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Engineering Design Challenge

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Building a voltaic cell in the high school chemistry classroom

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The number of students majoring in science, technology, engineering, and math (STEM) is declining due in part to a lack of student interest (Fairweather 2008; NRC 2012; PCAST 2010). One reason may be the difference between how science is done in school and how it's done in the field (Osborne, Simon, and Collins 2003). An interdisciplinary approach that incorporates engineering design with the practical applications of science, however, may help spark student interest in STEM subjects.

This article describes an engineering design challenge in which students design and build an electrochemical (voltaic) cell with a motor and fan to help them observe the cell's energy production.

Background

We teach this activity in a chemistry class, but it is cross-disciplinary in nature and addresses current science standards (Figure 1). To focus on the engineering design aspect of this challenge (see sidebar, p. 35), we recommend using it as the culminating activity to an electrochemistry unit. Before starting the activity, students should be familiar with such terms as *cathode* and *anode,* be able to complete relevant calculations, and have appropriate laboratory skills (Figure 2, p. 32).

Many high school chemistry courses may not cover electrochemistry in depth, but this activity can be made appropriate for a unit on chemical reactions by adding more

FIGURE 1

Addressing the standards.

Next Generation Science Standards (NGSS).

Scientific and Engineering Practices	**Activity example**
Developing a model	Creating an electrochemical cell within the constraints of the project.
Carrying out investigations	Testing and redesigning the electrochemical cell.
Analyzing and interpreting data	Using data to determine the effectiveness of the electrochemical cell to turn the fan.
Using mathematics and computational thinking	Determining the concentration of salt solutions needed for the electrochemical cell.
Designing solutions	Identify best electrochemical cell based on data, feasibility, cost, and safety.
Obtaining, evaluating, and communicating information	Sharing electrochemical cell designs and results of the design process with peers.
Disciplinary Core Ideas	**Activity example**
Chemical reactions (PS1.B)	Oxidation-reduction reaction in the electrochemical cell.
Definitions of energy (PS3.A)	Electrochemical (cell), motor, and fan.
Conservation of energy and energy transfer (PS3.B)	Transfer of energy from electrochemical cell to the fan blades.
Energy in chemical processes and everyday life (PS3.D)	Use of chemical reactions as an energy source.
Crosscutting Concepts	**Activity example**
Scale, portion, and quantity	Minimum amount of chemicals used; scale up of electrochemical cell for use in industry.
Systems and system models	Defining what requirements are needed for making the fan turn using electrochemistry; explaining the electrochemical cell system.
Energy and matter: Flows, cycles, and conservation	Explaining the flow of energy between the electrochemical cell and fan; explaining the flow of electrons within the electrochemical cell.

teacher direction on how to create an electrochemical cell. For example, teachers can provide students with the structure of an electrochemical cell and a list of half-cell potentials for only the metals available to make the activity accessible for students with limited knowledge of electrochemistry.

The design challenge

The engineering design challenge typically takes two 90-minute class periods to complete. We begin by giving groups of two to four students a list of available materials and design requirements (Figure 3). This is similar to authentic engineering design, which is driven by specifications and constraints (see sidebar). We purchase the motors, alligator clamps, voltmeters, metals, and solid metal nitrates needed for this activity from a chemical supply company. Silver-based products such as Ag(s) and $AgNO_3$(aq) can be expensive, but they increase the variety of possible designs; other metals and metal salts can be used instead. Metal nitrate solutions can be used if solid metal nitrates are prohibited.

With the necessary materials and instructions, student groups engage in the engineering design process of planning, designing, testing, and evaluating their voltaic cells and fans (Figure 4, p. 34). Teachers can format a structured design log for students—or allow students to create their own—based on these steps. Let's look at each stage in more detail.

