Employing the Experimental Method to Inform Solar Cell Design

Mary A. Rose, Jason W. Ribblett and Heather Hershberger

Ball State University

In the 21st century, inquiry and technological innovation are inextricably linked in the collaborative efforts of scientists, engineers, and technologists who push the boundaries of knowledge to harness alternative energy sources and thus reduce our reliance upon fossil fuels. The research and development (R&D) collaborations of the National Renewable Energy Laboratory and the HelioVolt Corporation in photonics and nanotechnology are an illustrative case. Working together, these organizations developed a reliable process to mass-produce a thin-film (micrometers thick) solar cell that converts photonic energy (sunlight) into electricity using copper indium gallium selenide (CIGS) semiconductors (HelioVolt, 2006). One scientific challenge has been to discover the optimal chemical structure of the CIGS material which maximizes its photoelectric properties and conversion efficiency. Another engineering challenge has been to develop a reliable manufacturing process—akin to a printing process—that produces 15 and 30-cm wide solar modules (Bullis, 2007) directly onto traditional construction materials using non-vacuum and vacuum nanomaterial-based deposition processes (HelioVolt, 2006).

1. Experimentation 101

Conducting collaborative R&D requires multidisciplinary understandings about engineering, science, and the inquiry process. Simply stated, **inquiry** is a search for understanding that is spurred by intellectual curiosity and enabled by objective, measurable, and replicable methods. During inquiry, scientists observe phenomena, ask questions, hypothesize, systematically gather and analyze data, and theorize about the meaning of this evidence. When scientists attempt to explain cause-and-effect relationships, they employ the most powerful of inquiry techniques, a controlled experiment.

In an **experiment**, the focus of inquiry lies upon the relationship between two or more variables (a quality that varies), such as light intensity and electrical power. In particular, the researcher systematically changes (manipulates) one variable—called the **independent** or **treatment variable**—then measures the change in a second variable—called the outcome or **dependent variable**. Concurrently, the researcher deliberately controls for any other forces that might also influence the dependent variable. In effect, these controls generate confidence that the treatment is the cause of change. The goal of an experiment is to isolate the effect that one variable has on another.

In this article, the underlying logic of experimentation is exemplified within the context of a photoelectrical experiment for students taking a high school engineering, technology, or chemistry class. Students assume the role of photochemists as they plan, fabricate, and experiment with a solar cell made of copper and an aqueous solution of sodium chloride (Figure 1). This multidisciplinary activity enables students to examine principles of chemistry, photonics, and electricity while reflecting the *Standards for Technological Literacy* (ITEA, 2000) and the *National Science Education*

Figure 1. Students test the performance of their solar cell using a multimeter.

	Standards for Technological Literacy (ITEA, 2000)	National Science Education Standards (NRC, 1996)
Inquiry & Experi-mentation	10. Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.	As a result of the activities in grades 9-12, all students should develop: 1. Abilities to do scientific inquiry 2. Understanding about scientific inquiry
Energy	16. Students will develop an understanding of and be able to select and use energy and power technologies.	As a result of the activities in grades 9-12, all students should develop an understanding of: 3. Structure and properties of matter 4. Chemical reactions 5. Interactions of energy and matter

Table 1. Alignment to content standards in the United States.

Standards (NRC, 1996) shown in Table 1. Expanded from the work of Noon (1990), this activity was refined through the collaborations of a chemist, a pre-service teacher, and a technology teacher educator (Hershberger, Olds, Ribblett, & Rose, 2008) and tested with high school students who had met middle school science standards and possessed a working knowledge of DC circuits.

2. Experimenting With a Cuprous Oxide Solar Cell

Devising teaching and learning experiences around the principles and methods of inquiry is often referred to as **inquiry-based instruction** or **guided inquiry**. Following a cycle of inquiry, the instructor (1) exposes students to curious phenomena; (2) encourages questioning and hypothesizing; (3) scaffolds student thinking as they plan and implement an experiment, analyze data, and extend new understanding to new situations; and (4) prompts reflection upon the learning process. This example describes a process to apply this pedagogical strategy to a photoelectrical experiment.

