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Activity

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“Can” You Really Make a Battery Out of That?

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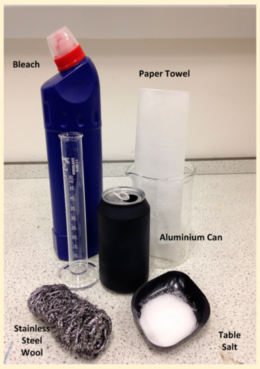
Supporting Information

ABSTRACT: This classroom activity introduces students to battery electrochemistry through the construction of a simple battery made from household products. Students will use a set of simple design rules to improve the performance of the battery, and power a light emitting diode. The electrochemical performance of the batteries is characterized using potentiostatic cyclic voltammetry and chronoampometry, and suggestions for implementing this activity into a high school teaching environment are presented. Designed for United Kingdom secondary schools and exam boards, the supplementary teaching package contains problem sheets and activities appropriate for students age 14 and up.



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■ INTRODUCTION

Batteries are used in a wide range of applications including mobile devices, hybrid and electric vehicles, and off grid electrical storage.[1] Batteries are an important energy storage technology and it is important that future generations understand how they work so that the next generation of technologies can be developed.

A classroom activity is a great way to inspire students, and to this purpose, the electrochemistry special interest group of the Royal Society of Chemistry (RSC) has sponsored the design of a battery experiment for United Kingdom (U.K.) secondary schools that fulfils the requirements of the major U.K. exam boards general certificate of secondary education (GCSE, ages 14−16), and advanced level (A-level, ages 16−18) qualifications.[2−6]

Batteries work through the controlled redox reactions of materials. In general, a battery consists of four major components:

1. The anode (negative electrode): The site at which oxidation occurs and where electrons are generated.
2. The cathode (positive electrode): The site at which reduction occurs. Electrons travel via an external circuit to the cathode where they reduce a neutral or positively charged species e.g. a molecule or cation.
3. The electrolyte: An ionic conductor that connects the two electrodes, completing the circuit.
4. A separator: A barrier that prevents the anode from touching the cathode, electrically insulating them. The separator is porous, allowing the ions in the electrolyte to travel through it.

The performance of a battery is measured by the voltage and the current it produces. The voltage is a thermodynamic quantity determined by the chemistry. The current depends on the rate of chemical reactions, the batteries’ internal resistance, and the materials used in its construction, all of which can be modified through design. We present an activity that allows students to develop an understanding of these concepts.

The activity is based on previous experiments in the chemical education literature[7−12] including an aluminum−air battery,[7] and an aluminum−bleach battery.[8] This activity consolidates these existing works into a simple experiment that can be performed at home or in a classroom using readily available household products. The use of household products makes the activity accessible to everyone and avoids the use of specialist chemicals or components. Demonstrators may wish to build on this activity by constructing an aluminum− air battery that uses an activated carbon cathode,[7] or building a more powerful aluminum−bleach battery that uses aluminum and copper plates as the anode materials.[8] The Supporting Information contains a “ready to use” guide for teachers’ and students aged 14−18 to use over one or two 50−60 min lessons.

