

THE MICROBIAL FUEL CELL AS AN EDUCATION TOOL

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According to Accreditation Board for Engineering and Technology (ABET) outcome 3d, graduates from engineering programs must have the ability to function on multidisciplinary teams.^[1] Unfortunately, evaluation shows that engineering students are not well positioned to understand new concepts from a variety of disciplines and integrate them into what they learn in their own disciplines.^[2] This is especially true for concepts in emerging areas, such as life sciences. Obviously the emergence of technological breakthroughs in new arenas is stimulating faculty members to include related multidisciplinary concepts in their course designs so that students can be prepared to meet the industrial challenges presented in applying new technologies within industrial settings.^[1]

Motivated by the lack of appropriate tools that can be used to teach chemical engineering undergraduate students, especially to teach them how to integrate life sciences and

engineering concepts, we have developed the microbial fuel cell education module (MFCEM), a hands-on learning module that can be used for learning multidisciplinary concepts in an active group-learning modality. This module uses the principles of mass and energy conversions applied in a microbial fuel cell (MFC) to integrate various concepts taught in biology, chemistry, electrochemistry, and engineering. In this paper, our goal is to show how the MFCEM can be used as an aid in teaching a senior-level course in chemical engineering—Introduction to Bioprocess Engineering (ChE 475). Figure 1 shows the components of the module and how we implemented it in the classroom.

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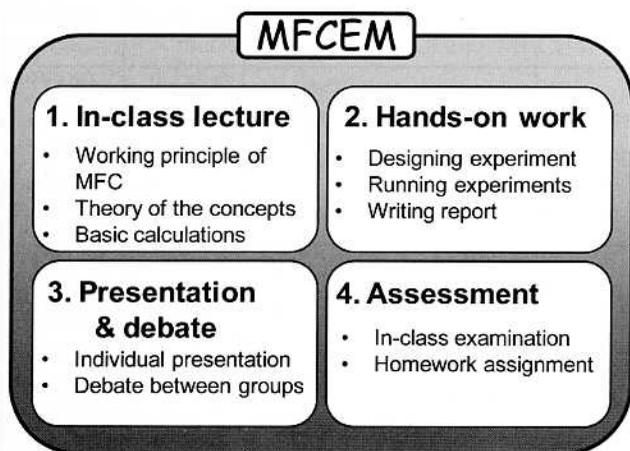


Figure 1. Methodology for implementing the microbial fuel cell education module.

MICROBIAL FUEL CELL EDUCATION MODULE

Class lectures were used to introduce the theory of various processes important to understanding microbial respiration, the thermodynamic and kinetic principles of the processes involved in energy conversion in MFCs, and the basic calculations used in electrical engineering (e.g., current and power). The hands-on work consisted of the operation of an MFC in the laboratory. For the laboratory exercises, we prepared a manual to instruct the students about safety issues; equipment needed to run the

MFC, with photographs; step-by-step procedures, also with photographs; sample experimental results; sample calculations; and final-report requirements. The students, assembled into two groups, ran the MFC, computed the energy conversion, and presented the results to their classmates. Debates, moderated by the instructor, on the results obtained by the various groups, were aimed at reinforcing the concepts discussed in the lectures. Last, we assigned a set of problems to test understanding of the concepts and to evaluate the role of the hands-on active experience in the classroom.

TABLE 1
The Concepts, Related Topics, and Mathematical Expressions Introduced Using the MFCM