Planning: Brainstorming and research

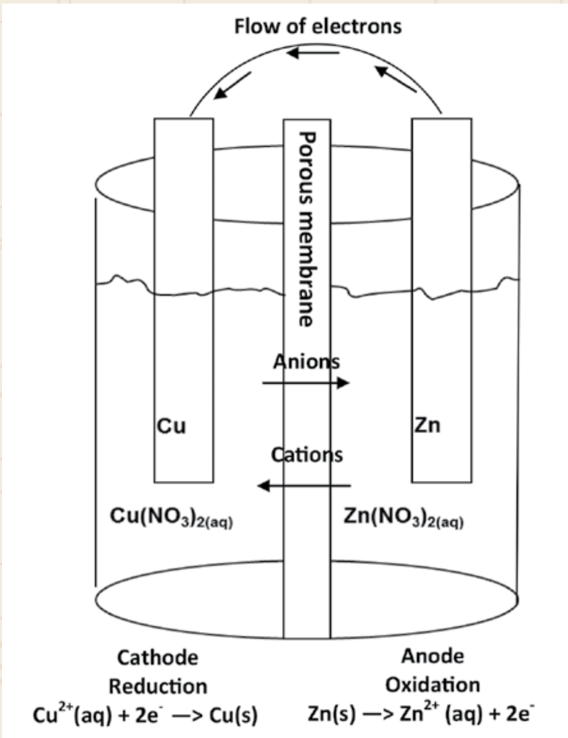
Students brainstorm how they might create a voltaic cell and conduct research to inform their design. We recommend having the materials (Figure 3) available to them during this part of the process so they can explore how the motor works and visualize the size of the cell's porous cups. Students may want to use the battery to see how electrical energy is converted to mechanical energy, for example, or feel the different materials available for their fans. While students are coming up with ideas for how they might approach the problem, we can formatively assess their understanding of electrochemistry.

After this initial brainstorming session, students conduct research to determine

FIGURE 2

Prior knowledge needed for this activity.

Students should know	Students should be able to do
The *cathode* is where *reduction* occurs in the cell. Electrons are *gained.* Ex. Cu^{2+} (aq) + $2e^-$ —> Cu(s)	Use half-cell reaction voltages to calculate the overall voltage of a redox reaction.
The *anode* is where *oxidation* occurs in the cell. Electrons are *lost.* Ex. Zn(s) —> Zn^{2+}(aq) + $2e^-$	Calculate the mass of a solid salt needed to make a solution with a specific volume and concentration.
Electrons flow from the anode to the cathode.	Identify the cathode and anode and explain the chemical processes occurring at each.
A *porous membrane* is needed to complete the circuit and allow for the flow of ions to maintain electrical neutrality. *Cations* flow toward the cathode; *anions* flow toward the anode.	Create an electrochemical cell and identify the cathode, anode, flow of electrons, and flow of ions.



Note: Depending upon the materials available, a salt bridge can also be used. A salt bridge decreases the contact area between the two solutions, reducing the potential difference between the half-cells.

how they might build a voltaic cell. During this phase of the planning, they write their questions in their design log and research the answers. For example, they might wonder how to determine which metals or salts will produce energy. Through research, they find that a positive cell potential from two half-cell reactions will produce energy, and that certain combinations produce more potential electrical energy than others. Some groups may be interested in how to design the fan blades to minimize air resistance and optimize the use of electrochemical energy. We encourage students to pursue these interests and lines of inquiry now.

After researching, students then return to their brainstorming and make modifications in their design logs in a different-colored ink. During this iterative process, students should identify the combination of metals, salts, and solution concentrations required to generate the minimum voltage needed to run the motor and turn the fan blades. Students use a standard reduction-potentials table, taken from a previous lesson, for the different metal and metal solutions available and calculate the combination of metals that will produce the required voltage using the following equation:

$$E^{o}_{cell} = E^{o}_{cathode} - E^{o}_{anode}$$

where E^{o}_{cell} is the cell potential at standard conditions, $E^{o}_{cathode}$ is the standard reduction potential for the reduction half reaction occurring at the cathode, and E^{o}_{anode} is the standard reduction potential for the oxidation half reaction occurring at the anode.

FIGURE 3

Design requirements and materials.

Note that the voltage of the cell should be equal to or higher than the voltage of the motor.

Goal: To make an electrochemical cell with enough voltage to turn a motor and fan blades.

