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Demonstration

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Exploring Real-World Applications of Electrochemistry by Constructing a Rechargeable Lithium-Ion Battery

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Supporting Information

ABSTRACT: The assembly and testing of a rechargeable 3 V lithium-ion battery in the common 2032 coin cell format is demonstrated in a classroom environment without the use of expensive and complex air-free equipment. The procedure has been developed to eliminate the use of highly toxic materials and flammable solvents, can be accomplished in 15 min, and is designed to be as inexpensive, safe, and simple as possible. The battery can be repeatedly charged with a cheap USB-powered charger and can be used to power an LED tea candle or similar device. A stopwatch and multimeter can be used to estimate the capacity and voltage of the battery. This demonstration offers a memorable, real-world application of electrochemical principles and gives students practical insight into the chemistry and construction of a lithium-ion battery.

KEYWORDS: *General Public, Elementary/Middle School Science, High School/Introductory Chemistry, First-Year Undergraduate/General, Demonstration, Oxidation/Reduction, Electrochemistry, Electrolytic/Galvanic Cells/Potentials, Green Chemistry, Sustainability, Systems Thinking*

Widespread adoption of renewable and sustainable energy requires effective energy storage in order to solve the intermittency of renewable power supply.[1] Batteries are a leading contender for providing grid-scale energy storage,[2] and large-scale deployments such as the Hornsdale Power Reserve in southern Australia display the exciting and ongoing investments in the storage of renewable energy.[3] Battery concepts are often taught by several different disciplines including physics, chemistry, and engineering; however, the principles of battery chemistry are rarely integrated in a complete systems-level approach. Chemistry demonstrations often utilize transparent glass cells to visualize the chemicals present at the anode and cathode. Although effective visualization tools, these demonstrations fail to emphasize the interdependence of electrode and membrane components for dynamic and high performance battery architectures that can enable high power electronics. Many classroom battery demonstrations continue to show copper/zinc "lemon" batteries, but these cells bear no physical resemblance to common batteries.

Lithium-ion batteries are increasingly used for transportation, and it is crucial for students to utilize systems thinking to understand the benefits and environmental costs across their fabrication and lifespan. Life-cycle analysis and greenhouse gas emissions related to the production of lithium-ion batteries have been reviewed, and results suggest that the replacement of materials such as lithium, cobalt, and fluorine remain longstanding challenges in their widespread deployment.[4−7] In addition, recycling at the end of the lifetime remains a longstanding challenge, especially given that a single electric vehicle may contain over 5000 individual cells in one large battery pack. Each of those cells would require disassembly and processing to recycle, dramatically increasing cost. Typically, only select materials, such as cobalt and nickel, are recycled from these batteries.[5] Assembly, anode material, and separators contribute minimally to total energy consumption and greenhouse gas emissions, while the cathode production, electrolyte components, and production of the metal housings account for the overwhelming majority of energy use and greenhouse gas emissions.[8] Providing students with a look "under the hood" of an operable lithium-ion battery can provide the context within which to spark a larger discussion about systems thinking of renewable technologies and about the benefits and longstanding challenges of green technologies.

Studies suggest that although students are typically very excited about real-world applications of electrochemistry,[9] both students and teachers alike often harbor negative opinions after exposure to the subject.[10] Laboratories that involve the demonstration of batteries have been shown to aid in correcting misconceptions about fundamentals in electro-

