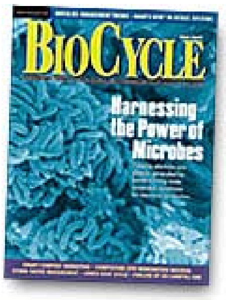

HARNESSING THE POWER OF MICROBES

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University researchers are advancing both the understanding and scalability of a biological process where bacteria living under anaerobic conditions consume organic waste and generate electrons and protons that are tapped for electricity production.

Diane Greer

IMAGINE a self-sustaining battery that never runs out of juice. While the notion may sound far-fetched, Dr. Leonard Tender at the Naval Research Laboratory in Washington, D.C. has developed just such a device. Even more surprising is the source of its power — bacteria.

The device, called a Benthic Unattended Generator or BUG, is a Microbial Fuel Cell (MFC) that harnesses electricity generated by microbes found in the sediment of the Potomac River in Washington, D.C. Tender is prototyping the BUG to power remote sensors and instruments deployed in marine environments.

The idea of employing bacteria to generate power is not new. An English botany professor discovered the phenomenon close to 100 years ago. For many years, MFCs did not generate enough electricity to be of much interest. Now technology advances are promising to move MFCs from the lab to commercial applications.

A basic MFC operates in a manner similar to a battery. It is composed of two chambers, one containing an anode and the other a cathode. Bacteria, residing under anaerobic (oxygen free) conditions in the anode chamber, consume (oxidize) organic wastes, generating electrons and protons as by-products of the digestive process. The electrons and protons are attracted to oxygen in the cathode chamber and move towards the chamber via two distinct paths. A selective membrane separating the two chambers allows the protons to pass through to the cathode. The negatively charged electrons, on the other hand, are transferred to the anode and travel via an external circuit to the cathode, where they combine with the oxygen and the protons to form water. The stream of electrons passing through the external circuit generates a flow of electricity.

THE BUG

Tender conceived the BUG while listening to Clare Reimers, professor at Oregon State University, describe an interesting phenomenon. In many marine environments a voltage meter inserted into the sediment registers a negative voltage, which gets more negative the deeper it goes. The negative voltage is caused by the actions of anaerobic microorganisms living in the sediment just a few millimeters beneath the sediment surface where there is no oxygen. In the absence of oxygen, the microbes transfer electrons produced during digestion to minerals in the sediment, explains Tender.

The BUG takes advantage of the voltage differential between the sediment and the overlying oxygen rich water to generate electricity. When the BUG's anode is embedded in the sediment and connected via a circuit to the cathode suspended in the water above, the microbes attach to the anode and start dumping electrons through the circuit to the cathode. "That electron flow is the current and that's power," Tender says. A prototype BUG produces enough power to run a meteorological buoy measuring air temperature, relative humidity and water temperatures in the Potomac River and transmit the data every five minutes to a computer in Tender's office.

To better understand the microbiology of the BUG, Tender collaborated with Derek Lovley, Principal Investigator of the Geobacter Project at the Environmental Biotechnology Center at the University of Massachusetts in Amherst. They discovered metal-reducing microorganisms in the family Geobacteraceae (geobacter) dominated the microbes coating the anode. Geobacter and other metal-reducing microbes exhibit a novel form of respiration. Instead of transferring electrons to oxygen when breaking down organic matter, they instead transfer electrons to alternative electron acceptors, such as iron oxides and sulphates, in the surrounding environment. This behavior makes them proficient at transferring electrons to another electron acceptor, the anode of a MFC. Lovley calls this type of organism an electricigen. "The microbes are living entities that are constantly rejuvenating themselves on the surface of the anode," Tender explains. "The result is a self-sustaining system that lasts indefinitely."

INCREASING EFFICIENCY AND POWER PRODUCTION

The discovery of geobacter removed a number of factors limiting MFC development. Previously, microbes used in many MFCs only converted a small percentage of the electrons available in organic fuels into electricity. "With the electricigen, you often get 90 percent conversions of available electrons into electricity," Lovley says. "That is a major difference."

Electricigens also eliminate the need for electron mediators, frequently used by MFCs to increase efficiency. Electron mediators are artificial compounds that promote electron transfer between the cell and the electrode, he explains. Unfortunately, electron mediator compounds tended to be expensive, unstable and toxic to humans. In addition, early MFC systems did not last very long. The organisms were not retaining sufficient electrons to sustain their own growth and so were not benefiting from promoting electricity production. Electricigens conserve a small amount of electricity from the process for themselves and use it to maintain the cells and grow. "We are finding that these systems are basically immortal," notes Lovely. "As long as you give them fuel, it is a nice self-sustaining process." He and his team are also reengineering the design of MFCs, with the goal of increasing power density — the amount of power generated relative to the MFC's volume. "Recently we have been able to increase the power density by a couple orders of magnitude just by better design of the fuel cells," he adds.

