Evaluating the Performance of a Battery

USING TEMPERATURE AND VOLTAGE PROFILES AND A BATTERY-RESISTOR CIRCUIT MODULE

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The chemical engineering field of study is undergoing changes with goals of introducing design earlier in the curriculum and increasing use of experiential learning throughout the curriculum.[1] A modular battery experiment has been developed and used in a sophomore-level mass and energy balance course and a junior-level measurements lab, toward these goals. These experiments assess the students' ability to use the techniques, skills, and modern engineering tools necessary for engineering practice, and also allow them to demonstrate their ability to design and conduct experiments, and to analyze and interpret data.[2]

An additional goal of this module is to introduce chemical engineering students to battery technology since batteries will play the pivotal role in energy security of modern societies. As an alternative to petroleum, batteries can be used in hybrid electric vehicles (HEVs) and plug-in HEVs to displace petroleum and increase the efficiency with which limited petroleum resources are consumed. Alkaline manganese–zinc batteries are the most convenient primary batteries as the source of power for portable electronic and electric appliances.[3] For advanced devices, alkaline MnO_2–Zn batteries are preferred, which use electrolytic manganese dioxide (EMD) and an alkaline electrolyte (KOH).[4] When used with the electric grid, batteries are able to enhance technologies related to wind power, solar power, and peak load shifting.[5] These topics provide students with exceptional platforms to which they can relate their investigations to contemporary issues.

The battery-resistor circuit module allows heat transfer, mass transfer, reactions, circuit theory, heat/mass balances, and product design to be studied in a single module. The module also provides a good preparation for the study of sensors, biosensors, and instrumentation because of its integrated approach using MATLAB, LabVIEW data acquisition systems, and virtual instruments—which incorporates different aspects of the engineering curriculum. Once the standardized work-

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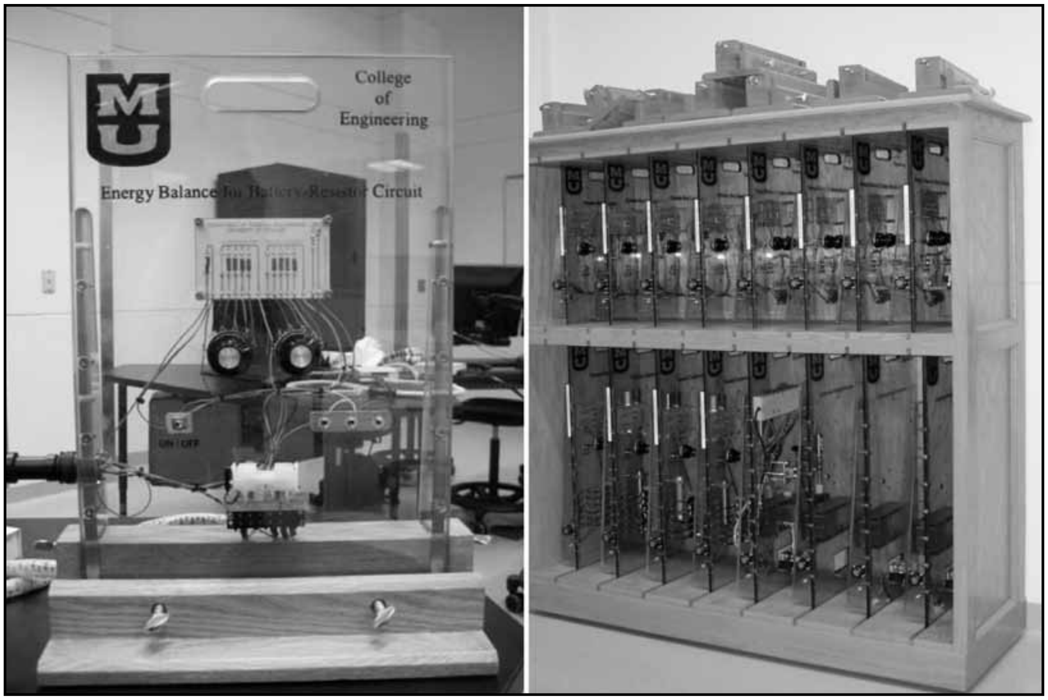

