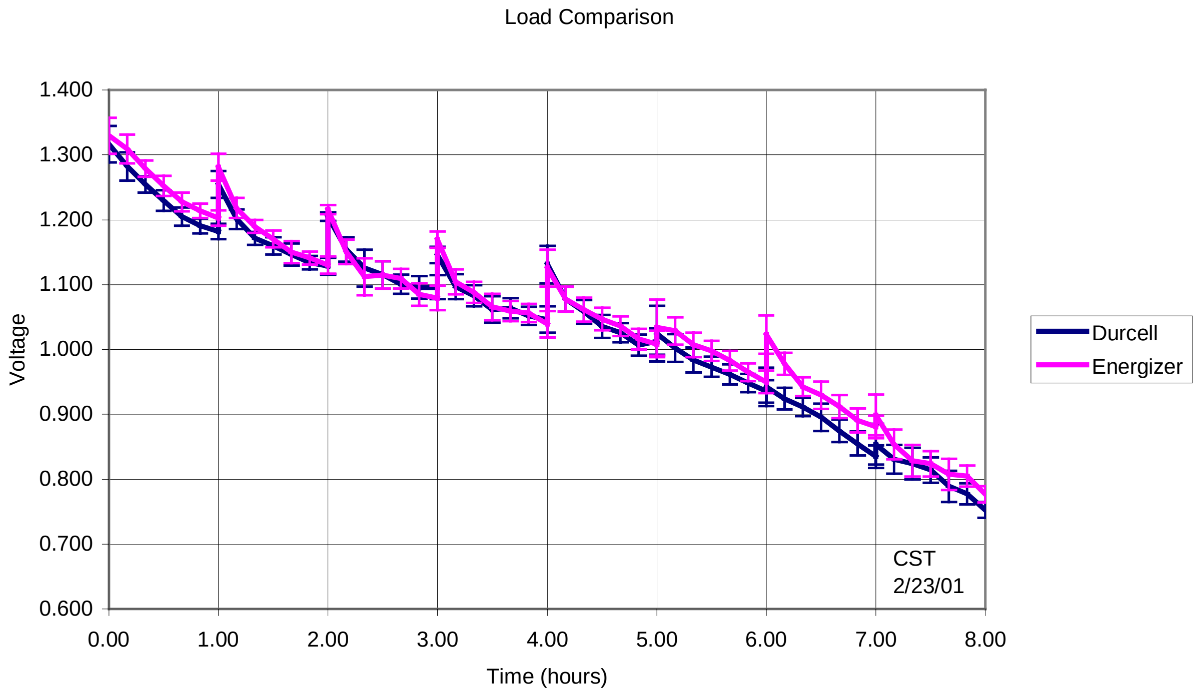

Figure 1: Voltage as a function of time under load comparison. Batteries were discharged one hour per day until the output voltage decreased to a specified limit (0.8 volts).

0.9V Discharge Time
t-Test: Two-Sample Assuming Equal Variances

	D	*E*
Mean	6.437317	6.785407
Variance	0.179444	0.218798
Observations	20	18
Pooled Variance	0.198028	
Hypothesized Mean Difference	0	
df	36	
t Stat	-2.40762	
P(T<=t) one-tail	0.010654	
t Critical one-tail	1.688297	
P(T<=t) two-tail	0.021307	
t Critical two-tail	2.028091	

Figure 2: Results of t-test on life data using a 0.9 volt cutoff.

Bibliography

1. Anonymous. Primary Batteries – Part 1: General (IEC 60086-1). Geneva, Switzerland: International Electrotechnical Commission (2000).

2. Anonymous. Primary Batteries – Part 2: Physical and Electrical Specifications (IEC 60086-2). Geneva, Switzerland: International Electrotechnical Commission (2000).

3. Anonymous. 2001-2002 Criteria for Accrediting Engineering Programs. Baltimore, MD: Engineering Accreditation Commission (2000).

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Appendix A: Sample Laboratory Exercise

Electrochemical Cell (Battery) Experiments (Version 1.0)
BE-103, Winter '00-'01, Dr. C. S. Tritt

Introduction and Background

In these experiments, you will perform a series of tests on two brands of primary electrochemical cells (batteries). You will then compare the results of these tests to the IEC standards and manufacture's claims. A clear limitation with these experiments is the relatively small sample size. Many more replicates would probably be required to draw definitive general conclusions about the relative performance of the brands of batteries investigated.

Electrochemical cells are referred to commonly, but incorrectly, as batteries. Electrochemical cells, or simply cells, are units consisting of a positive electrode (or anode) and a negative electrode (or cathode) separated by an electrically conductive and chemically reactive electrolyte. Technically, a battery is a series connection of two or more cells. Common AA, C and D "batteries" are actually single electrochemical cells, while common 9 volt batteries are indeed batteries. Each 9 volt battery contains 6 1.5 volt electrochemical cells.