2.1 Observe the Photoelectric Effect

To initiate the intellectual curiosity of students, the instructor should demonstrate a working cuprous oxide solar cell (Figure 1) by placing it in direct light from the sun and measuring its open and closed circuit voltages with a multimeter. As students observe the cell and the meter readings, the instructor should encourage students to ask questions, such as: "What is happening in this system? What are the inputs, processes, and outputs?" and "What forms of energy are at work?" If students do not spontaneously generate questions, the instructor might ask: "What happens if we block the sun from the cell?" or "What happens if we reverse the probes of the multimeter on the plates?"

During the discussion, the instructor should clarify that when photonic energy (light) strikes the surface of certain materials, the materials instantly absorb this energy and produce electrically-charged particles: electrons and ions. These materials, such as silicon, CIGS, and cuprous oxide, are used in solar or photovoltaic (PV) cells due to their semiconductive properties. A semiconductor has intermediate properties between an electrical insulator and a conductor. The energy from this phenomenon, called the photoelectric or photovoltaic effect, can be harnessed by directing the negatively-charged electrons through a conductive circuit to power lights or other load devices (see Figure 2). Common types of solar cells employ two layers of silicon which have been treated (doped) to adjust their electrical properties (Spring, Fellers, & Davidson, 2005). These materials produce a potential difference, or voltage, between the two layers, and generate direct current when exposed to sunlight.

As the discussion dwindles, the instructor should pass sets of copper plates (treated and untreated) among the students and ask: "What are the differences between these copper plates?" and "How are these differences related to the electrical action of the cell?" Eventually, students may point out that one of the plates has a red coating and that the polarity indicated by the multimeter suggests the direction of current flow, i.e., from the negatively-charged red-coated plate to the positively-charged untreated plate. The instructor should reveal that the red layer is an oxide of copper, called cuprous oxide, which forms as a result of heat processing. As a semiconductive material, cuprous oxide readily absorbs photonic energy producing electrons and positively-charged ions. The negatively-charged electrons migrate through the salt solution to the untreated copper plate where they enter the copper circuit and generate current flow. Then, electrons move to the cuprous oxide plate where they recombine with the positively charged ions (see Figure 2).

After this introduction, the instructor should challenge students to take on the role of a photochemist as they plan and conduct an experiment with the cuprous oxide solar cell. The inquiry activity will demonstrate the relationships among experimentation, engineering design, and technological innovation, as well as demonstrate how a solar cell converts photonic energy into electricity.

At this point, it is important to elicit students' existing understandings about the nature of experiments. As students identify experimental concepts (e.g., variables, controls, and measurement) and principles, the instructor should record these propositions in a public space so that all can see. As the discussion diminishes, the instructor explicitly states the goal of the experiment and defines key terms, such as independent and dependent variables.

2.2 Pose Questions and Encourage Hypothesizing

After a discussion of experimentation, the instructor should arrange students into teams of three or four and distribute a two–view drawing of the cell (Figure 3). The instructor should challenge teams to generate a list of variables that might influence the power production of the cell. The list of variables might include the semiconductive characteristic of a plate, the distance between the plates, the surface area of plates, the concentration of the salt solution, or the intensity of light.