Figure 1. *Photograph showing the Energy Balance for Battery-Resistor Circuit Module (left) connected to the data acquisition system cable and module storage cabinet (right) that is used to store 16 modules and mounting bases.*

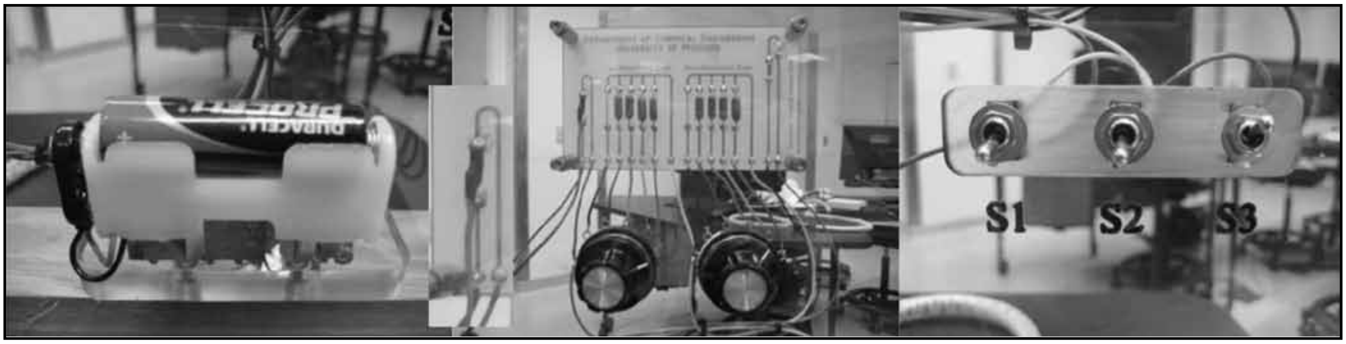

Figure 2. *Close-up images of module, including, from left to right: AA battery holder; expanded image of 1-ohm resistor with thermocouple attached with shrink wrap; circuit board with 1-ohm resistor, two resistor banks, and knobs for selecting resistance from two resistor banks; and switches used to select locations for voltage measurements.*

stations, stands, and storage are in place, individual modules can be produced for a few hundred dollars with four modules occupying about two square feet of space when stored in the storage cabinet.

APPARATUS

Figure 1 shows the experimental module composed of circuitry mounted on a 1 cm thick Lexan panel. The panel and reinforcing bases are mounted on an oak base. A cabinet allows compact storage of 16 modules and mounting bases. Each module connects to a computer workstation equipped with a National Instruments data acquisition card (NI PCI-6259), a shielded connector block (NI SCB-68), and LabVIEW 8.6 software. Use of a standardized 24-pin connector allows different experiments to use the same connector interface and respective workstation.

Figure 2 provides close-up images of the AA battery connector, resistor bank, and voltages switches. A small thermocouple embedded in the AA battery holder monitors the battery temperature, which is used for the energy balance.

A second thermocouple is attached to the 1-ohm resistor—the temperature profile of the 1-ohm resistor is the key measurement for the energy balance studies. The 1-ohm resistor is connected in series with two other resistors from two resistor banks as selected by the selector switches. Each selector switch has five settings allowing 25 different loads to be measured. These resistor banks allow variations in an assignment to be made so no two groups or individuals have the same exact experiment. This allows the students to compare their data with other individuals or groups to relate the effect of the changes in resistor load, promoting a more interactive learning environment.[6]

A series of three switches allows students to measure voltages at different locations in the circuit. Figure 3 provides a schematic of the battery (represented as a voltage source and internal resistance), the two resistor banks with the two associated selector-switches, and the three switches that allow voltages to be measured over the different loads.

Operating the module consists of the following steps:

1. *Insert and fasten the module on a base at a workstation and connect the 24-pin connector that links the module to the National Instruments based data acquisition system.*
2. *Place AA battery in the battery holder or connect ancillary battery to system.*
3. *Start module-specific LabVIEW virtual instrument file (VI).*
4. *Set module selector switches (N1 and N2) to provide experiment-specific resistance, put S1 and S2 in the down position and S3 in the up position to measure voltage across entire load.*
5. *Hit the start button on LabVIEW VI followed by switching the module on using the module's on/off switch.*
6. *Record data for the desired time (typically 5-10 minutes) and then click on the LabVIEW VI "STOP" button.*
7. *Return module switch to the off position and either repeat or disassemble the experiment.*