PIGGYBACKING VIA NANOWIRES

Reengineering the MFC design resulted in another important discovery. Under older configurations yielding lower power densities, only a single layer of microbes coated the anode surface. "As we improved other features of the fuel cell and the power density increased, we saw that the microbes started stacking on the surface," Lovley says. The resulting biofilm created by the cells piggybacking on top of one another ranged in thickness from 10 to 100 cells.

Surprisingly, the amount of current produced by the MFC was directly correlated to the amount of the biofilm that collected on the anode. "This would suggest that even through some cells are a substantial distance from the anode, they are still contributing equally to the power production," he notes. Further investigation of this phenomenon found that the microbes were growing wire-like hairs, called pili, which transfer electrons produced during digestion to metal atoms in the surrounding environment. In the absence of metal, these so-called "nanowire" structures attached to other cells forming a biofilm. The biofilm acts like a conductive mat, permitting bacteria not in direct contact with the anode to transfer electrons to the anode. "We have seen nanowires as long as 20 microns, which is quite long," he adds. "The cells are typically 1-2 microns in length."

Efforts continue to understand the chemistry and microbiology of the process in order to generate more power. One potential means of boosting geobacter's power production capabilities is through genetic modification. So far the effort has not resulted in significant increases in power output.

Lovley is now approaching the problem differently, letting Mother Nature lend a hand. He believes that by putting selective adaptive pressure on the microbes they will evolve to transfer electrons faster. "Once we have an organism that can transfer electrons faster, then we will go back and look to see what has changed," he says.

Instead of zeroing in on a specific species, Bruce Rittmann, Professor and Director of the Center for Environmental Biotechnology at Arizona State University in Tempe, is researching microbial communities that naturally develop in MFC settings. "We are trying to is take advantage of one billion or so years of evolution," Rittmann says.

Research is focused on setting up conditions within a MFC that strongly select for organisms excelling at power production by improving the ability of the system to move electrons through the circuit to the cathode. "The key thing we have seen is a marked increase in the energy density over the last few years," Rittmann explains. But studying microorganisms in MFCs is just one piece of a larger puzzle. "You really have to take a comprehensive approach to the entire MFC system," he adds. Beyond microbial ecology, research at the center is also exploring biofilms, materials, electrochemistry and kinetics.

MFC DESIGN AND SCALABILITY

MFC design is a major focus of the work at Washington University in St. Louis by Largus Angenent, Assistant Professor in the Department of Energy, Environmental and Chemical Engineering. His goal is to design a practical wastewater treatment system using MFCs. In such a system, microbes feed on organic matter in the wastewater, cleaning up the water and producing electrical power.

Angenent has increased MFC power output using a configuration he calls an upflow MFC, which borrows design principles from upflow anaerobic digesters. In the anode chamber, an upflow washes organic feedstock in solution through a porous anode consisting of graphite granules. Efforts are continuing to optimize the configuration. Work also is focusing on designing an anode from inexpensive materials that would permit the fuel cell to be scaled up cheaply, Angenent explains.

Scalability is also dependent on minimizing the internal resistance (the degree the flow of electric current is impeded) within the MFC. Designing miniature systems with low internal resistance is not difficult, but keeping the resistance low as the size of the MFC increases is much more difficult. "We have been able to lower the internal resistance every couple years by a factor of 10," Angenent says. "We want to keep that up, but it is obviously a challenge."

At Penn State, Bruce Logan, Kappe Professor of Environmental Engineering, has developed new designs for the anode and the cathode, which permits scaling of the technology for use in larger-scale electricity production. The anode of Logan's innovative MFC is composed of a graphic fiber bottle-brush. Previously, anodes were made from flat pieces of cloth or carbon paper. "This three-dimensional structure provides a large amount of surface area for the bacteria to grow," Logan explains. He suggests thinking about a MFC the size of a refrigerator. "The surface area of the anode would be equivalent to a couple of football fields."

Using the new anode, power production has increased from 500 to 1,000 milliwatts/m2 to 2,400 milliwatts/m2 over the past two years. "It is not a huge jump in power," Logan says. "But we have designed an anode where you do not need to worry about the surface area limiting us in terms of power production." The brushes exhibit good conductivity, are inexpensive to produce and offer tremendous flexibility in design and layout within a MFC. Logan is working on configuring the brushes to optimize surface area in larger MFCs.

He has also taken a different approach with the cathode by combining it with the MFC membrane. The new design starts with an ultra filtration tubular membrane commonly used in commercial water and wastewater treatment plants. "We essentially made the membrane itself the cathode by applying a conductive polymer and a nonprecious metal to the inside surface [of the tube]," he explains.