Electrochemical cell materials	**Fan materials**
Small DC motor (runs on 1.5-3.0V), battery, 2 alligator clamps	Copy paper, tissue paper, cardstock, construction paper, cardboard
Mg(s), Zn(s), Cu(s), Pb(s), Ag(s)	Scissors
$Mg(NO_3)_2$(s), $Cu(NO_3)_2$(s), $Pb(NO_3)_2$(s), KNO_3(s), $AgNO_3$(s), KNO_3(aq) (0.1M)	Paper clips
Voltmeter and clamps	Small fan (optional)
50 ml beakers, 150 ml beakers, graduated cylinders, porous cups	Timer

Safety and disposal:

- Use chemical-splash goggles whenever handling chemicals in the lab.
- Silver nitrate solutions are toxic and can stain skin and clothes. Wear gloves and a lab coat as a precaution.
- Dispose of metals and solutions as directed by the teacher.

Requirements:

- Use only the materials available. If you require additional materials, the score on the “effectiveness of your design” will be reduced.
- Use the minimum amount of materials to get your motor/fan to run for the allotted time.
- Your testing and design may only use a total of 150 ml of solution.
- Correctly explain the flow of electrons and transfer of energy from the electrochemical cell to the motor and fan (written or graphically).
- The motor/fan should be able to run for five minutes.

Design

The design stage allows student groups to create a drawing for their voltaic cell and fan based on their brainstorming and research. To help them connect their designs with chemistry concepts, we require them to include the following labels in their design:

- anode,
- cathode,
- flow of electrons,
- flow of anions,
- flow of cations, and
- porous membrane or salt bridge.

Students should also list the materials required for their design and show their calculations for the masses of solid salts needed to make the correct concentration of solution to run their motors. (Calculations aren't needed if students use premade solutions.) Student groups should discuss and document how they will assess their designs based on the requirements and should get approval from the teacher before advancing to the next stage. We check student design for safety issues and to confirm that the design is detailed—though not necessarily correct. Students can approach the design process from multiple directions and learn from their mistakes.

Construction and testing

In the testing phase, students construct their cell and fan to assess whether they meet the requirements. Since students are working with chemicals, they must wear safety goggles, lab coats, and gloves. If they are making solutions from the solid metal salts, students begin with their solutions. Then they create their cells using their materials, write their observations in their design logs, and collect data to help them decide whether their design meets the requirements. See Figure 5 for one possible configuration for cell, motor, and fan.

In our own chemistry classrooms, we have found that the order in which students assemble their voltaic cell can affect whether it meets the requirements. For example, since the oxidation-reduction reaction begins once the cell is complete, and the potential of the cell decreases as the reaction proceeds, having the fan, metals, and clamps in place before adding the solutions and submerging the metals can improve success. Using a salt bridge instead of a porous membrane reduces the potential difference between the cells as the ions

FIGURE 4

Engineering design overview to guide students' creation of their design log.

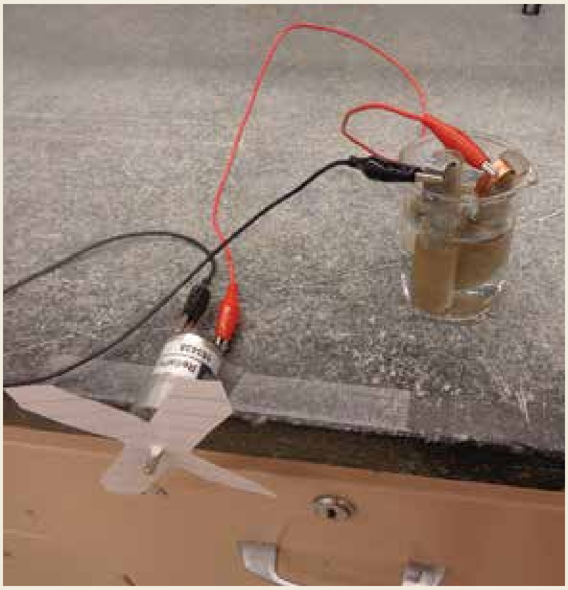
Stage	Student directions and probing questions
1. Brainstorming	Write any ideas that you have about how to complete the challenge successfully in your design log. Include sketches and any additional materials needed.
2. Research	Find out what there is to know about this challenge. Write questions you want to research in your design log. (What does it take to run the motor? What types of materials are best to use for the electrochemical cell?) After you write what you have learned, go back to Stage 1. In a different color, make any changes or additions to your original ideas.
3. Design	Make labeled drawings of the cell and list materials you will need to make your apparatus in your design log. Get approval from your teacher before moving on to Stage 4.
4. Construction and testing	Construct your electrochemical cell with motor and fan. Test your design, record data, and assess its effectiveness. (Do the fan blades turn? How would your design work in the long term?) Write one suggestion to improve your design in your design log. Then go back to Stage 3 and make changes or additions to your design in a different color.
5. Redesign	Based on your initial tests and design modifications, remake and retest your electrochemical cell with motor and fan. Sketch the final version of your design in your design log.
6. Evaluation	Evaluate your new design based on the original design. (How, if at all, was your design improved?) Evaluate the use of electrochemical cells as a source of energy. (How is electrochemistry being used and how could it be improved? You may need to do additional research to answer this question.)