Primary cells convert chemical energy into electrical energy. The chemical energy is "stored" in cells during their manufacturing process. This is the result of the inclusion of dissimilar materials for the electrodes and the presence of a chemically reactive and electronically conductive electrolyte. Primary cells are not rechargeable (chemical reactions in them can not safely be reversed). The voltage produced by a cell is the result of differences in chemical reactivities and concentrations of the various materials in the cell. However, as long as no electrical current flows, no chemical reactions occur. When electrical current does flow from the cell, chemical reactions occur. These reactions deplete the chemicals in the cell over time. This results in the eventual exhaustion of the battery.

Engineering analysis often makes use of "models." In this context, a model is a representation of reality. The model is expected to respond in the same fashion as the actual device or system being modeled. All models have limitations and are only applicable to situations in which their response is sufficiently similar to that of the actual system being modeled.

Figure 1 shows a typical electrical model of a electrochemical cell. The ideal voltage (technically, electrical potential) of the cell, V_{ideal}, is the result of the potential chemical reactions in the cell. The exact value of V_{ideal} depends on the chemicals in the cell and their concentrations. Cells stored for long periods are subject to a process called self-discharge. This is the result of an effective self-discharge resistance, R_{sd}, connected in parallel with the electrochemical reactions in the cell. This resistance allows a small amount of current to flow resulting in the slow discharge of the cell. Another effective resistance within cells is the internal resistance, $R_{internal}$. This resistance acts as if it is in series with the ideal voltage. A voltage drop occurs across $R_{internal}$ as current flows from the cell. This results in the voltage measured at the battery terminals being less than V_{ideal} when the battery is “under load.”

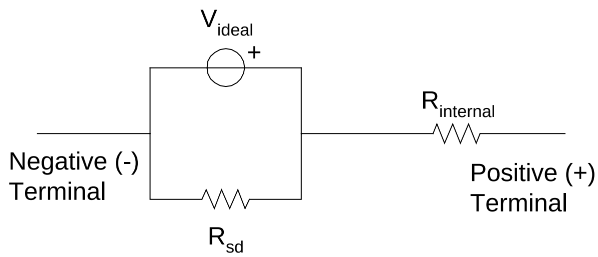

Figure 3: Electrical model of a battery.

Electrochemical cells can be tested in a number of ways and the results of these tests interpreted in terms of the model shown in Figure 1. Three possible test arrangements are shown in Figure 2. The open circuit voltage test measures V_{ideal} in the model. Either the closed circuit voltage or short circuit current measurement, when combined with the open circuit voltage measurement, can be used to estimate $R_{internal}$. The two methods typically result in different $R_{internal}$ values. Actually, a somewhat different approach is used in the IEC standard and by battery manufactures to specify and measure $R_{internal}$, but the idea is essentially the same. You will not be measuring $R_{internal}$ in these experiments.

Both V_{ideal} and $R_{internal}$ are functions of the degree of discharge of the battery. As a cell is discharged, V_{ideal} decreases and $R_{internal}$ increases. Ordinary battery testers measure V_{cc} to estimate the degree of discharge of a particular cell or battery. The measurement of V_{cc} effectively combines the effects of changes in V_{ideal} and $R_{internal}$.

The measurement of R_{sd} requires that the batteries be stored and tested over a long period. Storage temperature strongly affects R_{sd}. Cold storage increases R_{sd} thus slowing the rate of self-discharge. You will not be measuring R_{sd} in these experiments.

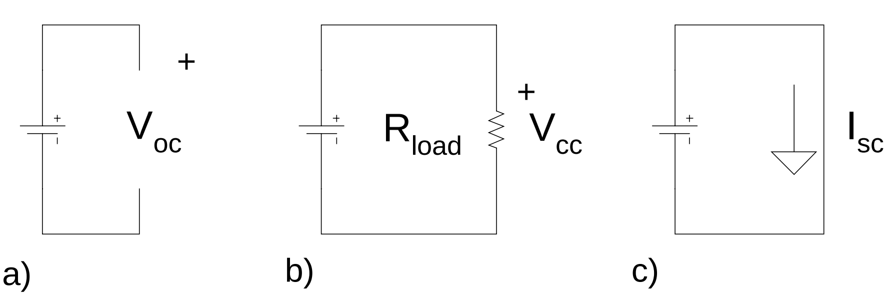

Figure 4: Three electrical test circuits for batteries: a) Open circuit voltage, b) Closed circuit voltage and c) Short circuit current.

Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition

Electrical energy and total charge delivered are also important electrochemical cell attributes. Energy is the time integral of the product of voltage and current. Energy is best measured in Joules and indicates the amount of work that can be done by the cell. Change delivered is a direct result of the electrochemical reactions that occur in the cells. Charge is measured in Coulombs in the S.I. system, but units of mA-hrs are commonly used.

International standards are often used to specify the expected or required performance of particular devices. The most popular international standard for electrochemical cells and batteries is International Electrotechnical Commission (IEC) standard 60086. This standard is divided into five parts, with the first two being most relevant to this investigation. The standard IEC 60086-1, 9th ed. contains general information about the primary battery standards while IEC 60086-2, 10th ed. contains physical and electrical specifications for particular types of cells.

In the U.S., primary batteries and cells are designated using words and letter codes. You can all probably picture 9 volt, AA, C and D batteries. Unfortunately, batteries and cells are designated differently in international standards. Table 2 shows the relationship between the two systems along with category information used in IEC 60086-2.

Table 1:U.S. and international battery designations (with IEC catagory).

	Typical International Designations		IEC Category
U.S. Designation	Carbon Zinc	Alkaline	
AA	R6	LR6	1
C	R14	LR14	1
D	R20	LR20	1
9 volt	6F22	6LR61	6

Equipment and Supplies

A set of measuring calipers is to be shared among the groups.

Equipment needed (for each group):

1 DMM
1 Circuit Designer box
2 4-battery, battery holders
8 3.9 Ω resistors
Wires, alligator clips and patch cords as needed.

Supplies

4 Duracell Size AA cells
4 Energizer Alkaline Size AA cells

Suggested Hypotheses

1) The cells tested meet selected mechanical dimension requirements specified in IEC 60086-2 pages 11-15 and the manufactures' specifications (where available).

2) The cells tested meet the open circuit voltage limit specified in IEC 60086-1 4.1.4 and 4.2.4 and the manufactures' specifications (where available).

3) The cells tested meet the service life requirement for Motorized Toys (3.9 Ω load, 1 hour/day discharge) specified in IEC 60086-1 4.2.5 and IEC 60086-2 pages 11-15.

4) The two brands of cells have equal service capacities for the size and conditions investigated and meet the manufactures' specifications (where available).

Suggested Procedures (Hypothesis 1 – Mechanical Dimensions)

Mark your batteries for later identification. I suggest you use your team number followed by a dash followed by a battery number (1 to 8).

Figure 3 defines the cell dimensions specified in IEC60086-2 while Table 2 specifies the required and specified values of these measurements. If using metal calipers, place a small piece of electrical tape over the negative (flat) terminal of the battery to prevent the creation of a short circuit when taking mechanical measurements. Also measure the thickness of a sample piece of tape (usually about 0.007 inches) and correct your measurements for this thickness as appropriate. Measure and record these dimensions for each of your cells. Compare your measured results to the expected values.

PHYSICAL AND ELECTRICAL SPECIFICATIONS — CATEGORY 1 BATTERIES

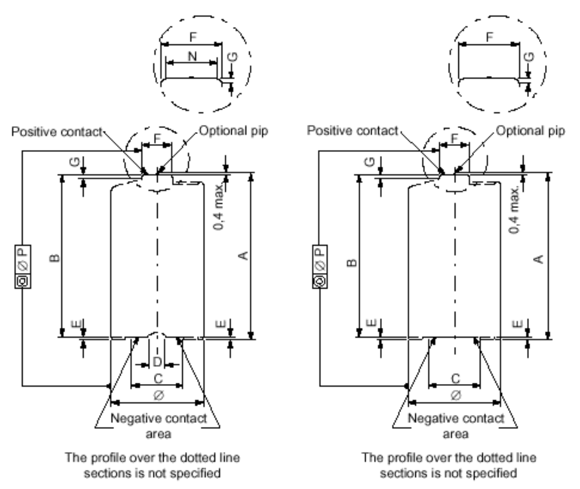

Figure 1a

Figure 1b

Batteries complying with these physical and electrical specifications are:

Designation	OCV Max. V
R1, R03, R6C, R6P, R6S, R14C, R14P, R14S R20C, R20P, R20S	1,725
2R10	3,450
LR8D425, LR1, LR03, LR6, LR14, LR20	1,65
CR12A604	3,7

For the definition of the dimensions, see clause 5.

The cylindrical surface is insulated from the contacts.

Terminals: flat/cap and base.

for terminal details, see respectively 4.1.3.5 and 4.1.3.2 of IEC 60086-1.

For general information, see IEC 60086-1.

Figure 1a: negative contact C may not be flat over the whole area.

Figure1b: negative contact shall be essentially flat over the whole surface area.

For batteries complying with figures 1a and 1b, flat negative contact is not necessarily recessed.

When the flat negative contact surface forms the lower part of the battery, dimensions "A" and "B" are both measured from the surface and dimension "E" is zero.