Data files created by LabVIEW are readily accessible by MS Excel and include columns of time, resistor temperature, battery temperature, and voltage (as selected by the switch settings). The first time the experiment is run by a group, it takes about 25 minutes. Subsequent runs take about 10-15 minutes. Typical errors of experiments include use of depleted batteries or operating experiments with switches in the wrong positions. The modules are available in an open-format laboratory for 45 hours a week in an environment that better resembles a computer workstation lab than a chemical engineering lab. Students are performing experiments (experiential learning) side-by-side with students performing homework and writing reports.[7]

This paper explains three different experiment-based projects that can be performed using this module.

PROJECT 1: BATTERY-RESISTOR ENERGY BALANCE

The purpose of the Mass and Energy Balance Experiment is to predict and then model the transient temperature profile of the 1-ohm resistor that is connected in series with two resistor banks and an AA battery. The students are given minimal guidance in the initial prediction of the temperature profile beyond a schematic of the circuit, knob settings, and the specification of the brand name and type (zinc-alkaline) of battery.

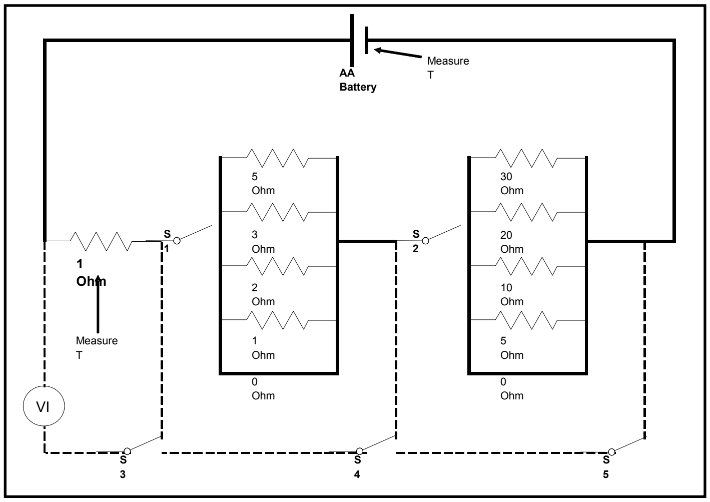

Figure 3. *Schematic of the experimental system that shows the different resistors in series and switch settings for voltage measurements.*

The students are responsible for the derivation of governing differential equations such as the equation for change in resistor temperature as a function of time, $\frac{dT_{res}}{dt}$ which can be derived from the change in internal energy over time; $\frac{dU}{dt}$.[8] The students are to identify how voltage drop and amperage translate to a heat input term in a first law balance, and they are to estimate parameters such as heat capacity and mass. They are encouraged to use MatLab to solve the differential equations that govern the system.

The following are pertinent governing equations:

$$\frac{dU}{dt} = Q - W \tag{1}$$

$$\frac{m_{res} C_{res} dT_{res}}{dt} = Q - W \tag{2}$$

$$\frac{m_{res} C_{res} dT_{res}}{dt} = V^2 / R - hA\left(T_{res} - T_{ambient}\right) \tag{3}$$

During initial predictions the students will typically neglect the convective cooling of the resistor by ambient air or they will struggle to identify how to model the heat transfer. Most students have not had a course in heat transfer, and when they identify the need to apply an engineering science that they have not yet covered they are directed to research the use of heat transfer coefficients.[9] The need to take into account the convective heat transfer term to model the temperature profile of the resistor will become evident when they obtain experimental temperature profiles. If convection was not identified during the predictive modeling stage of the project, the temperature profile indicates the need to modify the model battery. The modeling process provides a conceptual learning element because the students can visually relate how changing the heat transfer coefficients modifies the temperature profile.[2]