At this point, the instructor should model

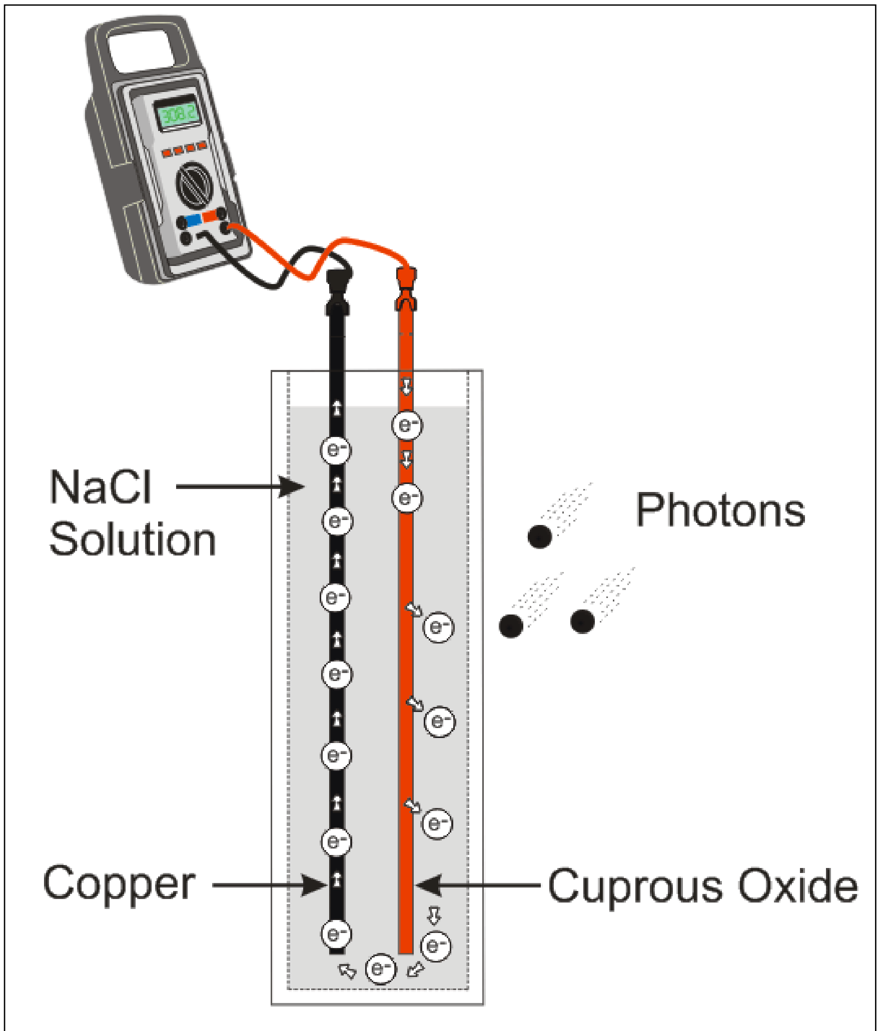

Figure 2. Reaction of a cuprous oxide solar cell when exposed to photonic energy.

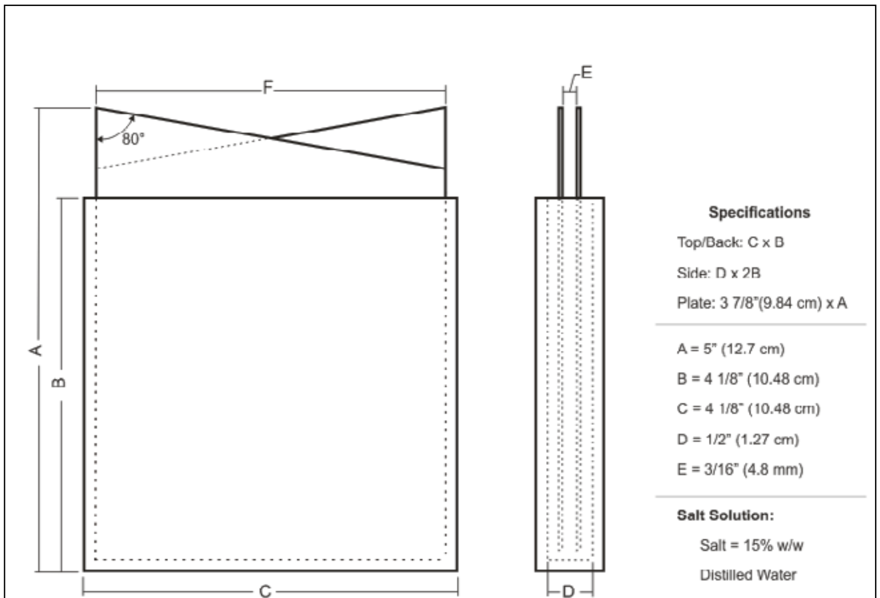

Figure 3. Specifications for a cuprous oxide solar cell.

