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Battery Power Comparison to Charge Medical Devices in Developing Countries

Alesia M. Casanova, Andrew S. Bray, Taylor A. Powers, Amit J. Nimunkar and John G. Webster

Abstract—**Many people in developing countries cannot afford or rely on certain modes of electricity. We establish the reasonability of relying on lead-acid batteries, 9 V alkaline batteries, and lithium-ion batteries for charging low-voltage medical equipment. Based on the research and tests we conducted, we determined that using these battery types to charge medical devices truly is a reasonable solution.**

I. Introduction

Most medical devices require electricity, and therefore, draw on a constant power supply or use a battery that needs to be charged. Generally, the power requirement for most medical devices is not huge. For example, devices such as pulse oximeters, spirometers, and temperature sensors could be powered with 3.3 V and less than 500 mA [1]. Our goal is to determine whether such devices and others can function if they are charged using either a lead-acid car battery, a lithium-ion battery from a cell phone, or a standard 9 V alkaline battery.

Energy in developing countries is rare and oftentimes expensive. The pattern of the power grids and the power flow within them closely follows the national urban and industrial hierarchy. This means that the majority of power is prioritized to factories, and the local population is charged higher rates with rural areas being excluded [2]. In addition to high prices, developing countries experience small but frequent blackouts; while, the U.S. experiences larger, less frequent blackouts. This is due to developing countries having a less connected infrastructure that is less dependent on electricity [3]. A major concern during electricity failures is how medical devices in hospitals are supposed to continue functioning.

Currently, there are many ways that people in developing countries charge medical devices. Of these ways, some of the most common include electricity from solar energy and power grid electricity generated from fossil fuel plants, and dams. Although many developing countries have an abundant source of sunlight throughout most of the year, harnessing solar energy is very expensive. At their current state in economic development, these nations cannot afford to become completely dependent on solar energy [4].

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Alesia M. Casanova is with the Department of Electrical and Computer Engineering at the University of Wisconsin-Madison, Madison, WI 53706, (email: acasanova@wisc.edu).

Andrew S. Bray is with the College of Engineering at the University of Wisconsin-Madison, Madison, WI 53706, (email: abray2@wisc.edu).

Taylor A. Powers, Amit J. Nimunkar and John G. Webster are with the Department of Biomedical Engineering at the University of Wisconsin-Madison, Madison, WI 53706,(corresponding author: phone: 608-263-1574; fax: 608-265-9239; email: webster@engr.wisc.edu, tapowers@wisc.edu, ajnimunkar@wisc.edu).

II. Background

A. Chemistry

A car battery is a form of lead-acid battery. Inside each cell, there is one plate of lead and another of lead dioxide with sulfuric acid acting as the electrolyte [7]. The lead combines with the sulfate ion to create $PbSO_4$ and a free electron. From this step, the PbO_2, H^+, SO_4^{-2} and the electron in the lead plate produce $PbSO_4$ and H_2O on the PbO_2 plate. These oxidation-reduction reactions are completely reversible, and therefore, allow the batteries to be recharged many times [8]. This process is shown in the following equations:

Anode, oxidation: $Pb_{(s)} + SO_4{}^{-2}{}_{(aq)} \rightarrow PbSO_4 + 2e^-$

Cathode, reduction: $PbO_2 + SO_4{}^{-2}{}_{(aq)} + 4H^+{}_{(aq)} + 2e^- \rightarrow PbSO_4 + 2H_2O$ (1)

Net ionic equation: $Pb_{(s)} + 2SO_4{}^{-2}{}_{(aq)} + 4H^+{}_{(aq)} \rightarrow 2PbSO_4 + 2H_2O$ $E° = 2.041$ V [9]

Lithium-ion batteries use a graphite anode where the cathode can vary from lithium cobalt oxide, lithium iron phosphate, or lithium manganese dioxide. These are submersed into an organic solvent, commonly ether, which acts as an electrolyte [10]. One reaction using the lithium cobalt oxide can be written as follows:

Anode, oxidation: $Li_{(s)} \rightarrow Li^+{}_{(aq)} + e^-$

Cathode, reduction: $Li^+{}_{(aq)} + e^- + CoO_{2(s)} \rightarrow LiCoO_2$

Net ionic equation: $Li_{(s)} + CoO_{2(s)} \rightarrow LiCoO_2$ (2)
$E° \approx 2.5$ V [7]