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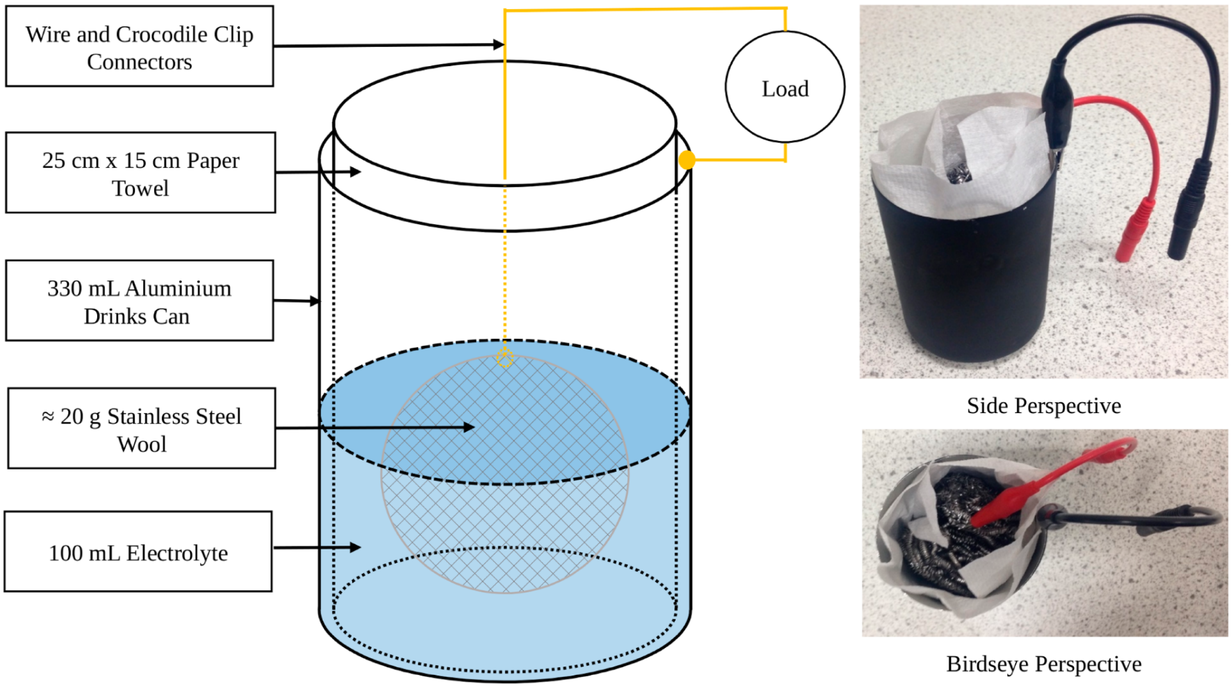
Table 1. List of Components, Estimated Costs, Dimensions, and Chemicals Needed To Construct the Battery

Component	Dimensions	Typical Chemical Composition	Estimated Cost (GBP)
Aluminum Can[13]	330−500 mL	Al	£ 0.75−1.00 per can
Stainless Steel Scrubber[13]	20 g	∼12−14% Cr, ∼0.20−1% Mo, >2% Ni, ∼0.1−1% C, ∼84% Fe	£ 1.00 per scrubber
Paper Kitchen Towel[13]	∼15 × 25 cm	N/A	£ 1.50 per role
Domestos Household Bleach[13]	100−300 mL	5 vol % NaClO, <5 vol % NaOH, <5 vol % Amines, C_{12-18}-alkyldimethyl, *N*-oxides	£ 5.00 per 750 mL bottle
Aluminum Cooking Foil[13]		Al	£ 8.00 per role
Salt[13]	100−300 g	NaCl	£ 2.00 per 750 g
Sodium Hydroxide[14]	<1 g	NaOH	£ 24.00 per 500 g
Distilled Water	100−300 mL	H_2O	N/A



Side Perspective

Birdseye Perspective

Figure 1. Schematic and pictures of an aluminum can battery made from a 330 mL soft drinks can.

■ EXPERIMENTAL SECTION

Part 1: Construction of an Aluminum−Air Battery

This section describes the construction of a battery made from products obtained from a typical supermarket. Table 1 contains the dimensions, typical chemical composition, and estimated price in GBP of the components needed to assemble the battery.

It is found that battery performance can vary with the bleach used in the experiment. Some products instantaneously react with the aluminum. All experiments were carried out with Domestos original bleach.

The battery anode is made from a 330 mL aluminum drinks can that is carefully prepared by removing the end with the "stay-tab ring opener" with a can opener and scissors. This exposes the internal aluminum surface, which is used in the electrochemical reactions. This is the most hazardous part of the experiment due to the sharp edges left on the can. These must be removed using scissors, and filed smooth using wet and dry sanding paper. Instructors may wish to prepare cans before the class.

The internal aluminum surface is cleaned and "roughened" with wet and dry sanding paper removing the protective epoxy resin layer from the inside of the can. The cathode is prepared using one 20 g stainless steel scrubber, typically used for kitchen cleaning. The stainless steel scrubber also has a large surface area, which is beneficial for electrochemical reactions. The scrubber is wrapped inside a 15 cm × 25 cm piece of paper kitchen towel. This separates the anode and cathode preventing short circuit. The stainless steel scrubber, wrapped in paper towel, is then placed inside the aluminum can, as illustrated and pictured in Figure 1.