Solar Cell				
		Parts & Materials List		
Component	**Function**	**Parts**	**Material**	**Qty - Size**
Case	Water–tight transparent housing	Front/Back	1/8" Acrylic	2 pcs of 4 1/8"" x 4 1/8"
		Sides/Bottom	1/8" Acrylic	1 pc of 1/2" x 12"
Plates	Harness photons	Anode Cathode	0.020" Copper, Unpolished	2 pcs of 3 7/8" x 5"
Salt Solution	Medium of ion exchange		Salt (NaCl reagent grade)	15% w/w* NaCl or 17.6 g
			Distilled Water	85% w/w H_2O or 100 ml

Other Equipment and Supplies	
Expendables	**Equipment**
	Digital Multimeter (Range in mA & mV)
Nitric Acid Solution (15%)	Alligator Clips
Acrylic Adhesive	Hot Plate
	Strip Heater
Safety	Balance
Gloves	100-mL Graduated Cylinder
Chemical Splash Goggles	250-mL Beaker
Safety Glasses	Glass Rod
	Tongs or Pliers
	Shears (Copper)
	Saw (Acrylic)

*weight to weight

Table 2. Materials and equipment for the cuprous oxide solar cell experiment.

how to pose a research question and a hypothesis using a treatment and outcome variable, e.g., "How does the concentration of the salt solution (independent variable) affect the electrical power produced (dependent variable) by a cuprous oxide cell?" After this demonstration, teams should generate a list of research questions and present them to the class. After whole class discussion, the class should select a single research question to guide team experiments. The instructor should explain that each team will fabricate a solar cell that will represent one level of an independent variable. Given the previous example with "concentration of salt solution" as the independent variable, each team would manufacture the same case and plates, but each team would prepare and test different salt solutions, e.g., 6%, 12%, and 18% salt by weight. Then after testing the cells, all the data would be compiled to provide the evidence required to answer the research question.

To close the day's activities, the instructor should challenge students to learn more about semiconductive materials, the photoelectric effect, and how solar cells work by conducting a literature search. Nova (2007), Molecular ExpressionsTM (2006), and the Photovolatics section of the Solar Energy Technologies Program (USDE, 2008) are excellent on-line sources of information.

2.3 Manufacture the Cell

During the second and third day, teams of students should manufacture a solar cell while maintaining tight tolerances (e.g., 1/16") to assure that other factors (extraneous variables) do not influence the electrical performance of the cell (dependent variable). As shown in Table 2, the cell is made of acrylic, copper plates, and a salt solution. A single 12" x 36" sheet of soft-temper 0.020" copper (Cost ≈ $70.00) may yield 7 to 10 solar cells depending upon machining capabilities. With minor reconditioning, these copper plates may be reused with future classes, thus offsetting the initial cost.