Concepts	Specific topics	Mathematical expression*	Reference
Cellular respiration Microbial growth kinetics	<ul style="list-style-type: none"> Metabolic pathway Electron transport chain Redox reactions in respiration Microbe-solid interactions Monod kinetics 	$\frac{dX}{dt} = \mu_{\max} X \frac{S}{K_S + S}$ $\frac{dS}{dt} = -\frac{\mu_{\max} X}{Y_{x/s}} \frac{S}{K_S + S}$	[6,9]
Electrode potential (Electrochemical equilibrium)	<ul style="list-style-type: none"> Nernst equation 	$E_A = E_M^{\circ} + \frac{0.059}{2} \log \frac{(M)_{\text{ox}}}{(M)_{\text{red}}}$ $E_C = E_{O_2}^{\circ} + \frac{0.059}{4} \log \frac{1}{p_{O_2} \cdot [H^+]^4}$	[6,7,10]
Overpotential (Electrode kinetics)	<ul style="list-style-type: none"> Butler-Volmer equation Electrode polarization 	$i = i_0 \left[\exp \left(+ \frac{0.5\eta F}{RT} \right) - \exp \left(- \frac{0.5\eta F}{RT} \right) \right]$	[6,10]
Current	<ul style="list-style-type: none"> Faraday constant Calculation of current from material balance and growth kinetics in MFC 	Faraday constant = electrical charge of an electron \times Avogadro constant $I = \frac{V}{R_{\text{ext}}}$	[7]
Power	<ul style="list-style-type: none"> Differences between current & power and energy & power 	$P = V \cdot I = \frac{V^2}{R_{\text{ext}}} = I^2 \cdot R_{\text{ext}}$	[7]
Charge conservation	<ul style="list-style-type: none"> Faradic efficiency 	$\epsilon_c = \frac{\int_0^t I dt}{F n \frac{\Delta S}{M}}$	[7,11]
Energy conservation	<ul style="list-style-type: none"> Energy efficiency Material and energy balance for MFC 	$\epsilon_E = \frac{\int_0^t V \cdot I dt}{\Delta H_c \cdot m_{\text{in}}} = \frac{\int_0^t I^2 \cdot R_{\text{ext}} dt}{\Delta H_c \cdot m_{\text{in}}}$	[7]
Sustainability	<ul style="list-style-type: none"> Definition of sustainability Sustainability of power generation in MFCs 	-	[12,13]

* Details on the development of these equations, and example calculations using experimental data, were included in the MFCM handout given to the students.

The incorporation of the MFCEM into the bioprocess engineering course, ChE 475, gave us an opportunity to teach the concepts through an active-learning process. Compared to standard lecture-based, passive learning, the hands-on active-learning process helps students to visualize and more fully think through what they learn and helps them to make connections between concepts that they learned before.^[3] As claimed in the well-known learning retention pyramid,^[4] students remember concepts best when they see a demonstration (50%), engage in a debate or discussion (70%), or have a chance to do something real and apply their knowledge immediately (90%). With the MFCEM we particularly emphasized practice by running experiments that were an immediate application of the in-class lecture and having the students prepare reports, perform homework assignments, and hold in-class debates with the active involvement of the other students in the audience, who asked questions or expressed opinions on one side or the other of the debate. The remainder of the material in ChE 475 was taught in a passive manner, with the professor lecturing and the students taking notes and completing homework assignments based on their notes and reading. We expected that the introduction of the MFCEM into our course would significantly increase learning retention of the topics in ChE 475 and of the multidisciplinary concepts introduced by the MFCEM.

IN-CLASS LECTURE: THEORY

In the ChE 475 course, we used *Bioprocess Engineering*, written by Shuler and Kargi (2002).^[5] After completion of the first six chapters students were familiar with the fundamentals needed to understand MFCs and we then introduced multidisciplinary concepts using the MFCEM. We do not discuss all the concepts in this paper because of space limitations; however, they were discussed in considerable detail in the classroom and in the MFCEM manual given to the students. While some of the concepts had been taught in previous courses, we reintroduced them so that students could connect the new concepts with previously learned concepts. The concepts, related topics, and mathematical expressions^[6-8] that were introduced using MFCEM are summarized in Table 1.

The topics were presented by asking a series of questions and helping the students find the answers. The following paragraphs present selected questions we asked and give a brief discussion of how they were implemented.

How did the scientist who ran the first MFC think to use microbes? Our theory section started with this question and it was actively discussed in the classroom in a group format to give the main idea behind the MFC. Then we introduced the concept of how a single cell grows, duplicates, and gains energy. We showed a single cell (Figure 2A) and described the main idea behind MFCs, which is separating the oxidation and reduction reactions in the respiration system. After showing Figure 2A, we asked the students to build an MFC. The

students worked to separate the two environments and make the MFC depicted in Figure 2B. This process helped them to understand the basic principle of the MFC, that of separating the oxidation and reduction reactions using a proton-exchange membrane (PEM) and connecting the two reaction environments through an external circuit. Later we discussed in detail and explained why we need to use a proton-exchange membrane (Figure 2B). This helped the students better understand what a cathode and an anode are. They learned that oxidation happens at the anode and reduction at the cathode.

How are the electrons transferred from bacteria to the solid electrode? The interaction of microbes with solid materials is a fascinating new topic, not only in MFC research but also in microbiology and environmental science. Electron transfer mechanisms were introduced and the students were taught why electrons cannot jump directly from microbes to solid surfaces, *i.e.*, that electrons must be transferred by a redox reaction via: 1) a mediator, a chemical that accepts electrons resulting from the microbial respiration process and transfers them to the solid electrode, or perhaps 2) linkage of the microorganisms with the electrode surface by nanowires or cytochromes. The students were excited about these topics, which constitute cutting-edge research questions in microbiology.