Note: For students who need more structure, this can be made into a design log worksheet for students to follow.

FIGURE 5

One possible configuration.

Using two porous cups allows the "salt bridge" to be a solution of KNO_3 (0.1M) in the beaker holding the cups.



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mix, which may make the order of assembling the design less essential. Regardless of the method used to create electrical neutrality, however, we suggest that teachers allow students to work through the process of identifying the best order for design construction themselves.

The voltmeter allows students to observe the actual voltage of their completed system. Using their observations and data, students revisit their original design and make modifications in different pen or pencil colors to help them visualize the iterative nature of the engineering design process. They also record the positive and negative results of each modification in their design logs.

Redesign

Using the findings from their most recent design, students then redesign their voltaic cell, fan blades, or both to help optimize their systems. For example, students may observe that the fan blades turn too slowly, so they might decide to change the type of material used to make the blades or alter their angle. Some groups might find their motor doesn't run. This is most often due to incomplete circuits in the cell or the wiring, incorrect solutions, or calculation errors. We suggest that teachers circulate and provide support through questions and feedback as students troubleshoot to prevent frustration and help them better understand their design and the overall engineering design process. Students should evaluate their voltaic cell every time they test it by writing their observations in their design logs, collecting data, and making assessments of each redesigned system next to their original. One suggested structure for this process is available online (see "On the web").

Evaluation

At the end of the activity, students discuss how it applies to the real world by evaluating their final voltaic cell and fan design. Students reflect on the changes made to their design over the course of the activity and assess their final product based on the modification process and whether their design met the requirements.

Students also evaluate their cell as an energy source. Outside research may help them understand how electrochemical energy is currently used as well as its limitations or barriers. For example, students might discuss the use of batteries as an energy source (e.g., in electric vehicles) and the benefits and limitations of different chemical processes used in different types of batteries. Students in our classes have observed how voltaic cells "run down," so we prompt them to investigate the energy required to recharge batteries and where this energy comes from.

Students should address additional issues related to large-scale or long-term use of electrochemical cells. For example, metal ore mining and waste disposal are electrochemistry issues that students can use to evaluate this energy source.

At the end of the activity, they should also reflect on the iterative nature of engineering design.

Engineering design in action.

Through this activity, students engage in scientific and engineering practices that are essential to understanding how professional engineers and scientists tackle real-world problems. Engineering design in education is defined as:

> "The process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation" (ABET 2011, p. 4).

The activity described in this article allows students to engage in most of the fundamental elements of the engineering design process.

Assessment

We assess this activity through a grading sheet provided to students at the beginning of the activity (see "On the web"). We award points based on how long their designed fans run and the amount of solution they use to turn the blades. We also allot points based on fan function and ability to meet the criteria provided, and we review students' design logs. Finally, students complete a group and self-assessment, kept confidential and used to evaluate individual student contributions (see "On the web").

Modifications and extensions

Teachers can emphasize fan blade design rather than the voltaic cell. In a physics class, for example, teachers can direct students on how to create the voltaic cell and have them concentrate on designing an effective and efficient fan to better understand mechanical energy.