A 100 mL aqueous solution of 2 M NaCl and 0.03 M NaOH is added as an electrolyte, creating an aluminum air battery. NaOH is used to reduce the overpotential of the oxygen reduction reaction (ORR) taking place at the cathode.[15] The electrolyte is made by dissolving ∼11.6 g of NaCl and ∼0.13 g of NaOH in 100 mL of distilled water.

Students should determine the electrochemical half-cell equations, and the theoretical voltage (E_o) of the cell. These are outlined below in eqs 1−4.[7] E^0 is calculated at 2.71 V.

Anode Reaction:

$$\mathrm{Al} + 3\mathrm{OH}^- \rightarrow \mathrm{Al(OH)_3} + 3\mathrm{e}^- \qquad E^o = -2.31\ \mathrm{V} \tag{1}$$

Cathode Reaction:

$$\mathrm{O_2} + 2\mathrm{H_2O} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^- \qquad E^o = +0.4\ \mathrm{V} \tag{2}$$

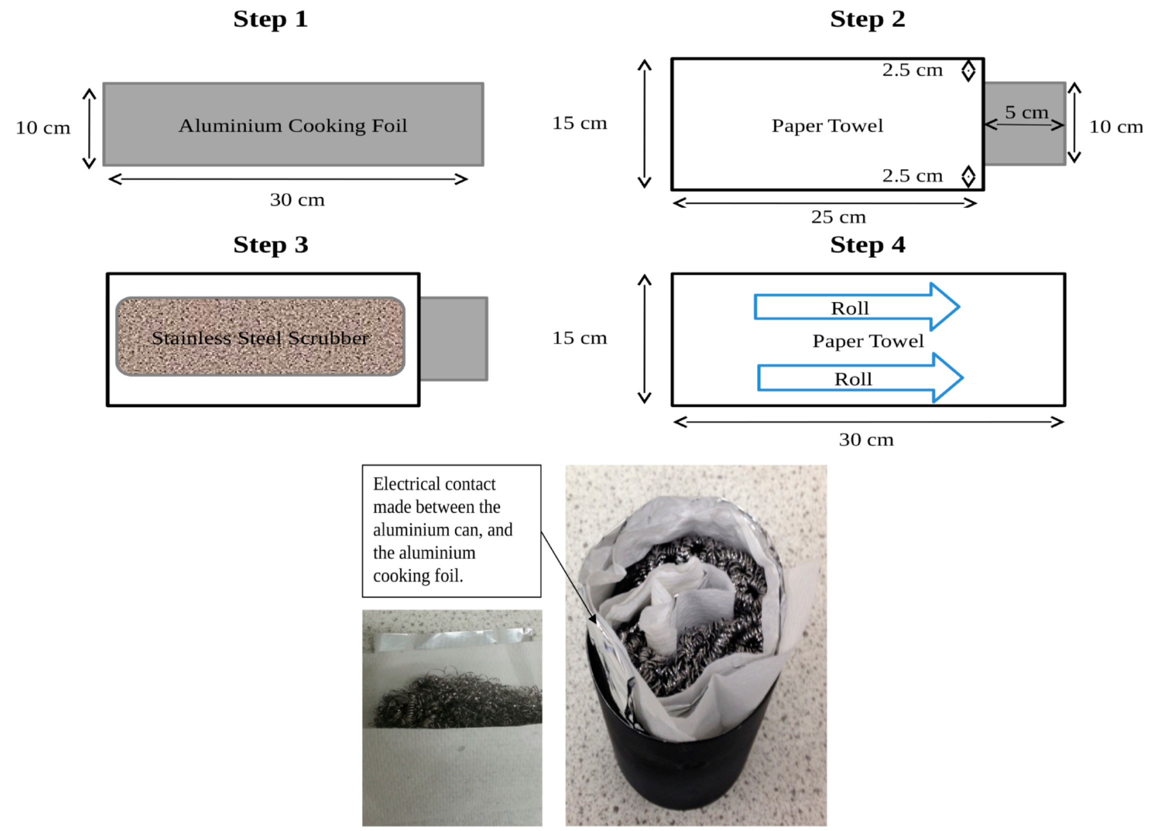


Figure 2. Schematic and pictures of the aluminum foil, paper towel, stainless steel scrubber, paper towel "sandwich", which is rolled and placed into the aluminum drinks can.