A standard 9 V alkaline batteries, although not rechargeable, provide a good comparison for lead-acid and lithium-ion batteries. Alkaline cells produce 1.54 V each with the following oxidation–reduction reactions occurring in each of the 6 cells within a standard 9 V alkaline battery:

Anode, oxidation: $Zn_{(s)} + 2OH^{-}_{(aq)} \rightarrow ZnO_{(s)} + H_2O_{(l)} + 2e^{-}$

Cathode, reduction: $2MnO_{2(s)} + H_2O_{(l)} + 2e^{-} \rightarrow Mn_2O_{3(s)} + 2OH^{-}_{(aq)}$

Net ionic equation: $Zn_{(s)} + 2MnO_{2(s)} \rightarrow Mn_2O_{3(s)} + ZnO_{(s)}$ $E°=1.54$ V [9]

The specifications and ratings of batteries are vital in comparing different types of batteries and recognizing how they will perform in different situations. A battery's ampere-hour (A·h) rating is extremely useful in the analysis of battery usage. The ampere-hour rating is defined as how long a battery can operate when certain amperage is being drawn from it. The voltage of the battery is useful when determining what types of devices it can power based on what voltage that is required for the device.

III. Discussion

A. How often batteries need to be recharged

An important consideration is how often batteries need to be charged. This translates into how long they will be able to power a device. Two factors come into play when considering how long a device can operate on a battery: the ampere-hour rating of the battery and the current drawn by the device. A main consideration for the amount of current drawn by the device is how much resistance it has. The amount of current drawn in amperes will be based upon the equation (3).

$$I = V/R \tag{3}$$

$$H = A{\cdot}H/A \tag{4}$$

V is the voltage supplied and R is the resistance of the device in ohms. Once the current is determined, the amount of time until discharge can be determined from the ampere-hours of the battery using equation (4). Where H is the number of hours available, $A{\cdot}H$ is the ampere-hour rating of the battery, and A is the number of amperes being drawn from the circuit and determined using equation (3). In this way it can be determined how long a charge on a battery can last, and therefore, how often it needs to be charged. A battery will lose its recharging ability over its life. This is addressed when dealing with the battery's state of charge and its state of health.

Lead-acid batteries should be recharged before they go below 50% of their state of charge in order to maintain a high state of health. State of health refers to the ability of the battery to perform as well as it could if it had never been discharged before. State of health decreases over time and use of the battery [13]. These batteries should be maintained at or near full charge to prevent sulfation of the lead plates within them. If the plates become covered in sulfate ions from the electrolyte their state of health permanently decreases [17]. Also, it is never a good idea to discharge a battery completely [14].

The most common method of charging rechargeable batteries is by applying a negative voltage to the negative battery terminal and a ground wire to the positive battery terminal. This forces the electrons to travel in the opposite direction, and therefore forces the chemical reaction to go in the opposite direction as it does when the battery is being discharged [15].

For lead-acid batteries, one of the simplest ways of recharging is by putting it into a car and using the alternator.

B. Safety Hazards

The risks of electrical shock and chemical exposure from a lithium-ion or 9 V alkaline battery are very rare, and therefore, our focus will be on the risks of lead-acid car batteries.

The safety hazards of lead-acid batteries are relatively minimal. There are two main sources for safety concern with car batteries: chemical exposure and electrical shock. Chemical exposure is relatively minimal when working with lead-acid batteries. For example, lead-acid battery workers having prolonged exposure from working in factories in Jamaica have experienced symptoms due to their exposure. Muscle weakness was the most prevalent with 39% those having 60 μg/dl of lead in their bloodstream reporting this symptom [11].

The main risk of exposure in normal use would be from a leak or explosion. An explosion would only occur from overcharging causing a pressurized buildup of hydrogen gas. Many lead-acid batteries have a ventilation system to prevent this buildup. The hydrogen and oxygen would then need to be ignited by a spark to cause any major damage. Furthermore, a battery that leaks is rarer because it means the battery was damaged or defective. Electrical burn is another risk of danger when working with lead-acid batteries. A car battery has enough amperage to kill, but doesn't have enough voltage to push it through your body [12]. The safety hazards presented by car batteries are minimal enough to allow them to be considered for use with medical devices.