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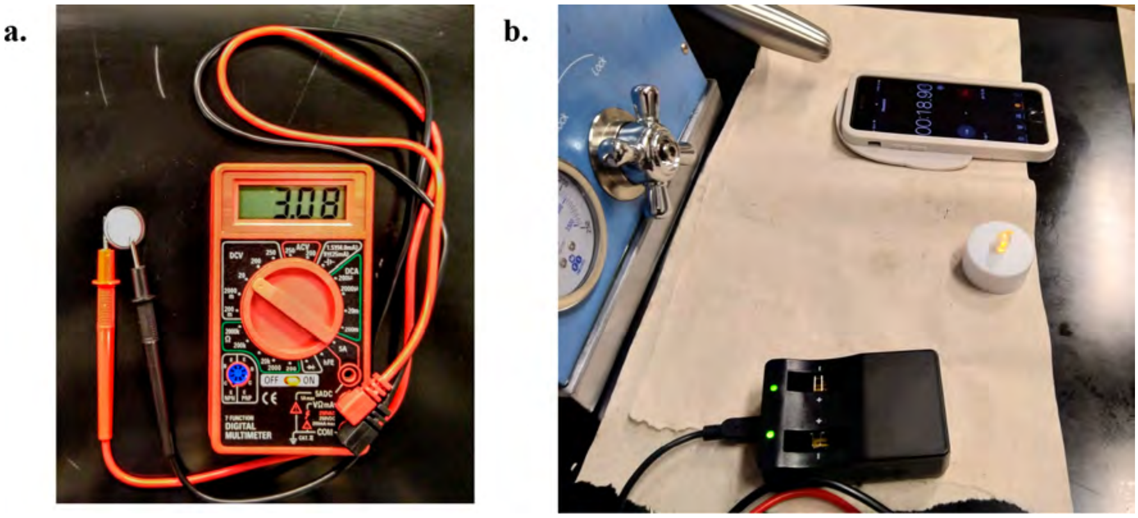

Figure 1. (a) Voltage of the battery after charging. (b) Timing the discharge of the battery in the tea candle. The USB battery charger is shown at the bottom.

chemistry in both teachers[11] and students.[12] Several creative and accessible experiments have been designed to power small electronics with redox reactions,[13−16] and excellent battery analyses and laboratory experiments have been recently reported.[17−21] To the best of our knowledge, however, the construction and demonstration of a lithium-ion battery (LIB) has not been reported.

Here we describe a demonstration for students studying introductory chemistry at the middle, high school, or undergraduate levels that results in a working 2032 coin cell lithium-ion battery capable of illuminating an LED tea candle. This procedure is modified from research laboratory sources[22,23] to be minimally toxic and flammable and can be performed in air without the usually required expensive fabrication equipment. The transformation of basic chemicals into functional materials integrates multiple scientific disciplines and ignites student engagement in systems thinking of renewable energy processes. This procedure has been demonstrated to students ranging from fifth grade to college-level undergraduates and routinely generates an incredible amount of excitement. A few of the students expressed explicit interest in pursuing further electrochemical research.[24]

■ MATERIALS

A complete and detailed description of the materials, equipment, sourcing, and costs is provided in the Supporting Information along with a detailed demonstration procedure. The equipment costs are dominated by the cost of the crimping device used to seal the battery. The marginal consumables cost per battery is about \$5; however, certain items are only available in bulk quantities.

Consumables

The following are needed: $LiMn_2O_4$ powder, graphite powder, a suspension of PTFE binder, lithium trifluoromethanesulfonate, propylene carbonate (anhydrous), a set of coin cell 2032 battery cases, spacers and springs, glass fiber filter paper, and 200 mesh stainless steel cloth.

Equipment

The following are used: heating plate or oven, battery crimper with a 2032 sized die, multimeter, balance, stopwatch, 2032 coin cell battery charger, and LED tea candle.

■ APPROACH AND HAZARD MITIGATION

Research-grade lithium-ion batteries are fabricated using a plethora of expensive (>\$100k) fabrication equipment including a tube furnace, ball mill, vacuum mixer, film coater, rolling press, vacuum oven, precision disc cutter, and hydraulic crimper.[25] Furthermore, the chemicals used for fabrication include acutely toxic materials such as *N*-methyl-2-pyrrolidone (NMP), highly flammable solvents such as dimethyl carbonate (DMC), and lithium hexafluorophosphate ($LiPF_6$) electrolyte, which generates toxic hydrofluoric acid upon exposure to moist air. Our procedure eliminates almost all of the expensive fabrication equipment and substitutes toxic, hazardous, and expensive materials with benign alternatives. Specifically, NMP was replaced with water, DMC was replaced with propylene carbonate (PC), and $LiPF_6$ was replaced with lithium trifluoromethanesulfonate (LiOTf). The resulting battery can then be charged with an inexpensive USB-powered charger and discharged with an LED tea candle light. Although the resulting battery performance is severely impacted, this is an advantage for the demonstration because the battery can be charged within 20 s and discharged for 80 s, allowing for repeated battery cycles in a short amount of time. These times are also appealing because short discussions can take place between charge/discharge cycles, while the LED candle continues to engage the student's attention.