Redox:

$$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3 \qquad (3)$$

Cell Potential:

$$E_{cell} = E_{red} - E_{ox} = 0.4 - (-2.31) = 2.71\ V \qquad (4)$$

Students will record the open circuit voltage (V_{oc}) and short-circuit current (J_{sc}) of the cell using a voltmeter and ammeter. The negative (black wire) of the voltmeter/ammeter should be attached to the aluminum can, while the positive (red wire) should be attached to the stainless steel scrubber. Students will measure a positive voltage and negative current. By approximating the can as a perfect cylinder of radius $r \approx 3.32$ cm, we can calculate the internal surface area of the aluminum anode. This allows the current to be expressed as a current density in units of mA cm^{-2}. Details of these calculations are provided in the Teachers' Notes. When 100 cm^3 of electrolyte is added to the can, the surface area of the aluminum anode is ~95 cm^2. The performance of the cell is very poor. It is only possible to achieve an instantaneous current density of ~0.6 mA cm^{-2}, while the V_{oc} is measured as ~0.8 V.

Students should explore reasons why the cell does not produce the theoretical voltage ($E°$). Some suggestions include the following: the parasitic side reaction of water with the aluminum (which evolves hydrogen at the anode), and the large internal resistance of the cell due to the large diffusion distances between the anode and cathode (estimated as 0.2−3 cm).

Part 2: Improving Current and Voltage by Changing Cell Chemistry

The performance of the cell can be improved by changing the chemistry. The electrolyte is replaced with 100 mL of household bleach containing 5 vol % sodium hypochlorite (NaClO). NaClO acts as an oxidizing agent, providing an alternative source of hydroxyl ions. This increases the cathode potential and improves the rate of chemical reaction. The addition of table salt (NaCl) to the bleach improves the ionic conductivity through the introduction of additional charge carriers. NaCl should be added to bleach in the ratio of 10 g of NaCl per 100 mL of bleach.

Students should rewrite the half-cell equations and recalculate $E°$. These are outlined below in eqs 5−8.[8] E^0 is calculated at 3.21 V.

Anode Reaction:

$$Al + 3OH^- \rightarrow Al(OH)_3 + 3e^- \qquad E° = -2.31\ V \qquad (5)$$

Cathode Reaction:

$$ClO^- + H_2O + 2e^- \rightarrow Cl^- + 2OH^- \qquad E° = +0.9\ V \qquad (6)$$

Redox:

$$2Al + 3ClO^- + 3H_2O \rightarrow 2Al(OH)_3 + 3Cl^- \qquad (7)$$

Cell Potential:

$$E_{cell} = E_{red} - E_{ox} = 0.9 - (-2.31) = 3.21\ V \qquad (8)$$

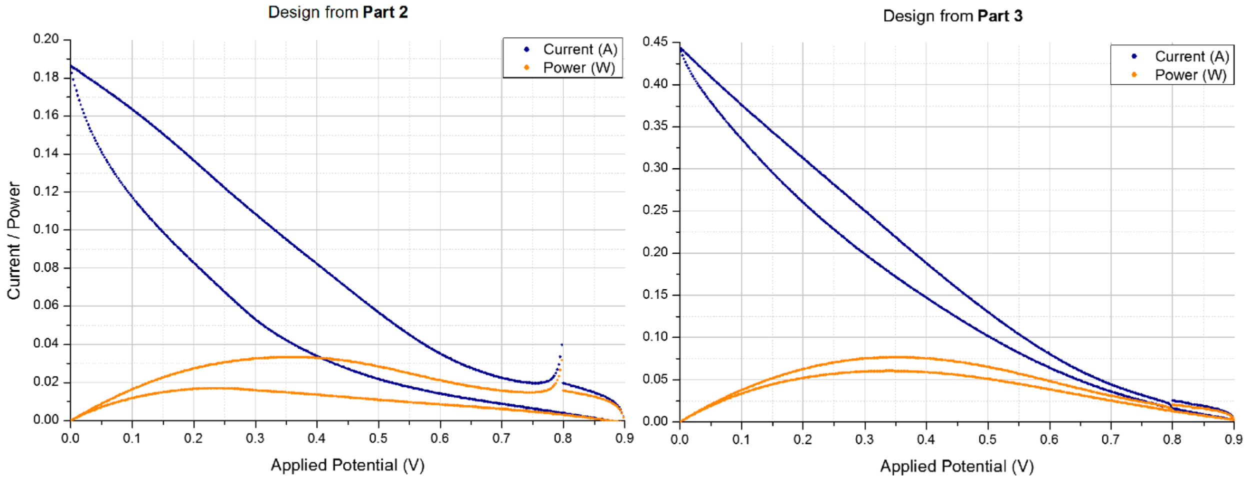


Figure 3. Average potentiostatic cyclic voltammetry, and voltage power plots of the different aluminum can battery designs. Left: battery design from Part 2. Right: Battery design from Part 3.