What are the source of and the sink for the electrons? This question was answered by revisiting the major metabolic pathway concepts, taught earlier in the course. We showed how electrons are derived from the microbial respiration system and transported to an electron acceptor (in this case a solid electrode) through the electron transport chain. This used to be a mundane subject for the students, but now there was a

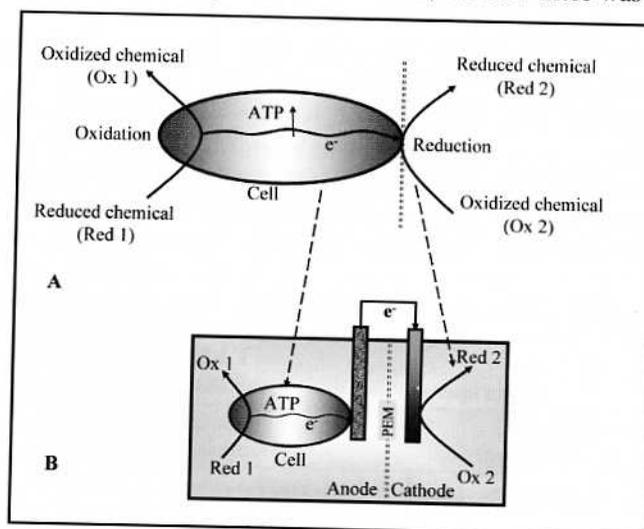


Figure 2. The original idea of a microbial fuel cell described using a single cell. (A) The redox reactions—oxidation and reduction—in the microbial energy generation process. (B) The separation of the oxidation and reduction reactions, using a proton exchange membrane, to build a microbial fuel cell.

real-life application for the metabolic pathways and therefore they appeared to be engaged in the subject as evidenced by the energy demonstrated by students when they expressed their ideas and the content of their group discussions. To further facilitate discussions, the idea of using two different types of bacteria was introduced—one using lactate and the other using glucose as the electron donor.

What do we mean by the electrode potential, current, energy, and power of a fuel cell? The electrode potentials are thermodynamic properties and are calculated using the Nernst equation (Table 1). When current is passed through the electrode, however, the thermodynamic equilibrium does not exist anymore; rather the current needs to be calculated using the Butler-Volmer equation describing electron transfer kinetics. As a result of this discussion, the students improved their understanding of the differences between equilibrium and non-equilibrium processes. The concept of overpotential is vital to understanding batteries, fuel cells, corrosion processes, and electrochemical sensors. Using the MFCEM, students were introduced to the concepts of polarization curves (cell potential vs. current) and overpotential. In addition, they learned basic electrical engineering concepts such as electrical potential, current, power, and energy, and how to perform measurements for and calculations of their values in MFCs.

How much electrical charge or how many electrons can we derive from microbial reactions? This question was asked to introduce the concept of Faradic efficiency. The students learned how to calculate the maximum possible number of electrons transferred as a result of the differences in oxidation states of chemicals and the concentrations of chemicals in the growth medium. Students had to do material balances to calculate Faradic efficiency. Discussions resulting from this question helped to introduce the concept of charge conservation in electrochemical systems and the Faraday constant (Table 1).

How much power can be harvested from an MFC for a given amount of substrate? The calculation of power from current and potential helped students to understand simple electrical engineering concepts and taught them the differences between potential and current, and between power and energy. These concepts often confuse students in the electrical circuit course required during their undergraduate

studies. Thus, the MFCEM allowed them to integrate electrical engineering concepts with chemical and biochemical engineering concepts.

How sustainable is power generation in an MFC? Students are often exposed to general terms, such as the sustainable development of the economy of a country, and they need to extend the application of the term “sustainable” to power generation in MFCs. Sustainability of power generation in MFCs is defined as the ability to generate power at a constant rate over long periods, and it is evaluated by monitoring the energy production and consumption using different loads on the MFC. There is no general criterion by which one cell produces power in a sustainable manner and another does not: it all depends on the ratio of the power generated to the power consumed. When the rate of energy consumption is higher than the rate of energy generation by the microorganisms, the MFC does not produce power in a sustainable manner. The opposite is true as well, however, the MFC produces power in a sustainable manner when the rate of energy consumption is lower or equal to the rate of energy generation by the microorganism.^[14]