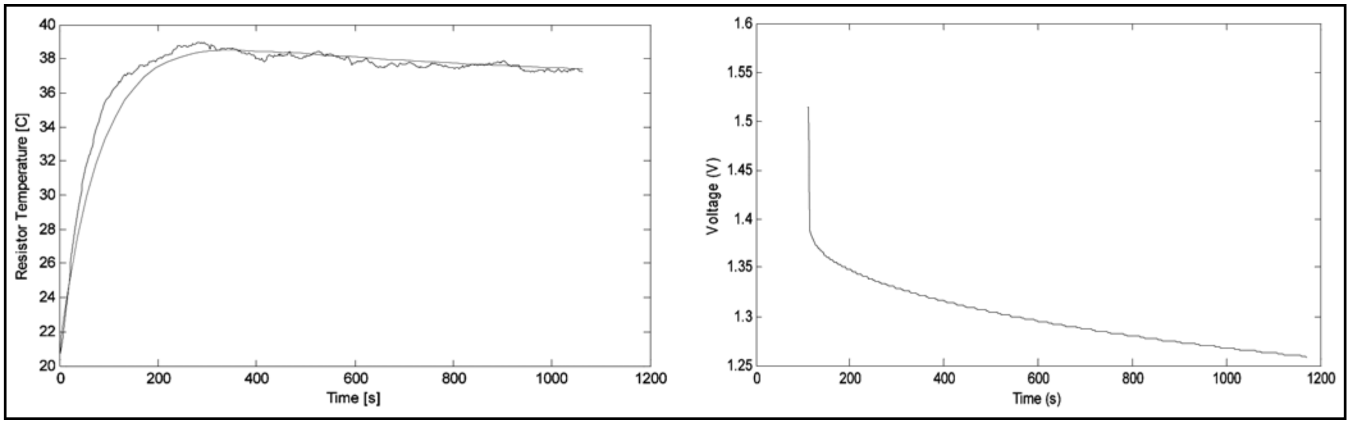

Figure 4. *A plot of the resistor temperature with superimposition of modeling results (left) and voltage profile of the battery operating with a 3-ohm total resistor (right). For voltage profile plot the experiment was initiated at t=100 s.*

Figure 4 provides a typical resistor temperature vs. time profile and a voltage profile for battery discharge operating with a 3-ohm total resistance load.

The resistor temperature vs. time profile can be used to model the resistor temperature as a function of time by manipulating hA, the heat transfer coefficient, and mC, the heat capacity, in the MATLAB program. The decreasing temperature is a manifestation of decreasing voltage power output from the AA battery, which is under a heavy load.[10] This aspect of the project introduces the challenge of how to handle the modeling of the resistor temperature for a non-constant voltage term—this introduces the utility for numerical solution of ordinary differential equations when analytical solutions may not be an option.[11]

Another aspect of this lab can be used to measure battery efficiency by measuring actual voltage, shown in Figure 4, delivered by the battery divided by the ideal voltage. The students will be able to follow the temperature profile of the battery and visually understand and verify what happens to the lost energy.[12]

For semester-long projects, the students are able to sequentially perform the following:

1. *Convert the voltage profile of Figure 4 to battery efficiency vs. time.*
2. *Obtain battery voltages at a specified times (*e.g.*, 30 seconds into discharge) over multiple resistances then use these data to prepare a battery performance curve (Voltage vs. Amperage).*
3. *Fully deplete a battery to obtain the amp-hours of energy the battery is able to deliver and compare this to the mass of the battery components (as estimated based on Material Safety Data Sheet (MSDS) information).*
4. *Use the performance curve (from Reference 2), amount of active reagent utilization (from Reference 3), and membrane surface area (membrane that separates cathode from anode, an estimated value) to design a battery for a different application (*e.g.*, powering a 20 W light bulb for 2 hours).*

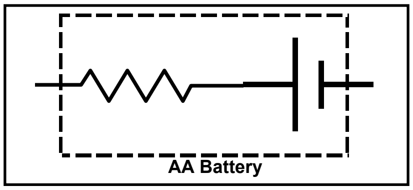

Figure 5. *Schematic of a battery as a voltage source in series with an internal resistance.*

A project based on these steps provides a valuable experiential learning process involving: energy balances, transient energy balances, basic circuit theory, modeling vs. predictive simulation, convective heat transfer, analytical vs. numerical solution methods, mass balances, transient mass balances, battery performance curves, and product design.[13]

PROJECT 2: EVALUATING THE INTERNAL RESISTANCE OF A BATTERY

A common representation of a battery in circuit theory is as a resistor in series with a voltage source (see Figure 5). The goal of this project is to identify the utility and accuracy of this commonly used model for a battery in a circuit. In the first phase of this experiment, the students evaluate an AA battery identifying the voltage at 10 seconds for each of several module-set resistances (from high to low).