Like the anode, the cathode needs to be scalable, provide substantially more surface area and be made from inexpensive materials. The tubular membrane is both scaleable and inexpensive. Previously, cathode designs employed platinum to catalyze the combining of oxygen with the electrons and protons to form water. But platinum is very expensive. The new design employs a nonprecious metal catalyst, which is substantially cheaper.

While the new cathode did not produce as much power as a flat cathode with a similar surface area per volume ratio, "at least it is a proof of concept," says Logan. "This is the first time we have ever tried something like this and we know we can improve it." Tests combining the new anode with two tubular cathodes resulted in a MFC producing 17.7 watts of power with an efficiency of more than 70 percent.

The next step is to explore alternative materials and catalysts to improve power production at the cathode. "We also have to reduce what we call internal resistance, or the barrier that the membrane represents to protons, oxygen and electrons all getting to the catalyst," he adds.

COMMERCIALIZING MFCs

Small niche MFC applications, like remote sensors, are on the verge of commercialization. "Some applications really do not need a lot of power," Lovley notes. "We are actually at the power levels we need now, so it is really more of an engineering issue."

For example, remote sensing devices and instruments employed by oceanographers are specifically designed to operate at very low power levels. "For a watt or even a half a watt, you can do all sorts of complicated measurements and also use satellites to collect the data," Tender says. He is developing BUG prototypes to demonstrate their use powering different types of equipment and addressing strategies for scaling the technology. For example, multiple BUGs could work in tandem for devices requiring more power. "There is tremendous flexibility in the design," he adds.

There are also practical issues to address, like how to push an anode into the sediment from a ship when the anode is 100-ft below. "My gut feel is that we are pretty close to having a prototype that will stimulate a company to take a look and commercialize it," Tender says.

Angenent foresees MFCs used in distributed energy applications, with a great potential in the developing world. Utilizing MFCs instead of small anaerobic digesters to convert waste to biogas would not only provide energy for cooking but also electricity, he points out.

Beyond small niche applications, most point to wastewater treatment as a viable application. "I think the very first applications will be industrial wastewater treatment," Logan says. Industries spend a lot of money on wastewater treatment. "If you can figure out how to turn it into a gain and generate electricity to run your plant economically, then it is a no-brainer."

Logan believes his newly designed MFC, employing graphite fiber brush anodes and tubular membrane cathodes, is ready for commercialization: "We have more work to do to improve the technology, but with a minimal amount of optimization, which is already going on, this is ready for pilot-scale testing. With these breakthroughs, companies now realize that this is a very viable technology."

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Page 52 MICROBIAL FUEL CELLS GENERATING HYDROGEN

IN ADDITION to producing electricity, Microbial Fuel Cells (MFC) can generate hydrogen. Stephan Grot, President of Ion Power, conceived the idea of a hydrogen-producing MFC. He approached Bruce Logan, Professor of Environmental Engineering at Pennsylvania State University, who is experienced with MFCs, to work on the project. The team modified the design of a MFC to create a bioelectrochemically-assisted microbial reactor or BEAMR. The design is similar to a fuel cell except oxygen is eliminated at the cathode and a small amount of electricity is added to the circuit.

Under normal conditions, bacteria generate hydrogen during the fermentation of glucose. But there is a "fermentation barrier" limiting the amount of hydrogen bacteria can produce from each molecule of glucose. Essentially, the bacteria do not have enough energy to convert the remaining by-products of the process, acetate and butyrate, into hydrogen, Logan explains. The team found they could overcome the fermentation barrier by giving the bacteria a little energy, in the form of 250 mV of electricity added to the circuit. This added electricity provides enough energy for the bacteria to breakdown the acetate into hydrogen.

As with a traditional MFC, the microbes consume biomass, in this case glucose, and produce electrons in the anode chamber. The electrons flow via the external circuit to the cathode. Protons go into solution and travel to the cathode through the membrane separating the two chambers, where they are electrochemically assisted (by the 250 mV of electricity added to the circuit) to combine with the electrons to produce hydrogen gas.

The BEAMR produces four times the amount of hydrogen as fermentation alone, Logan says. "We went from a net yield of 2 moles of hydrogen to 8 or 9 moles of hydrogen."

Research is underway to raise the yield even further. “The geometric limit, if you write out the equation, is 12 moles of hydrogen per mole of glucose,” he explains. “We are confident that we can produce 11 moles per mole of glucose.” As with a MFC, the BEAMR is not limited to glucose as a feedstock. “We can use anything that is biodegradable,” Logan adds.

Grot envisions using the BEAMR technology in wastewater treatment facilities. Instead of glucose, microbes would feed on the organic matter in the wastewater and in the process clean the water while generating hydrogen as a by-product.

Ion Power received a $100,000 Small Business Innovation Research grant from the U.S. Department of Energy for a feasibility study to develop the process and is requesting a Phase II grant. He hopes to identify commercialization partners during Phase II. “The right partner is someone who is willing to dabble,” he says. Grot expects the commercialization process to take five years.


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