■ DEMONSTRATION

The following outlines the basic demonstration procedure. A detailed description is provided in the Supporting Information. The anode, cathode, and electrolyte solutions are prepared in advance of the demonstration. The anode consists of a paste of graphite powder, PTFE binder, and water, pressed into a 1 cm^2 piece of stainless steel mesh cloth. The cathode consists of a paste of graphite powder, lithium manganese oxide, PTFE binder, and water, pressed into a piece of stainless steel mesh cloth. The anode and cathode are heated in an oven or on a hot plate at 150 °C overnight to thoroughly dry the electrodes. The electrolyte is prepared by dissolving LiOTf in PC to generate about 15 mL of a 0.1 M solution.

For the demonstration, the anode and cathode are separated by a piece of glass microfiber filter paper that is saturated with

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electrolyte solution, and placed inside a 2032 coin cell battery case with a Belleville washer and spacer to compress the electrodes and maintain electrical contact. The battery is then sealed in a hydraulic coin cell crimper.

The battery is charged using an inexpensive coin cell charger with a light that changes from red to green when the battery is finished charging. The time that this light is red is measured with a stopwatch. The battery is then removed from the charger, and the voltage is measured with a multimeter, which should display about 3 V (Figure 1a). The battery is inserted into an LED tea candle, and a stopwatch is used to determine how long the LED remained visibly bright (Figure 1b). Seeing the candle light up and eventually fade out often invokes cheers from the students. The current provided by the battery charger and drawn by the LED light can be measured with a multimeter in advance; thus, the quantitative capacity and efficiency can be determined by recording the time the battery takes to charge and the time it takes to discharge. A detailed explanation of these calculations is in the Supporting Information.

HAZARDS

As with most laboratory experiments, gloves and protective goggles should be worn by the demonstrator for handling the battery before it is sealed. After the battery is sealed and cleaned, it should be no more hazardous than a widely available CR2032 coin cell battery. PTFE, $LiMn_2O_4$, and graphite powder are not classified as hazardous substances; however, contact with skin and inhalation of dust should be avoided. Propylene carbonate is a skin and eye irritant and is flammable. Due to the very low vapor pressure (boiling point = 240 °C) and the small quantity used in the demonstration, it can be handled for short periods of time without trouble. LiOTf is hazardous due to the lithium ion; the fact that sodium trifluoromethanesulfonate is not hazardous suggests that the anion is relatively benign. Large quantities of lithium salts can be toxic and psychoactive; however, the scale on which these materials are used during this demonstration limits the maximum exposure to below hazardous levels (15 mL of the electrolyte solution contains less than 10 mg of lithium total). The voltages and currents used in this demonstration are not dangerous. The charged battery may contain a very small amount of pyrophoric material and should not be disassembled after being sealed. After the demonstration, the battery should be disposed of as hazardous waste or in a battery recycling bin that accepts lithium-ion batteries.

CONCLUSION

Lithium-ion batteries power our laptops and phones and are now increasingly used in automotive and renewable energy applications. Although these devices contain very complex electronic components, the battery construction is surprisingly simple. This practical demonstration helps bridge the gap between fundamental classroom concepts and practical applications of electrochemistry that are at the forefront of 21st century technology. Seeing how a classroom-made battery can power a real-world device can enable students to better retain electrochemical concepts and can provide motivation for students and teachers to deepen their knowledge in renewable energy systems.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00328.

Detailed preparations and instructions for the demonstration, item list, alternative materials and equipment, suggested quantitative analysis for the experiment, and suggested postdemonstration questions (PDF, DOCX)

Video of coin cell battery assembly (MP4)

Video of coin cell battery testing (MP4)

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Notes

The authors declare no competing financial interest.

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