Students will remeasure the V_{oc} and J_{sc} of the cell. When 100 cm^3 bleach and 10 g of NaCl are added to the cell, it is possible to achieve an instantaneous current density of ~2 mA cm^{-2}, while the V_{oc} is measured as ~1.0 V.

Part 3: Improving Total Cell Current through Design

The total current of the cell can be improved by increasing the surface area of the anode. This is achieved by rolling additional aluminum cooking foil into the can as pictured in Figure 2. Following the schematic at the top of Figure 2, a "sandwich" of aluminum cooking foil, paper towel, stainless steel scrubber, and paper towel is constructed. First, a piece of 20 cm × 30 cm aluminum foil is folded in half to make a 10 cm × 30 cm sheet (**Step 1**). Aluminum cooking foil typically has a shiny side and a nonshiny side. It is recommended that the foil is folded so that the nonshiny side is on the outside. A piece of 15 cm × 25 cm paper towel is placed on-top of the foil (**Step 2**), followed by a stainless steel scrubber (**Step 3**). Finally, a second 15 cm × 30 cm piece of paper towel is placed on top of the scrubber (**Step 4**). The "sandwich" is then rolled so that the aluminum foil forms the outermost layer. It is vitally important that the aluminum foil does not touch the stainless steel scrubber. The roll is then placed inside the can so that the aluminum foil and can make electrical contact. Wires are connected to the can and scrubber in accordance with the schematic in Figure 1.

When an electrolyte mixture consisting of 100 mL of bleach and 10 g of NaCl is added, a total current of ~450 mA can be achieved. This is in contrast to the total current of ~190 mA measured when 100 mL of bleach and 10 g of NaCl are added to the cell design presented in Part 2.

HAZARDS AND SAFETY

The main hazards of this activity come from the use of sodium hydroxide (NaOH), bleach, and the rough edges left on the aluminum can after the end with the "stay-tab ring opener" has been removed. NaOH and bleach are poisonous and corrosive. It is recommended that safety goggles, lab coat, and gloves are worn when handling these chemicals. It should also be noted that bleach should never be added to acid, as this will evolve chlorine gas.

To reduce the risk of students cutting themselves on the sharp edges of the can, it is recommend that a can opener is used to remove the top of the can, and scissors are used to cut off the sharp edges. The sharp edge should then be filed smooth using wet and dry sanding paper.

A clamp stand is recommended for clamping the battery and preventing it from getting knocked over. The battery should not be left in an assembled state beyond the end of the lesson as the aluminum will eventually corrode and spill electrolyte. All solutions can be safely washed down a sink by carefully adding a large excess of flowing water.

ELECTROCHEMICAL PERFORMANCE AND POWERING LIGHT EMITTING DIODES

In this section, we present the electrochemical performance of the different battery designs. These experiments require the use of a potentiostat, and it is unlikely that this part of the activity will be suitable for high school teaching. This section may be suitable for a university teaching laboratory, where it could serve as a useful introduction to potentiostatic cyclic voltammetry and chronoampometry. It should be noted that additional safety requirements need to be considered regarding the safe handling of electrical equipment.

The different battery designs were tested using potentiostatic cyclic voltammetry (CV) and chronoamperometry. Potentiostatic CV is a technique that measures the cell current with respect to an applied electrode potential that varies with time. This can be used to determine the J_{sc}, and electrode potential at which the maximum power occurs. When the electrode potential is 0 V, the cell is short circuited giving the J_{sc}. The power of the cell is calculated by multiplying the electrode potential with the measured current. A scan rate of 100 mV s^{-1} was used to measure the current of the battery as the electrode potential was varied between 0.8 V → 0 V → 0.9 V → 0.8 V. The current was recorded every 2.5 mV giving 40 data points per 100 mV. These experiments were performed using a potentiostat manufactured by Autolab. The results were interpreted using the software program NOVA. The battery designs from Parts 2 and 3 were tested with an electrolyte mixture consisting of 100 mL of bleach and 10 g of NaCl. Figure 3 plots the electrode potential against the magnitude of the average current and average power, for the two different designs. Full details of the experimental method can be found in the Teachers' Notes.