Students can learn more about the practical applications of electrochemistry by researching the history of batteries—the most common type of voltaic cell—beginning with the development of a wet cell. Students can also evaluate alternative sources to electric car batteries, such as solar and hydrogen, in a whole-class debate or as an essay assignment.

Another extension has students researching the history of plumbing and the importance of understanding electrochemistry (i.e., metals used in pipes) and physics (i.e., flow and direction of pipes). The corrosion process occurs when pipes made of certain materials (i.e., lead and iron) are oxidized—an electrochemical reaction. Teachers can assign student groups a historical time period involving different types of plumbing and have them present their findings to the class. A whole-class discussion can help them draw connections between historical decisions and scientific concepts.

Conclusion

Students really enjoy this activity and are excited when their fans turn. A lab filled with rotating fan blades powered by chemistry is quite a sight. The activity can be easily modified to incorporate physics, history, writing, and forensic debate and to engage the interests and goals of teachers and students alike. It provides the opportunity for students to think about the process engineers use to design and build in the real world and to experience how engineering can be integrated in the classroom. ■

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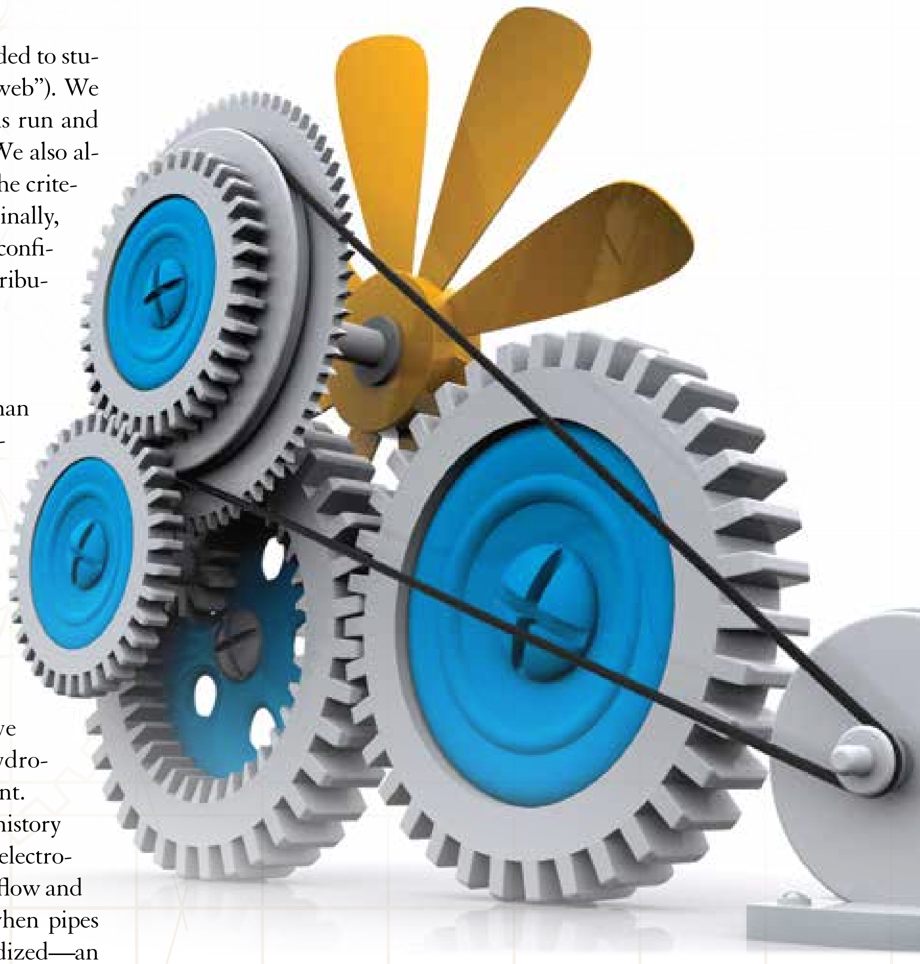

On the web

Student design log, grading rubric, and group- and self-assessment grading sheets: *www.nsta.org/highschool/connections.aspx*

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