HANDS-ON WORK: EXPERIMENTS

We had nine students run the experiment (selection of students was on a volunteer basis), and the group of experimenters was divided among two teams, each of which was assigned one of two options. One team ran the MFC experiments using *Shewanella oneidensis* while the other used *Klebsiella pneumoniae*. The goal of using two different microorganisms was to observe the difference in power generation and later to arrange a debate on the role of the different respiration systems in accounting for that difference. During the experiment each team tested the effects of the selected variable (microorganisms, see Table 2). To implement the pedagogy in crowded classes, multiple groups could be used and each group could be subdivided into smaller teams: each team would investigate one of the variables listed in Table 2 and report their findings back to their other group members. This paper describes our classroom experience, in which only one group consisting of two teams worked on understanding the roles of different microorganisms in MFCs. The remaining 14 students received

information via lecture, from listening to debate presentations by the two groups, and from participation during and after the debate through asking questions and expressing their own opinions.

At the end of the experiments, the teams prepared reports and gave class presentations. The presentations had the format of a debate. The two teams, which had used different microorganisms, compared their

TABLE 2
Experimental Conditions, Variables Tested, and Topics for the Debate

Variable (for groups)	Conditions in the MFCs (for teams)	Topics for debates between teams
Microorganisms	1. <i>Shewanella oneidensis</i> 2. <i>Klebsiella pneumoniae</i>	Cellular respiration
Electrode material	1. Graphite 2. Stainless steel	Microbe-solids interaction
Substrate	1. Glucose 2. Natural biomass	Renewable energy source
Load	1. Low resistor 2. High resistor	Sustainability

power generation. Debates centered around why one of the microorganisms produced more power than the other, and a team's position had to be substantiated using the calculations shown in the theory section. We noticed significant involvement of the students, interesting questions, and many recommendations on how to increase the power generation in such devices.

Construction of the MFC. To run the experiments, students used a two-compartment MFC. The components of the MFC and the steps required to construct it are shown in Figure 3. The compartments were made of polycarbonate (8 cm × 8 cm × 3.7 cm) and were furnished with openings at the top to make electrical connections with the electrodes. Cation exchange membrane (ESC-7000, Electrolytica Corporation) was used to separate the compartments. The cover plates were made of polycarbonate and had three openings for inlet and outlet tubing connections. To prevent leakage, rubber gaskets were used between compartments and between the compartments and cover plates. Screws with wing nuts were used to hold the reactor together. Silicone rubber tubes were used to deliver liquids and gases and to remove them from the respective compartments. The electrodes were made of graphite plates (GraphiteStore.com, Inc.) with surface areas of 23 cm² for the anode and 63.4 cm² for the cathode. These were placed against the cation exchange membrane, parallel to each other.

To construct the MFC, students followed the steps shown in Figure 3. The steps are: 1) inserting the electrodes into the compartments, 2) placing a gasket on the inner side of each compartment, 3) placing the cation exchange membrane over

the first gasket, 4) placing another gasket on the other side of the membrane, 5) putting the compartments together, 6) placing gaskets outside of the compartments, 7) placing the cover plates, 8) holding the compartments and cover plates together using wing nuts and bolts, and 9) connecting the tubing and then autoclaving the MFC. After autoclaving, the reactor was cooled down to room temperature and the anode and cathode compartments were filled with anolyte and catholyte, respectively. The anode was inoculated with the selected bacteria for each group. Then in step 10 students placed the reference electrode in the cathodic compartment and connected the electrical wire, resistor, etc. These step-by-step procedures are described in a written manual, and it is available upon request from the authors.

ASSIGNMENTS

The assignments were designed to evaluate understanding of the multidisciplinary concepts taught using the MFCEM. In constructing assignment questions we considered the different levels in Bloom's taxonomy^[15] and the levels of learner knowledge described by Apple and Krumsieg(2001)^[16] that are expected to be evident in responses generated by college graduates. We summarize the assignment problems in Table 3 (next page), and match the assignments with levels in Bloom's taxonomy and with Apple and Krumsieg's levels of learner knowledge. The questions are discussed in the following sections; however, because of space limitations we give only selected answers here. The full range of answers is available upon request.