C. Cost

The goal of using alternative sources is to be able to have low cost electricity available for medical devices. The sources of energy are assumed to already be present, which means that there is no direct cost to them. Also, it is assumed the medical device itself has already been obtained. The only costs incurred would be the costs of a transformer device when needed. A dc-dc converter would be needed to step down the voltage when using a battery with more voltage than can be handled by the device. This is especially true if using a car battery delivering 12 V which is on the higher end of the battery voltage spectrum. A voltage regulator is already built into most devices to regulate whatever voltage input it would regularly receive. The costs associated with using batteries to charge medical devices would be minimal.

D. *Ease of Availability*

The availability of the batteries is a key factor in determining how reliable they are for powering medical devices, and therefore, to what extent they will be used for such purposes. Lead-acid, lithium-ion, and 9 V alkaline batteries are commonly found in cars, cell phones, and other common devices, respectively.

A lithium-ion battery can be recharged between 300 and 500 times before it dies. There are roughly 500 million lithium-ion batteries currently being used in the world inside laptop computers and cell phones [5].

Car batteries are very abundant as well. There are approximately 625 million cars in the world today. Most are in developed nations, but cars are still very prevalent throughout the developing world. This means lead-acid car batteries are abundant in developing countries [6].

In comparison, standard 9 V alkaline batteries are very common as they are used in everyday items, such as in cameras, flashlights, and toys [7].

These three types of batteries are available to much of the developing world, and they can be made more available anywhere without large startup costs as would be the case with electricity from any type of power plant.

E. *Battery Disposal*

In the United States, both lead-acid and lithium-ion batteries can be recycled or returned to the manufacturer for proper disposal. However, in many developing countries, this convenience may not exist. Therefore we must consider the environmental effects of improper disposal. According to the United States government, lithium-ion batteries are not an environmental threat and are considered non-hazardous waste [18]. Lead-acid batteries can be recycled indefinitely, and only the lead poses an environmental threat if there is a leakage or explosion [11].

IV. Analysis

A. *Background*

We performed experiments to demonstrate how a lead-acid, 9 V alkaline, and lithium-ion battery behave when supplying a constant resistance load. This will help us determine the feasibility of using these batteries and others for powering medical devices. We expect the graphs of voltage versus time to show a relatively constant voltage, and then, at some point in time, experience a fairly dramatic voltage drop ending with a voltage close to zero.

B. *Battery Testing Procedure*

1) Charge battery to a full state of charge.
2) Connect voltmeter to the appropriate battery terminals. In our experiment, we ran a LabVIEW program that measured the voltage over time.
3) Connect the appropriate load resistor as determined by the ampere-hours.
4) Take voltage readings manually or with a computer program as a function of time.
5) Disconnect the resistor and stop the program when the battery has been discharged to a low voltage.

C. *Results*

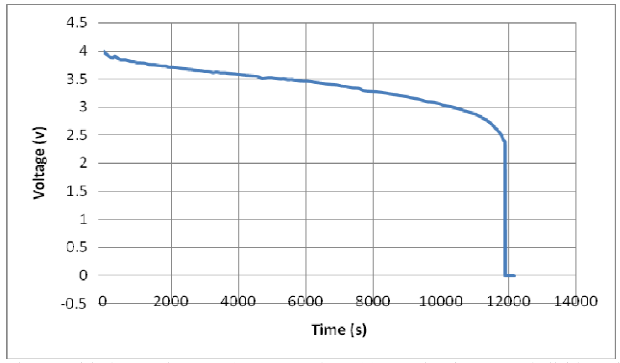

Fig. 1. This is a voltage (V) versus Time (s) graph of a 3.7 volt lithium-ion cell phone battery. This test used an 18 Ω resistor.