Chronoampometry was used to measure the cell current at a fixed electrode potential over time. The electrode potential was fixed to 0.43 V, which is approximately the potential at which the maximum power of the bleach battery presented in Part 2 is reached. The current was recorded every second over 1800 s (0.5 h). The results are plotted in Figure 4, while the average power and the total work done by the cell are recorded in Table 2. The work done is calculated by multiplying the average power by the time period. A full description of the chronoampometry experimental method can found in the Teachers' Notes.

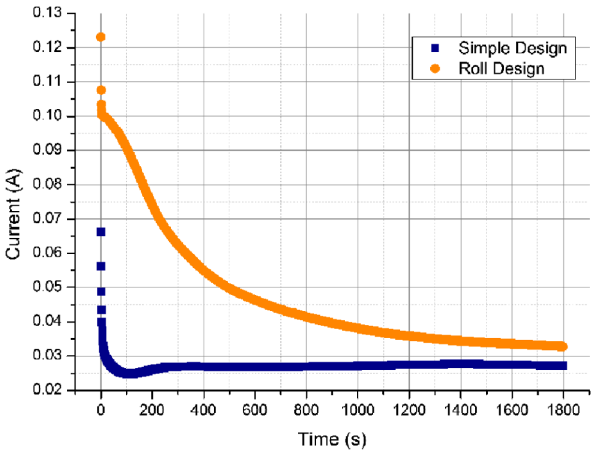


Figure 4. Chronoampometry results for the two different cell designs.

Table 2. Average Power and the Total Energy Results for Two of the Aluminum Can Battery Designs

System	Steady State Voltage (V)	Average Cell Power (mW)	Total Work Done (J)
Aluminum can, stainless steel scrubber, paper towel, 100 mL, bleach, 10 g salt	0.43	11.6	21
Aluminum can, stainless steel scrubber, paper towel, aluminum foil roll, 100 mL bleach, 10 g salt	0.43	20.3	37

The results of Figures 3 and 4 and Table 2 show that the design presented in Part 3, which incorporated an aluminum foil roll into its construction, produces a significantly better J_{sc} and maximum power than the design from Part 2. The J_{sc} is ~2.3 times greater, while the average power is ~1.75 times greater. When any two aluminum–bleach batteries are connected in series, enough voltage is produced to illuminate a red LED (e.g., RS components stock number 815-4360).

DISCUSSION

To evaluate the activity, four 16+ high school students and a science teacher were invited to test the experiment. Dr. Rhazaoui of Keystone Tutors read the teaching package and prepared two 1 h lessons based on the A-level student handout.

Dr. Rhazaoui prepared four aluminum cans before the lesson. This took approximately 15 min. The experiment was performed in groups of two, with each student making one battery. Students used the A-level student handout, and completed Parts 1 and 2 within a 1 h lesson. Students recorded the voltage and current of the aluminum–air battery presented in Part 1 before safely disposing of the salt NaOH electrolyte solution and preparing an aluminum-bleach battery as presented in Part 2. Students reused the same can for both parts of the experiment. Each pair of students connected their aluminum–bleach batteries in series to power a red LED.

Part 3 was completed in a second 1 h lesson with students reusing the same can and observing the improved performance of the battery. Students then combined their improved aluminum–bleach batteries to power a red LED. Students provided feedback on the experiment. Students gave the experiment 4/5 for enjoyability, 4/5 for usefulness, and 2/5 for difficulty.

CONCLUSION

With a growing interest in batteries for delivering a cleaner energy future, it is important to design an appropriate battery experiment for U.K. schools in order to inspire the next generation of scientist and engineers. To this purpose, a simple battery experiment has been designed and tested.

ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00496.

GCSE student lab script ages 14–16: lab script, questions, and answers, for a 1 h classroom lesson (PDF, DOCX)

A-level student lab script ages 16–18: lab script, questions, and answers, for 2 × 1 h classroom lessons (PDF, DOCX)

Teachers' slides: A short set of slides introducing battery chemistry (PDF)

Teachers' Notes: supporting calculations, experimental setup, hazards (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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