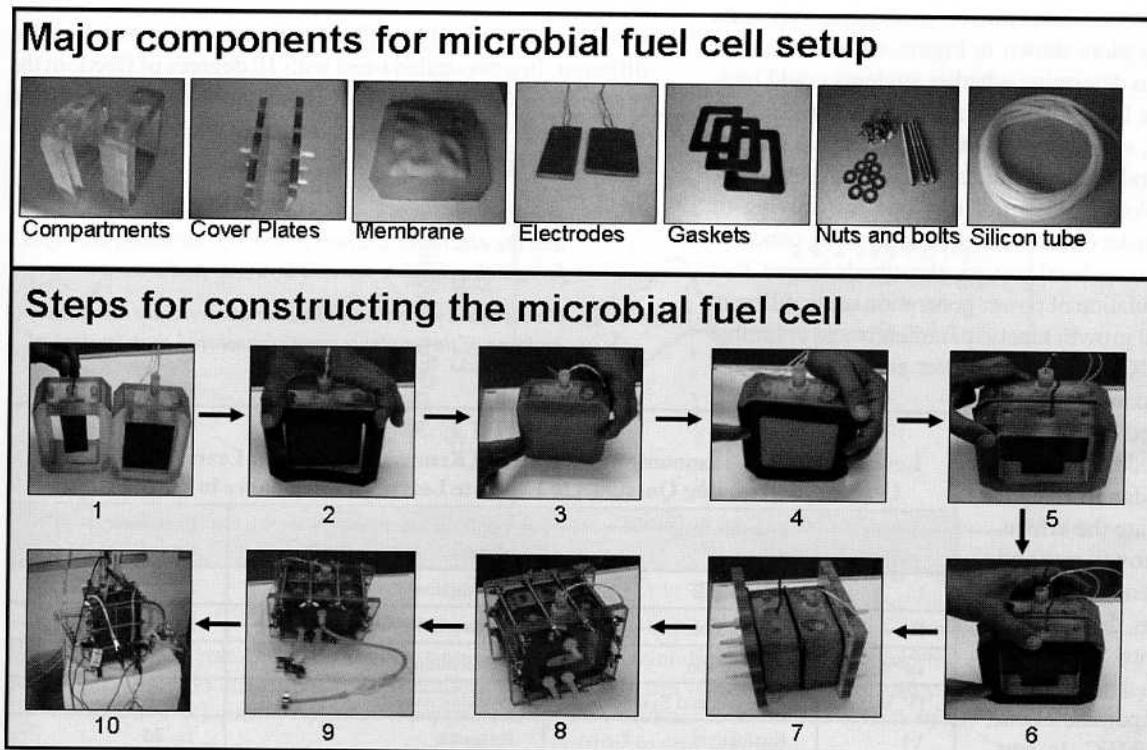


Figure 3. Major components used and steps followed to construct the microbial fuel cell used by the students.

The first problem was designed to determine whether the students understood the principles of the process and could perform basic calculations quantifying processes in MFCs, electrochemistry, and electrical circuitry. Solving this problem required use of Bloom's levels of knowledge, comprehension, application, and evaluation, and Apple and Krumsieg's corresponding levels of learner knowledge, as shown in Table 3. In Problem 1a, the students described the basic idea of MFCs using their knowledge of microbial respiration and the electron transport mechanisms. In part 1b, they used the concepts of material balance and charge balance to calculate current, power, current density, and power density. In part 1c, the students used their conceptual understanding of electrical circuits and material balances to calculate the amount of glucose required to produce sufficient energy to power a light bulb for one hour. In part 1d, they were asked to think creatively and apply learned concepts to MFCs. This problem also tested the students' ability to integrate concepts from electrical engineering with those from chemical engineering and apply them to scaling up a device. In part 1e the students were asked to discuss the future of MFCs and evaluate their potential for providing an alternative energy source.

The second problem was designed to relate concepts surrounding cell-growth kinetics in bioreactors with those relevant to MFCs, both of which are taught in this course. This problem was designed to include the analysis and synthesis, and evaluation levels of Bloom's taxonomy, and the corresponding working expertise and research levels of Apple and Krumsieg's taxonomy. In part 2a, students were asked to develop a mathematical model to quantify variations in substrate concentration and power generation over time and to construct the plots shown in Figure 4A and 4B. This part was designed to determine whether students could integrate the idea of the Faraday constant with mass and energy conservation laws, which are taught in physical chemistry/electrochemistry and basic chemical engineering courses. Constructing the plots in Figure 4 required the solving of simultaneous first-order differential equations, using concepts taught in our sophomore-level numerical methods course. Part 2b required the calculation of power generation using different values for microbial growth kinetic parameters and columbic efficiency. Figure 4C shows how power generation and the time to reach the maximum power depend on the Monod kinetic constant (K_s). The students needed to draw plots similar to that in Figure 4C to evaluate the effects of the maximum growth rate and the columbic efficiency. This part of the problem was designed to evaluate the students' abilities to interpret the physical meaning of the growth kinetic parameters in the context of the MFC. In part

2c, the students discussed how the columbic efficiency would change if an external electron acceptor (oxygen) were present in the anodic compartment. This question was asked to assess their understanding of how electron transport is involved in the microbial respiration system. Part 2d was open-ended and matches with Bloom's levels V and VI, synthesis and evaluation, respectively, and Apple and Krumsieg's Level V, research. In this part students were able to assess the variation in power generation as a function of actual process variables including temperature, pH, and conductivity.