Analysis of the data for this project can be obtained by linear regression of an equation derived as follows.[14] Where:

$$V_o = I\left(R_{Battery} + R_{Circuit}\right) \tag{4}$$

The current (I) for each experiment can be identified by this same equation evaluated over the circuit load rather than the theoretical voltage of the battery:

$$I = V_{Circuit} / R_{Circuit} \tag{5}$$

or

$$V_{Circuit} = V_o - R_{Battery}\left(V_{Circuit} / R_{Circuit}\right) \tag{6}$$

where linear regression can be used to identify V_O (constant) and $R_{Battery}$ (slope).

Figure 6 illustrates experimental data plotted according to Eq. (6) with an excellent correlation and little scatter. The students are expected to analyze their data and understand why the internal resistance of the battery stays constant, using equations to justify their results. The internal resistance of the battery is relatively constant for data taken at a constant time of exposure to a load. For low resistances, the resistance of the battery will decrease with time due to increased diffusion over-potential as the substrates closest to the membrane are consumed.[15] This trend is seen for the right-most data point, and for this reason, the linear regression was performed without including that data point.

Extensions of this project could include evaluating the internal battery resistance at different times the battery is under load.[16] Detailed discussions related to transient diffusions in packed-bed anodes could be used to explain the dependence of the internal battery resistance on time. If the students are able to do the sophisticated modeling, the diffusion in the packed bed could be modeled, converted to diffusion over-potential, and interpreted in terms of a resistor model.

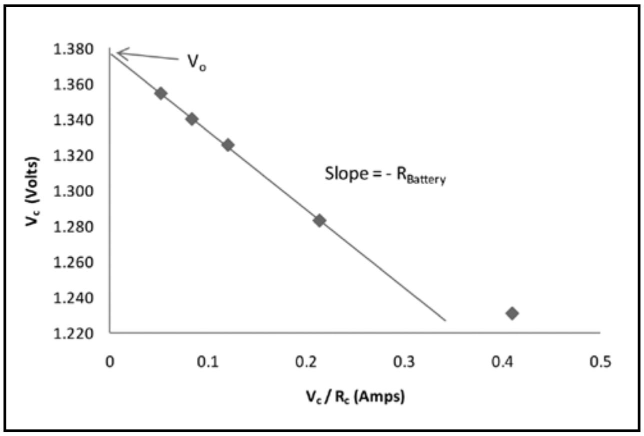

***Figure 6.** Example results from PROJECT 2 and Eq. (6) for evaluating the internal resistance of a battery. The data are for different circuit resistances evaluated with the experimental module.*

PROJECT 3: DIFFUSION AND PERMEABILITY IN MANGANESE DIOXIDE- ZINC BATTERY

The objective of this project is to evaluate batteries that the students assemble. The students are also to relate fundamental differences of the battery performances to properties of the materials and the cell geometry, and to quantitatively correlate the performance to diffusivity resulting from varying the separator material. The use of a zinc electrode anode is important because of its high open-circuit voltage in the KOH electrolyte, a low corrosion rate, and a low material cost.[17]

A schematic of the battery assembly is provided by Figure 7. Prepared anode packing, cathode packing, separator materials, and premixed electrolyte are provided to the students for assembling the batteries. The electrode packings are volumetrically dispensed into the cell being separated by the separator materials. Alligator clips are used to connect the current collectors of the battery assembly to the AA battery holder points of contact on the experimental module.

The experimental procedures include assembling several Zn-MnO_2 batteries with different separator materials and evaluate the performance in a 33-ohm circuit. Zinc powder is used as the anode packing in preference to zinc foil or plates because of its large surface area to distribute solid and liquid phases more homogeneously.[18] A high zinc surface-area-to-volume ratio is needed for high-rate capability and since zinc oxide will form on the surface of the zinc as summarized by the following half reactions:[19]

$$\mathrm{Zn(s)} + 2\mathrm{OH^-(aq)} \rightarrow \mathrm{ZnO(s)} + \mathrm{H_2O(l)} + 2\bar{e} \qquad (7)$$