The primary steps of manufacturing the solar cell are outlined in Table 3. Oxidizing one copper plate by heating it on a hot plate is a critical step. As oxidation is time intensive (≈ 45 min.), this process could be demonstrated once

Step	Process	Safety Considerations
1. Prepare the copper plates.		
A.	Cut copper to overall size using a brake, shears, or tin snips.	Wear safety glasses.
B.	Cut one end of each copper plate to a 5-10° angle. This angled end should serve as the handle for gripping and attaching the plate to the multimeter.	Caution: Nitric acid is a powerful oxidizing agent. Wear protective gloves, apron, and chemical splash goggles.
C.	Dip plates into nitric acid solution; then rinse with water. This step should be performed by the instructor.	
D.	Heat one copper plate on a preheated hot plate for about 45 minutes. The surface will become coated with a layer of black cupric oxide.	
E.	Using tongs, carefully remove the copper by its angled end and place it on a metal surface to cool.	Caution: Hot surfaces.
F.	While the copper plate cools, the black oxide will flake off.	
G.	Using paper towels, carefully remove any black oxide still remaining while protecting the red oxide layer.	
2. Prepare a water-tight case.		
A.	Cut acrylic parts to size using a table saw, back saw, or laser engraver.	Wear safety glasses.
B.	Lay-out bend lines on the side/bottom piece. Along these lines, use a back saw to cut kerfs about ½ the thickness of the acrylic.	Caution: Hot surfaces. Work in a well-ventilated lab. Wear protective gloves and chemical splash goggles.
C.	Using a strip heater, heat and bend the kerfs at 90° angles to form the interior u-shape of the case.	
D.	Per manufacturer's instruction, apply acrylic adhesive to edges and join acrylic parts to form a case.	
E.	After curing, add water to the case to test its seal. If a leak occurs, dry the case and apply more adhesive.	
3. Assemble and charge the cell.		
A.	Insert the copper plates into the case, being certain to place the top of the oxidized copper plate facing outward. Use acrylic spacers to assure that plates do not touch and are suspended above the bottom of the case.	
B.	Using a balance, beaker, and graduated cylinder, measure and mix a 15% salt solution by weight.	
C.	Immediately before testing, carefully pour the salt solution into the case.	

Table 3. Procedure for manufacturing a cuprous oxide solar cell.

during class, then completed by the instructor throughout the day. During the final minutes of heating, it is important to focus student's attention upon the formation of the oxides on the surface of the plates. This is an opportune time to explain that copper, which has only one electron in the outer cloud or valence shell of the atom, is an excellent conductor of electricity and readily combines with oxygen—oxidizes—when heated. In fact, two oxides form on the copper plate including a red cuprous oxide and a black cupric oxide (Table 4). These oxides have different electrical properties, with cuprous oxide acting as a semiconductor and exhibiting the photoelectric effect (Pollack & Trivich, 1975).

In addition to explaining the key steps of processing acrylic and sheet metal, assembling the acrylic case, and cleaning and oxidizing (heating) the plates, the instructor should review key safety issues with students prior to their independent work.

Safety Issues. Manufacturing the solar cell requires the use of two toxic chemicals: nitric acid (HNO_3) and a light-activated acrylic adhesive. Nitric acid is a powerful oxidizing agent that is recommended to clean the surface

Type	Formula	Color	Photoelectrical Property
Copper I oxide or cuprous oxide	Cu_2O	red	Yes
Copper II oxide or cupric oxide	CuO	black	No

Table 4. Heating copper promotes the oxidation of copper.

of the copper. Due to its corrosive and reactive nature, the instructor should prepare the nitric acid solution, perform all cleansing operations, and store nitric acid in an isolated storage cabinet according to manufacturer specifications. In addition, the heating of copper creates cupric oxide (black), a known irritant. Nitric acid, the acrylic adhesive, and cupric oxide should be handled in a well-ventilated area while wearing chemical splash goggles, neoprene gloves, and clothing protection. If directly exposed to any of these chemicals, immediately flush the affected area with water. For further discussion of lab safety, see the National Institute for Occupational Safety and Health (NIOSH, 2006).

2.4 Planning and Conducting the Experiment

On the fourth day, the entire class should plan and implement the same experimental procedure to inform a single research question. To begin, the instructor might ask: "What strategies do researchers use to generate valid and reliable results from experiments?" After time for discussion, the instructor would clarify that researchers not only employ multiple samples, but also apply treatments and take measurements in the same, consistent way. These strategies help eliminate other explanations that might explain changes observed in the dependent variable. The researcher's goal is to isolate the effect that a variable of interest (independent) has upon a second variable (dependent).