ASSESSMENT OF THE MFC EM

The assignments (Box 1, pg. 164) could be completed if the students could successfully integrate multidisciplinary concepts. For example, to construct a model equation (Problem 2a) for the substrate concentration, current and power generation in a batch MFC, students needed to integrate the concepts of microbial growth kinetics, mass and charge conservation, and Faradic efficiency.

The effectiveness of the MFC EM was assessed by: 1) comparison of the results of the assignments completed by the students who had run hands-on experiments with those of students who had not; 2) our observations during the experimental activity and the debate; and 3) the students' comments. Since the students running the experiment had volunteered we expected them to be more curious, take more initiative and be self-motivated, and therefore to be better prepared to learn the MFC concepts. We indeed found this to be true, as they earned 42% more points on average than the students who did not run the experiments. The result was shown to be statistically significant using a 95% confidence level ($\alpha = 0.05$) and the null hypothesis that the two averages were different. In a two-tailed t-test with 18 degrees of freedom the p value was 0.019 ($< \alpha$). Also, there were several interesting observations made during the debate between the two teams doing the experiments:

- 1) *The students discussed aspects of microbial respiration and the electron transport processes, including concepts for which scientists are still trying to find answers;*
- 2) *Current and power calculations were vividly discussed, and one of the students even commented that "potential,*

TABLE 3
Levels in Bloom's Taxonomy and Apple and Krumsieg's Levels of Learner Knowledge Used in Constructing Questions to Evaluate Learner Performance in the MFC EM

Levels	Bloom's level ^[15]	Apple and Krumsieg's level of learner knowledge ^[16]	Problems assigned
I	Knowledge	Information	1b, 2a
II	Comprehension	Conceptual Understanding	1a, 1c
III	Application	Application	1d
IV, V	Analysis and Synthesis	Working expertise	2a, 2b, 2c, 2d
VI	Evaluation	Research	1e, 2d

current, energy, and power concepts finally made sense" to him; and

- 3) Many students who previously were silent in class were effectively involved in the discussions.

We are aware that our study is limited and a more detailed assessment of the effectiveness of this tool is needed. We expect to collect more data in the upcoming semesters. First, it will be important to come up with other performance measures besides homework assignments; we will likely include a critical-thinking rubric being developed in other companion work,^[17] concept inventories that our group will develop based on similar strategies taken by Streveler, et al. (2008).^[18] Also, it will be important to eliminate the possibility that only the more motivated students elect to participate in the active

experimental aspect of the course and that such students are already inclined toward a more independent learning component. To safeguard against this we will organize student groups by random selection or based on a fairly equal distribution of GPAs between students within the active experimental groups and those exposed to passive lectures. We could also have a second experimental activity of equivalent rigor in which the student groups are switched: those that first did experimental activity and formed debate squads would only have the passive lecture for the second experiment, and vice versa. Finally, a detailed survey on student perspectives could be used in which the students themselves compare the learning environments, their growth in understanding, and their ability to work with other group members independent of instructor input.