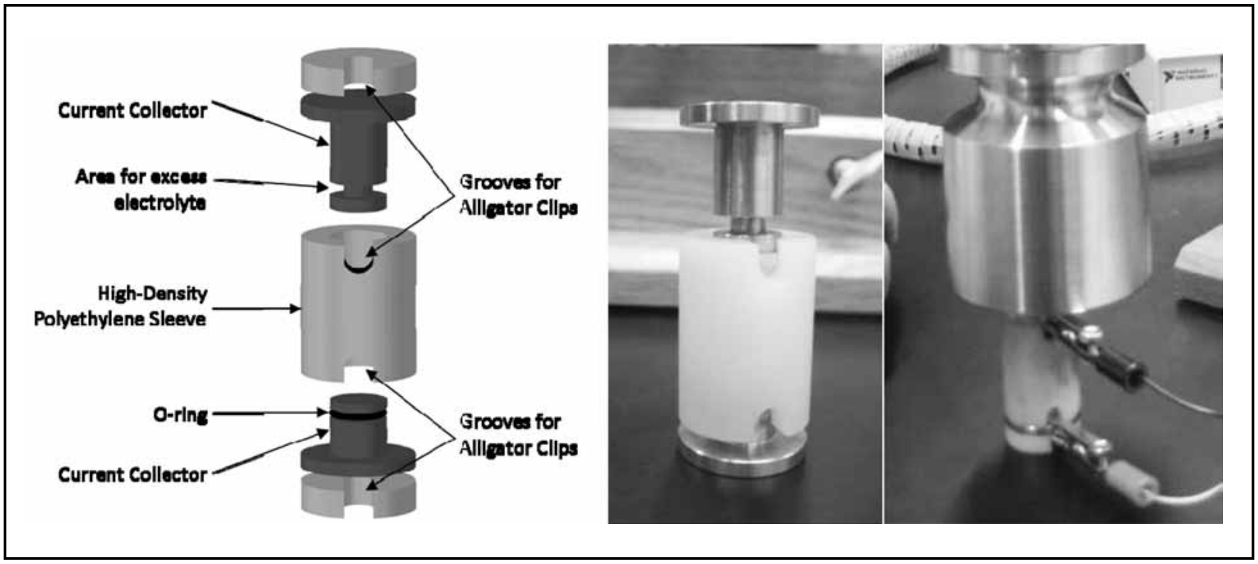

***Figure 7.** Pictorial representation of a compression cell used for the assembly of MnO_2 – Zn batteries (left) with picture of assembled cell (middle) and an assembled cell with weight to provide compression (right).*

$$2MnO_2(s)+H_2O(l)+2\bar{e}\rightarrow Mn_2O_3(s)+2OH^-(aq) \quad (8)$$

Manganese oxide powder mixed with a carbon black is used as the cathode. The carbon is used to increase conductivity of the positive active mass to reduce the internal resistance of the cell.[20] This material may require mechanical processing to maximize reactivity.[21] Potassium hydroxide (1M or 2M) in distilled water works well as the electrolyte because of its high conductivity, and results in a low internal resistance.[22] In the presence of KOH, the discharge behavior of MnO_2 occurs in a heterogeneous phase reaction.[23]

The separator materials provide the best opportunity to systematically vary a parameter that impacts battery performance. Sheets of permeable material can be punched to sizes that match the inner diameter of the battery's polyethylene sleeve. When preparing the battery, care must be taken to assure that the permeable separator totally separates the anode from the cathode or the battery will short circuit. Filter paper works well as a separator with the experimental parameter being the number of sheets of filter paper placed between the anode and cathode. The filter paper used in this experiment is a qualitative type with coarse porosity and a fast flow rate, from Fisher Brand. More sheets will create greater resistance to diffusion and greater over-potential losses.[15] It is also beneficial to have a negative control of a non-permeable polypropylene membrane to confirm that in the absence of a diffusive path between the anode and cathode, the battery voltage will immediately go to zero.