To help standardize the experimental procedure, the instructor assigns one task to each team (i.e., Setting Up, Measuring, and Recording) and then challenges teams to develop and record a procedure for completing their task (e.g., a series of steps or a recording tool). After a few minutes, teams present their written recommendations to the class using projected media. The instructor points out inconsistencies and encourages improvements. The following experimental procedures are particularly important:

- **Setting Up the Experiment.** When measuring closed-circuit current, a load device of consistent resistance should be placed into the circuit with the solar cell. In addition, there should be specific directions for positioning the solar cell relative to a light source, including orientation to the sun and tilt of the cell. In case of inclement weather, tests can also be conducted with a lamp, e.g., 1000 lm light-emitting diode.
- **Measuring:** Adjust the multimeter to the proper function (DCV and DCA) and range (milli-).
- **Recording:** Within the data table, provide prompts to record independent and dependent variables, multimeter functions, units, and unit prefixes.

After clarifying the experimental procedures, teams charge their cells with the salt solution, implement the experimental procedure, and independently record their results. An example of data obtained during testing is offered in Table 5.

2.5 Analyzing, Interpreting, and Applying Data

Before the fifth day of the activity, all test data should be compiled into a single digital spreadsheet. As students enter class, the instructor might ask "How can our experimental data help answer the research question?" and "How shall we look for patterns in this data?" This line of questioning should result in suggestions for graphing the data, calculating descriptive statistics (e.g., means and standard deviations), and possibly, conducting hypothesis-testing by comparing the levels of the treatment using an inferential test, e.g., a t-Test or Mann-Whitney U. After distributing the data file to all teams, the instructor should challenge teams to analyze the data by calculating descriptive statistics for each treatment level and developing a graph to communicate these comparisons. As can be seen by the results in Figure 4, the power output is not dependent upon the salt concentration over this range. However, we observed that cell power drops significantly at concentrations below 10% w/w NaCl and over 24% w/w NaCl. Power output was found to be dependent on tilt angle, where the tilt angle is measured relative

20% NaCl				
Tilt Angle	Voltage (mV)	Error	Current (mA)	Error
45°	35.7	0.5	0.306	0.003
60°	36.8	0.5	0.328	0.003
90°	37.6	0.5	0.337	0.003
15% NaCl				
Tilt Angle	Voltage (mV)	Error	Current (mA)	Error
45°	37.5	0.5	0.309	0.003
60°	37.6	0.5	0.323	0.003
90°	37.9	0.5	0.326	0.003

Table 5. Example of data obtained by students.

to the sun. It was observed that optimal power production occurred when the cell was oriented perpendicular to the incident radiation.

To maximize the learning value of inquiry-based instruction, it is important to help students summarize what they have learned, relate this new information to other domains, and assess their learning process. Therefore, as students engage in data analysis, the instructor should prompt students to discuss and record written and graphic responses to the following questions:

1. What are the electrical properties of cuprous oxide, copper, and salt water? Which material is a semiconductor? How does the solar cell convert photons (light) into electricity?
2. What is the research question under investigation? What were the independent (treatment) and dependent variables?
3. Given your analysis, how would a scientist answer the experimental research question?
4. How might experimentation inform innovations in solar technology?