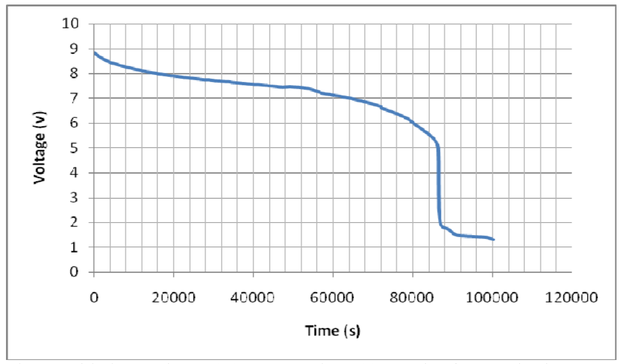

Fig. 2. This is a voltage (V) versus Time (s) graph of a standard 9 V alkaline battery manufactured by Duracell. This test used a 324 Ω carbon film resistor.

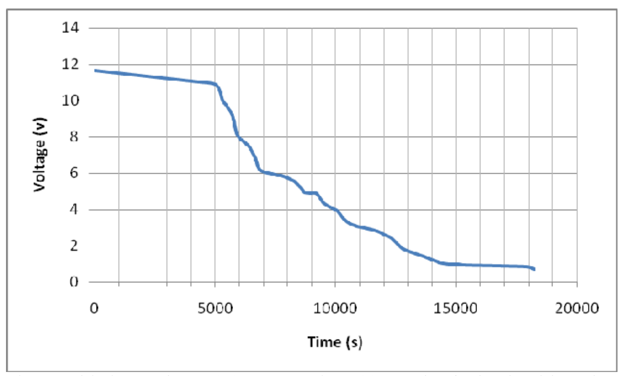

Fig. 3. This is a voltage (V) versus Time (s) graph of a lead-acid car battery manufactured by EverStart. This test used an overall resistance of 3.4 Ω.

The voltage behavior of the lithium-ion battery in Fig. 1 performed as predicted. The voltage is relatively constant until about 11800 s (3.28 h), however the voltage goes below 3.3 V at 7698 s (2.14 h) after which the battery would not be able to power most low-voltage medical equipment.

The voltage behavior of the 9 volt alkaline battery in Fig. 2. Also behaved as we predicted. The voltage is relatively constant until about 83725 s (23.26 h). The voltage goes below 3.3 V at 86532 s (24.04 h). If a medical device had a resistance of 324 Ω and required 3.3 V, it could function from a 9 V alkaline battery for 24.04 h provided it has some sort of voltage regulation system.Medical devices such as electrocardiograph machines would require at least 3 times more power than the device that was just described [1], therefore 9 V alkaline and lithium ion batteries would only be able to support very low power medical devices.

The lead-acid battery did not seem to have the same ability to maintain an approximately constant voltage near its voltage rating. This could be the effect of several different factors including battery state of health, battery temperature, or the chemical properties of lead-acid batteries. Temperature increase has been shown to increase the excitation of the electrons within the battery which causes the battery to have a higher potential than the voltage for which they are rated. However, this causes the battery's lifespan to decrease [16].

However, the fact that the lead-acid battery did not maintain a voltage near its initial voltage for long does not mean it would be a bad power source for medical devices. The voltage drops below 3.3 at 10587 seconds (2.94 h). If a medical device had a 3.4 Ω resistance and required at least 3.3 V, it could function off a lead-acid battery for 2.94 h provided it had some sort of voltage regulator. In this case, the lead-acid battery can supply enough power to run medical devices that had a resistance of 3.4 Ω for almost 3 h. With devices that require less power, it could power them for longer depending on their required voltage and resistance. With this test, we conclude that lead-acid car batteries are a reasonable power source for low-voltage medical devices; litium ion and 9 V batteries are a reasonable source for low-voltage and low-power devices.

V. Conclusion

In order to determine whether lead-acid batteries would be one of the most convenient and reasonable methods of charging devices such as pulse oximeters, temperature sensors, spirometers, and electrocardiograph machines, we must consider all of the advantages and disadvantages. Lead-acid batteries are widely available to rural, underdeveloped, and developing regions. Many of these batteries can be attained at low costs because they already exist in and can be recharged in vehicles. They provide enough power to run the medical devices for multiple hours. There remains minimal potential for lead exposure or electrical burn when working with these batteries. However, they may require a voltage regulation system. Lastly, all rechargeable batteries have a finite lifespan, and eventually the battery would fail. Amid these disadvantages, lead-acid car batteries and lithium-ion batteries still have great potential for charging low voltage medical devices in developing countries.

VI. Further Testing and Research

Further research includes developing and testing voltage regulating systems to provide a safe and efficient interface between the medical devices and the batteries.