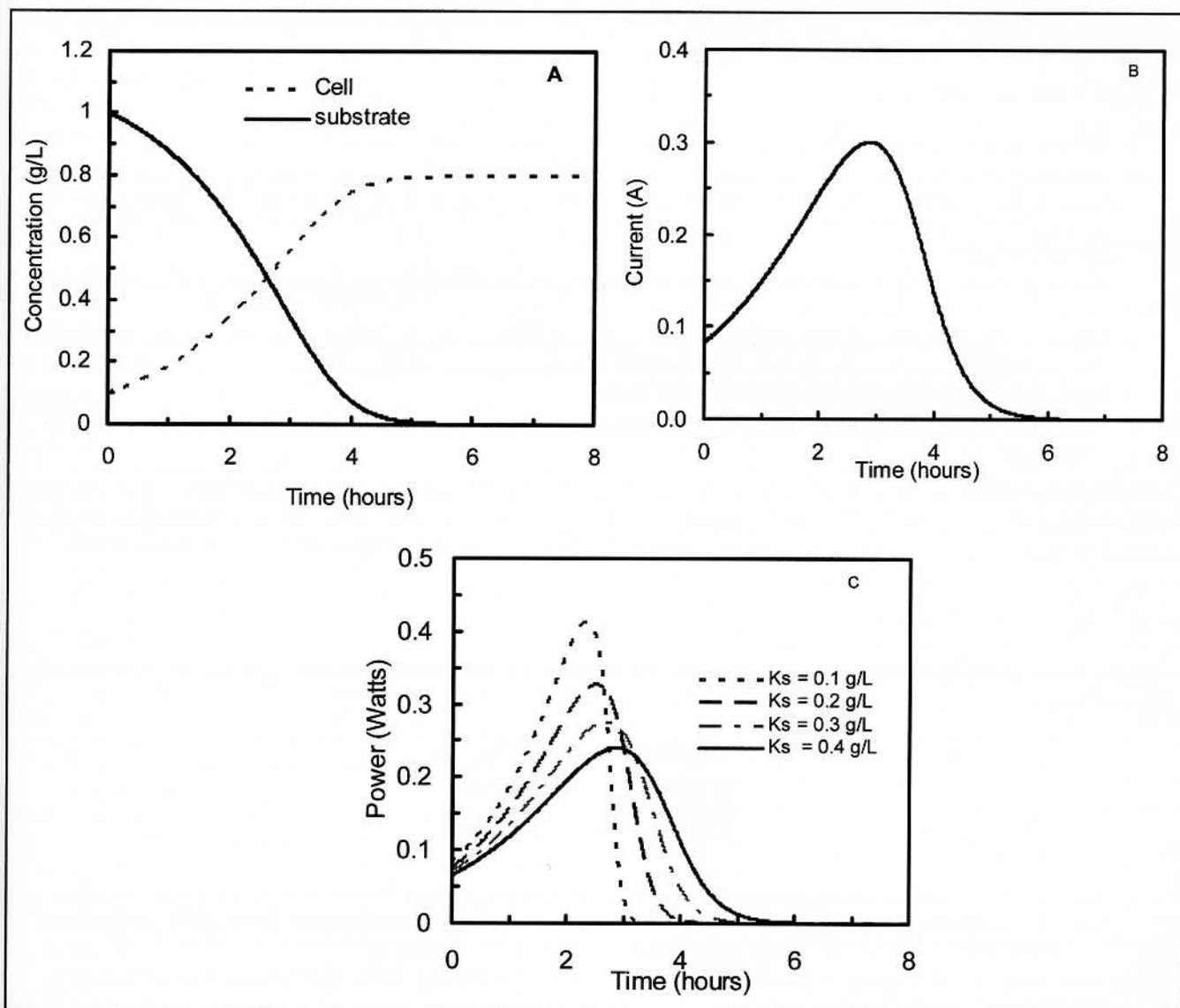
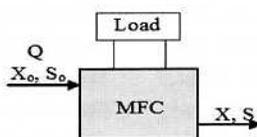


Figure 4. (A) Microbial cell concentration and substrate concentration vs. time plotted using the model equation derived in Problem 2a. (B) Current vs. time calculated for Problem 2a. (C) Power generation vs. time calculated for various Monod constants (K_s). Similar figures were plotted by the students to show the effects of the maximum growth rates and columbic efficiencies.

BOX 1: Problems assigned after introducing the MFCEM

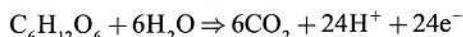
Problem 1. In a continuous microbial fuel cell (MFC) the cells are grown in the planktonic phase, anaerobically, using glucose as the electron donor, and the electrons are transferred to the solid electrodes without any kinetic limitation.



Suppose the cell growth rate can be described by Monod kinetics as

$$r_x = \frac{0.9 S \cdot X}{0.7 + S}$$

At a steady state, the sterile growth medium is fed at a rate of 1 L/h. The working volume of the anodic compartment of the MFC (the liquid volume) is 10 L. The inlet glucose concentration is 2 g/L and the cell yield coefficient ($Y_{x/s}$) is 0.5. Electrons are derived from the substrate according to the following reaction.

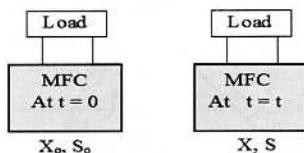


- Can you explain why and how the electrons are transferred from cells to the solid electrode?
- Calculate how much current can be produced if the Faradic efficiency is 1.0 (all the derived electrons are transferred to the solid electrode). If the cell potential is maintained at 0.5 V, what will the power produced by the MFC be? What will the current density and power density be if the anode surface area is 5 m² and the Faradic efficiency is 1.0 at an average cell potential of 0.5 V?
- How much glucose would be needed to power a 60-W light bulb for an hour, if the power generation were the same as that in part a?
- MFCs are an energy source characterized by low power generation. If the energy generation of the MFC remains the same as that calculated in part a, how would you scale up an MFC to harvest sufficient energy in two hours to power a laptop for one hour? Note that an Apple Mac laptop operates at 97 watts.
- How feasible is it to design a MFC that will power a laptop directly? Can you predict the future for MFCs as an alternative energy source?