The test cell (Figure 7) is basically a compression cell composed of two pistons inside a nonconductive sleeve. The battery is assembled by inserting the base of the compression cell first (the shorter piston). It is assembled as follows:

1. *Place a volumetrically dispersed amount of the cathode material (MnO_2) into the cylinder (enough to cover a thin layer on the bottom of the cell) and tap the cell to create an even distribution.*
2. *Cover the material with the correct number of filter papers (qualitative P8 Fisher Brand).*
3. *Wet the filter paper by placing a few drops of the electrolyte solution (~10-15 drops of 1M KOH).* Potassium Hydroxide is used as an electrolyte in Manganese Dioxide-Zinc batteries because of its strong conductivity.
4. *Add a thin layer of the anode material (Zn) and close the compression cell with the longer piston.*
5. *Bring the assembled battery back to the module and obtain a pair of wires. Remove the original AA battery, snap off the battery power adapters and connect them to the wires.*
6. *Attach the alligator clips to the assembled battery and put the two plastic pieces on the top and bottom of the assembled battery, aligning them with the notches.*
7. *Place a 6 kg weight on the assembled battery and run the program. The weight on the battery compresses the anode and cathode material together, making the electrons flow more efficiently, and creates a better voltage.[24]*

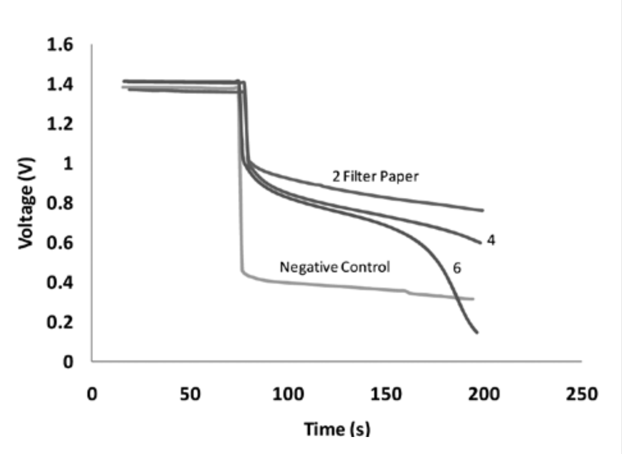

Figure 8. *Graph of results showing proposed trend of decreasing voltage with increasing resistance of separator between electrodes. The numbers indicate the number of layers of filter paper between the electrodes.*

Figure 8 summarizes representative data for a study of 2, 4, and 6 layers of filter paper, and a negative control using polypropylene as a nonpermeable membrane separating the anode material from the cathode material, keeping the time of the experimental runs constant. The polypropylene membranes used in this experiment were obtained using the same hole-punch technique as the filter papers, using a petri dish as the material. Battery performance typically consists of a steep drop in voltage initially and then a steady decline. At a constant load, an increase in resistance (more layers of filter paper) results in a lower voltage delivered to the resistor.[15] Ideally, the voltage for the nonpermeable membrane should immediately drop to zero; however, because of the difficulties involved in constructing a perfect separation seal, there may be some voltage detected due to the seepage and mixing of the anodic and cathodic material around the outer perimeter of the polypropylene membrane.

The students should be able to qualitatively understand how increased diffusion distances through permeable materials translate to increased voltage over-potentials.[15] In more advanced applications, the permeability can be related to voltage. Other variations from this experiment include use of battery assemblies with different inner diameters and use of non-permeable separators cut into washer-shapes that vary the cross-sectional area available for diffusion.

STUDENT FEEDBACK

For Project 1, the students recognized and appreciated how energy is converted from chemical to thermal forms and how transient differential models can relate underlying engineering science (Ohm's law, convective heat transfer) to observed phenomena. The most frequent problem encountered was a lack of attention by the students to which voltages were actually being measured during the experiment. Project 2 was a simple and straightforward experiment that validates a commonly used model for batteries. Students who expected the need for a detailed analysis based on differential equations were disappointed. Project 3 was effective in getting students to contemplate some more complicated aspects of mass transfer and how mass transfer limits the performance of a battery. The primary concern with Project 3 was that sloppy preparation of the assembled battery could result in inconsistent data.

SUMMARY

The battery provides an excellent basis for student projects in chemical engineering. The module described in this paper provides a way to deliver experiential learning with batteries in open formats that can be used with a variety of lecture-based courses. The students are able to directly connect with what they observe in the experiential learning because they encounter and frequently use batteries in their day-to-day routines. Different variations of battery-based projects allow students to use energy balances, transient energy balances, basic circuit theory, modeling vs. predictive simulation, convective heat transfer, analytical vs. numerical solution methods, mass balances, transient mass balances, battery performance curves, and product design.

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