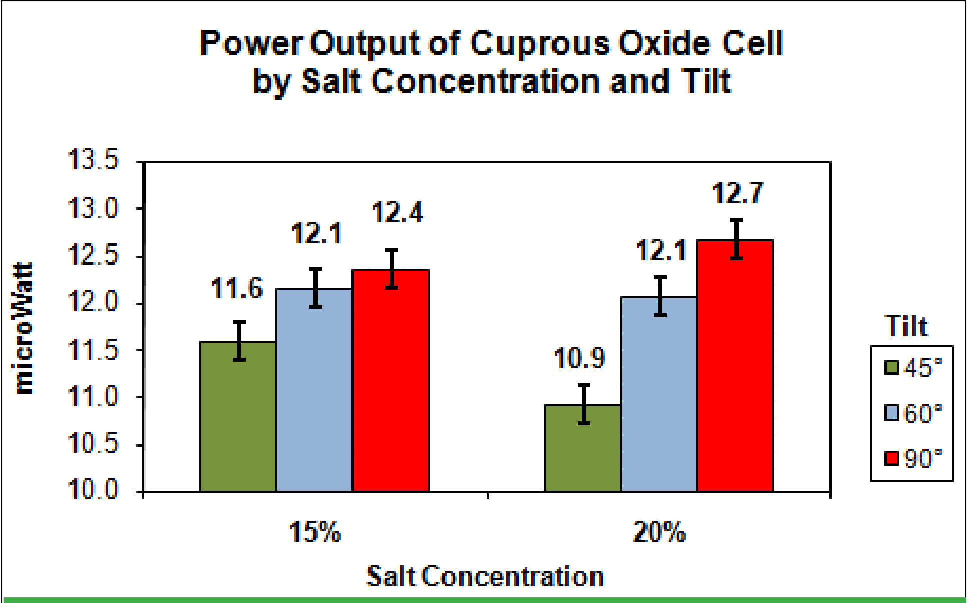

Figure 4. Results of data analysis for solar cell experiment.

5. What research question(s) would you experimentally test to improve the power output of a cuprous oxide solar cell? Describe a systematic procedure for gathering and analyzing data.
6. How might an engineer use the process of experimentation to help design a product?

Student responses to the previous questions provide valuable information to inform an assessment of learning achievement. However, individuals can still harbor misconceptions and faulty reasoning about science concepts and processes. Therefore, a valuable concluding activity is to lead a whole class discussion which prompts students to review the process and value of experimentation (variables, questions, procedures, and analysis), as well as other complex concepts, such as the photoelectric effect, conductivity, oxidation, and how a solar cell works.

3. Conclusion

Technological innovation is increasingly dependent upon the collaborative endeavors of scientists, engineers, and technologists to skillfully address critical global problems. The cuprous oxide solar cell provides a rich and authentic context in which high school students can actively learn about the logic of scientific inquiry and the process of experimentation. The activity capitalizes upon the contemporary challenges of harnessing solar energy while requiring students to fabricate a working solar cell and then plan and implement an experiment that would inform design improvements in the cell.

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Mary Annette Rose is an Associate Professor in the Department of Technology at Ball State University. She holds an M.A. in Technology Education from West Virginia University and an Ed.D. in Instructional Systems Technology from Indiana University. As a teacher educator, she facilitates the development of technological literacy, pedagogical skills, and inquiry skills among pre-service and practicing technology education teachers. Her research efforts examine strategies for teaching and learning in distributed environments, building technology assessment skills, and integrating sustainability goals and content into curriculum and instruction.

Jason W. Ribblett is an Assistant Professor in the Department of Chemistry at Ball State University. He received his Ph.D. from the University of Pittsburgh in Physical Chemistry. He has published a guided-inquiry-based lab manual for use in the General, Organic, and Biochemistry for the Health Sciences course at BSU. He is currently the acting teaching advisor for teaching majors in chemistry and the faculty advisor for the Student Affiliates of the American Chemical Society. He has been a finalist for the Excellence in Teaching Award twice, in 2005 and 2007. His research interests include computational drug discovery and design and developing multimedia for use in chemistry education.

Heather Hershberger is a middle school mathematics and science teacher. She received a B.S. in Elementary Education with an Endorsement in Middle School Mathematics and Science Education from Ball State University. Currently, she is continuing her education with an English Language Endorsement from the University of Phoenix in Los Angeles, CA.