Dimensions "P" to be measured in accordance with ISO 1101.

Figure 5: IEC 60086-2 physical and electrical battery specifications (from IEC 60086-2 page 10).

Table 2: Specified cell dimensions (all in mm).

	IEC	Energizer	Duracell
Ø min. or typical	13.5	14.5	13.5
Ø max.	14.5	N/A	14.5
A max.	50.5	50.5	50.5
F max.	5.5	N/A	5.5
G min.	1.0	N/A	1.0

Suggested Procedures (Hypothesis 2 – Open Circuit Voltage)

Place your cells into your battery holder. Using alligator clips, sequential connect wires from the cells to the DMM inputs. Record the open circuit voltage and compare your results to the IEC requirements and manufactures specifications. These values for LR6 cells are summarized in Table 3.

Table 3: Open circuit voltage specifications and expected values for R6 and LR6 cells.*

	IEC	Energizer	Duracell
Zn/MnO_2 (NH_4Cl)	1.725	>1.55	N/A
Zn/MnO_2 (ZnCl)	1.725	>1.60	N/A
Zn/MnO_2 (Alkali metal hydroxide)	1.65 max	~1.58	1.5-1.6

*Energizer/Eveready distinguishes between Zn/MnO_2 batteries with NH_4Cl and ZnCl electrolytes while IEC does not. Energizer/Eveready considers Carbon Zinc to be a generic term that describes both systems. They use the term *LeClanche* for batteries having a slightly acidic electrolyte of NH_4Cl and ZnCl in water. They use the term *Zinc Chloride* for batteries having a slightly acidic electrolyte consisting mainly of ZnCl in water. Duracell produces only alkali metal (specifically potassium) hydroxide cells.

Suggested Procedures (Hypothesis 3 – Service Life)

These procedures will have to be conducted over multiple days and will take a little over an hour each day. Your team should plan accordingly.

The service life is defined as the time (in hours) required to reach the cutoff voltage during the discharge of a cell or battery under specified conditions (duty cycle, load resistance and temperature). Specified cutoff voltages are summarized in the Table 4, in which all numeric values are in volts.

Table 4: Standard and specified cutoff voltages for LR6 cells.*

	IEC	Energizer	Duracell
Zn/MnO_2 (NH_4Cl)	0.80	0.75	N/A
Zn/MnO_2 (ZnCl)	0.80	0.75	N/A
Zn/MnO_2 (Alkali metal hydroxide)	0.80	0.90	0.80

*IEC uses 0.8 volts for motorized toy tests and 0.9 volts for other tests.

Measure the actual resistance of each nominal 3.9 Ω resistor and place them into your Circuit Designer such that the association between individual resistances and battery numbers are known. These are your load resistors. During each daily discharge period (I'd expect there will be 8 or 9 of these):

Measure and record the open circuit voltage of each cell.

Connect each cell to a resistor. Note which cells are connect to which resistors so that average currents can later be calculated.

Immediately measure and record the closed circuit (under load) voltage of each cell.

Every 10 minutes, repeat the closed circuit voltage measurements.

At the end of 1 hour, make a final close circuit voltage measurement and disconnect the cells from the load resistors.

Immediately measure the open circuit voltage of each cell.

Cells are considered to have reached the end of their service lives the first time their closed circuit voltage drops below the cutoff voltage. Note cells will have two service life values. One based in the IEC standard and one on Energizer's own, more stringent, standard. For comparison purposes, calculate Energizer style service lives for Durcell cells and Durcell/IEC style service lives for Energizer cells. Use linear interpolation to estimate the service life of each cell to within 1 minute. Note that only the time that cell has spent under load are considered in service life calculations. The IEC 60086-2 standard specifies a minimum average service life of 4.0 hours for LR6 cells discharged through a 3.9 Ω resistor for a period of 1 hour/day. Compare your results to this standard.

Suggested Procedures (Hypothesis 4 – Service Capacity Comparison)

Use your data from the Hypothesis 3 procedures to estimate the service capacity (in terms of energy and charge) of each of your cells. Compare these results to the manufactures' specifications that are listed in Table 5. Compare the average values for each brand of battery. Is there any difference. You will need to use material on numerical integration and statistics to be presented latter in this course to complete these procedures.

Table 5: Specified service capacities for LR6 cells.

	Energizer	Duracell
Joules		
mA-hrs	2850[1]	

[1]25 mA continuous drain to 0.8 V cutoff.

References:

Anonymous. Primary Batteries – Part 1: General (IEC 60086-1). Geneva, Switzerland: International Electrotechnical Commission, (2000).

Anonymous. Primary Batteries – Part 2: Physical and Electrical Specifications (IEC 60086-2). Geneva, Switzerland: International Electrotechnical Commission, (2000).