VII. Appendix

1) *Standard 9 Volt Alkaline Battery*

Voltage: 9 V; Amp-hours: 0.565 A·h

R = 9 V/0.0278 A = 324 Ω rated for 0.25 W

Hours = .565 A·h /.0278 A = 20.3 h

2) *Lead-acid Car Battery*

Voltage: 12 V; Amp-hours: 360 A·h

R = 12 V/3.53 A = 3.4 Ω rated for 90 W

Hours = 360 A·h /3.53 A = 102.0 h = 4.3 days

3) *Lithium-ion Battery*

Voltage: 3.7 V; Amp-hours: 0.780 A·h

R= 3.7 V/.26 A = 14.32 Ω rated for 0.96 W

Hours = .780 A·h/.26 A = 3 h

VIII. Acknowledgment

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IX. References

[1] Product Range. *Medical Point.* [online] Available: http://www.medicalpointindia.com/products.htm

[2] J. P. Dickenson and Colin Clarke, *A Geography of the Third World,* 2nd ed., Routledge, 1996, pp. 244-245.

[3] C. Suellentrop. (2003, August 15). Why this was a first world blackout*. Slate*. [online]. Available: http://www.slate.com/id/2087036

[4] (2008, June 12). Cutting the costs of solar power. *Think Solar Energy* [online] Available: http://www.thinksolarenergy.net/72/cutting-the-costs-of-solar-power/

[5] D. Hagopian. (2008, August 31). How many times can I charge my battery? *Battery Education* [online] Available: http://www.batteryeducation.com/2008/08/how-many-times.html

[6] (2006, October 18) How many cars are in the world. *I did not know that yesterday!* [online] Available: http://ididnotknowthatyesterday.blogspot.com/2006/10/how-many-cars-are-in-world.html

[7] T. Kotz, *Chemistry and Chemical Reactivity*, Belmont, CA: Thomas Brooks/Cole, ch. 20.

[8] M. Brain and C. W. Bryant. (2000, April 1). How batteries work. *Howstuffworks*. [online] Available: http://electronics.howstuffworks.com/battery3.htm

[9] E. W. Weisstein. (2007). Lead Storage Battery. *Wolfram.* [online] Available: http://scienceworld.wolfram.com/chemistry/LeadStorageBattery.html

[10] M. Brain. (2006, November 14). How lithium-ion batteries work. *Howstuffworks*. [online] Available: http://electronics.howstuffworks.com/lithium-ion-battery.htm

[11] T. D. Matte et al, "Lead exposure among lead-acid battery workers in Jamaica," *Am. J. Industrial Med.,* vol. 16, pp. 167-177, 1989.

[12] T. Magliozzi and R. Magliozzi. (2006, May 27). Car battery's 'electrocution' prompts physics lesson. *The San Diego Union Tribune.* [online] Available: http://www.signonsandiego.com/uniontrib/20060527/news_1dd27click.html

[13] (2005). Battery and Energy Technologies: State of Health (SOH) Determination. *Electropaedia.* [online] Available: http://www.mpoweruk.com/soh.htm

[14] John W. Stevens and Garth P. Corey. "A Study of Lead-Acid Battery Efficiency Near Top-of-Charge and the Impact on PV System Design." Sandia National Laboratories, Battery Analysis and Evaluation Department. [online] Available: http://photovoltaics.sandia.gov/docs/PDF/batpapsteve.pdf

[15] M. M. Lerner. (1999, October 21). "How do rechargeable batteries work and what makes the reactions reversible in some batteries, but not in others?" *Scientific American.* [online] Available: http://www.sciam.com/article.cfm?id=how-do-rechargeable-that

[16] (2005). Battery and Energy Technologies: Battery Life (and Death). *Electropaedia.* [online] Available: http://www.mpoweruk.com/life.htm

[17] I. Buchmann. (2001, April). "Can the lead-acid battery compete in modern times?" *Batteries in a Portable World.* [online] Available: http://www.buchmann.ca/Article7-Page1.asp

[18] Mitchell, Robert L. (2006, August 22). "Lithium-ion batteries: High-tech's latest mountain of waste." *ComputerWorld.* [online] Available: http://blogs.computerworld.com/node/3285