Problem 2. A laboratory-scale batch MFC is started with a cell concentration of 0.1 g/L in an anaerobic anode chamber with a volume of 0.25 L. The growth kinetic parameters are $\mu_{max} = 0.9 \text{ hr}^{-1}$ and $K_s = 0.4 \text{ g/L}$. The initial substrate (glucose) concentration is 1 g/L. The cell growth can be described using Monod kinetics, and the substrate consumption rate is

$$-\frac{dS}{dt} = \frac{\mu \cdot X}{Y_{x/s}}$$

where μ is the specific growth rate, X is the cell concentration and the cell to substrate yield coefficient $Y_{x/s}$ is assumed to be equal to 0.7.



- Construct a mathematical model to quantify the variation of substrate concentration, current, and power over time. How long will it take to consume 90% of the substrate? What will the concentration of cells be at that time? When will the MFC produce a maximum current? What would the maximum theoretical power be if the cell potential could be maintained at 0.8 V?
- What would happen to the power generation if the Monod half rate constant (K_s), the maximum growth rate, and the Columbic efficiencies were different?
- What inference can you make about the Faradic efficiency if the anode chamber is aerobic instead of anaerobic?
- Qualitatively predict the variation of power generation with the variation of reactor temperature, pH, and conductivity.

CONCLUDING REMARKS

We successfully developed and implemented the MFCEM to teach the concepts of microbial respiration, electrochemical equilibrium and kinetics in a fuel cell, charge conservation, energy, current, and power. The senior-level bioprocess engineering course was appropriate for incorporating our MFCEM. Initial assessments based on student assignments give strong supportive evidence that the MFCEM is an effective tool for teaching multidisciplinary concepts and that active experimentation surrounding its implementation is superior to learning through a passive lecture. Expanded activities and a more rigorous learning assessment are planned for the future.

ACKNOWLEDGMENTS

The authors would like to thank the Gene and Linda Voil and School of Chemical Engineering and Bioengineering for startup funds in support of the research (Dr. Beyenal) and the Institutional Review Board (IRB) of the Office of Research Assurances at Washington State University for approving the research study and processing the exemption determination application. The authors gratefully acknowledge the U.S. Office of Naval Research (ONR) (Grant #N00014-06-1-0217) (activities through this grant laid the groundwork for the UFCM), the National Science Foundation Grant #DUE 0618872 (activities through this grant laid the groundwork for the hands-on approach and its assessment), and 3M on the development of MFCEM.

NOMENCLATURE

E_A	Anode potential (Volts)
E_C	Cathode potential (Volts)
E_M^0	Standard reduction potential of mediator (Volts)
$E_{O_2}^0$	Standard oxygen reduction potential (Volts)
F	Faraday constant (coulombs/mole of electrons)
i	Net current flow to/from an electrode (A)
i_0	Exchange current (A)
I	Current through a resistor (A)
K_s	Growth constant (g/L)
M_{ox}	Mediator concentration at oxidation state (mole/L)
M_{red}	Mediator concentration at reduction state (mole/L)
m_{in}	Inlet flow rate of fuel (moles)
n	Number of moles of electrons produced per mole of fuel
P	Power (Watt)
PEM	Proton Exchange Membrane
P_{O_2}	Partial pressure of oxygen (atm)
Q	Inlet flow rate (L/hour)
R_{ext}	External resistor (ohms)
R	Universal gas constant (J/mole $^{\circ}$ K)
S	Substrate concentration (g/L)
S_0	Initial substrate concentration (g/L)
T	Temperature ($^{\circ}$ K)
t	Time (sec)
V	Potential drop across the resistor (Volts)

X	Cell concentration (g/L)
X_0	Initial cell concentration (g/L)
$Y_{x/s}$	Yield coefficient
ΔS	Rate of substrate consumption (g/hour)
ΔH_c	Heat of combustion of fuel (J/mole)
ϵ_c	Faradic efficiency
ϵ_E	Energy efficiency
μ	Specific growth rate (1/hour)
μ_{max}	Maximum specific growth rate (1/hour)
η	Overpotential (V)

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