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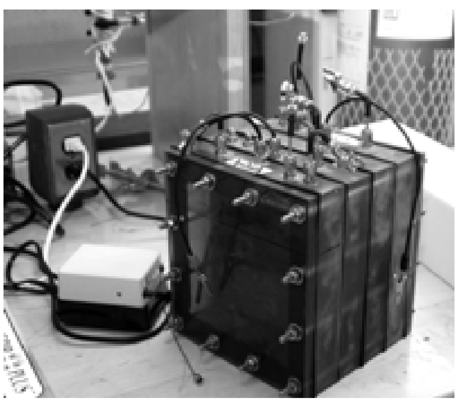
Lovley with a beaker of Rhodoferax ferrireducens (top). Below is an early attempt to create a bug-driven, fuel cell-like power source. A rudimentary bug battery hooked to a very sensitive voltmeter (Second below).



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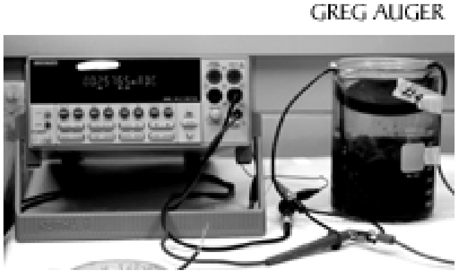

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Dirt to Energy at the University of Massachusetts

'Iron-Breathing' Bacteria Show Promise as Electricity Sources

By Wendy Williams

When it comes right down to it, generating electricity can be pretty basic: It's merely a matter of juggling electrons. And that's just child's play. Every toddler learns the funny result of rubbing her hair with a balloon on a dry winter day. Of course, she doesn't know that when her hair stands on end the bizarre anti-gravity effect is the result of having transferred electrons from her hair to the balloon.

Generating "electricity"—an imbalance of electrons—on a small scale may be a simple task, but capturing and directing those electrons on a large scale has proven to be both the boon and the bane of civilization.

In the 19th century, we discovered how to use spinning turbines to create the electron imbalance. Sadly, to spin these ever-larger turbines we've had to build mammoth dams or burn more and more fossil fuels. This isn't going to work much longer. In The Earth's Biosphere, scientist and scholar Vaclav Smil predicts we will quadruple our energy use by 2100. Unless we develop some new technologies, we're going to be in trouble.

In recent years hydrogen-powered fuel cells, a technology that captures the electron from the hydrogen nucleus, have been touted as the answer. This sounds good—hydrogen is the most abundant element in the universe. Unfortunately, hydrogen must be, in a sense, "mined," too. It's almost always tied up in compounds like water, H_2O.

The hydrogen must be separated out, a process which is terribly inefficient. You can get it from fossil fuels, but hydrogen comprises roughly only four to five percent of coal, 11 to 14 percent of oil, and 25 percent of natural gas. Or you can get it from water. Separating the H_2 from the O is easy, but an energy source is required, so you're back in the chicken-and-egg circle.

Now, though, a University of Massachusetts microbiologist may have found a much simpler way to harvest electrons. He suggests we let nature—in the form of an odd little one-celled mud-loving bacterium—do the job for us.

Derek Lovley, a bespectacled professor of microbiology, didn't start out looking for a potentially groundbreaking electricity-generating technology. He and his 50-person lab work primarily in the applied science of bioremediation—finding natural ways to clean up the environmental havoc wrought by a technologically overconfident 20th century.

The Lovley Laboratory at UMass pioneers in the exploration of the microscopic world of single-celled life. It's a fascinating world down there in the dirt and mud, nearly as vast and uncharted as the universe itself, and full of outlandish surprises.

For example, we surface organisms breathe oxygen, but Lovley plays with organisms that breathe iron. In fact, Lovley speculates that these "iron-breathers" were probably the first of earth's living organisms. Many scientists agree. "At the start of life there was probably a lot of ferric iron," says Lovley. "The evidence shows that the iron breathers came first. After that, there were blooms of other organisms, before we showed up."

Iron is nearly ubiquitous in soil and sediments, and iron breathers can be coaxed into doing jobs for us that we can't do for ourselves. In Colorado, Lovley is experimenting with an iron-breathing organism that he hopes will be able to clean up a uranium-contaminated water table. If he's on target, the cleanup process will be shorter, cheaper and safer than the

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typical, labor-intensive "muck, suck and truck" process. Iron-breathing organisms may also be able to clean up underground oil spills by chomping apart the long carbon macro-molecules, turning them into harmless little bits and pieces.

It was in the midst of these experiments that Lovley's lab found this very special, very unexpected microorganism, now called Rhodoferax ferrireducens. "It was part of our bioremediation research," he says. "We were recovering organisms from the environment by growing them on iron. Then we tested the organisms in various ways."

During the course of these routine experiments, graduate student Kevin Finneran found the organism (see sidebar). Swades K. Chaudhuri, a postdoctorate member of the lab team, performed the experiments, which showed how easily and how efficiently the bacterium could conduct electricity.

It works like this:

Our bodies use the oxygen we breathe to break apart the molecules of food that we eat. The end result is that we get energy.

R. ferrireducens uses iron instead of oxygen. Fortunately for us, at the end of the process, formally called "metabolism," the bacterium has an electron left over. In nature, it hands the spare over to iron, an element that's quite plentiful in most ecosystems.
R. ferrireducens is a flexible little fellow, however. The scientists have found that the bacterium is also willing to hand the electron over to an electrode. Indeed, the team found that if you stick a graphite electrode into a jar containing these bacteria, the bacteria quickly colonize the electrode and grow in number. All you have to do is feed it a simple sugar, like glucose or fructose—compounds that make up plant material.

This resilience, the fact that the organism is an easy keeper, has scientists very interested. Other iron-breathing organisms also conduct electricity, but they have needed more pampering than a movie star to keep them alive. Lovley's bacterium is a tough little guy, a street-fighter type, who just keeps going and going.

Additionally, R. ferrireducens is extremely efficient. Other organisms have conducted electricity with depressingly low efficiency. Several years ago, a Korean scientist reported finding a bacterium that passed on its electrons—but its efficiency was only 0.04 percent.

So far, R. ferrireducens has proven more than 80 percent efficient. In the world of electricity generation, that's a number to die for. Lovley and Chaudhuri have already lit up a small light bulb using a current produced by their microbe. Lovley's in the process now of applying for patents and developing partnerships with companies that will know more about how to bring this technology to fruition. He won't say with whom he's talking, but he will say he's very, very excited.

Nevertheless, there are hurdles. R. ferrireducens is efficient, but he's a plodder. Compared to the burning of fossil fuels, the process of breaking down the simple sugars and handing over the electrons is a pretty low-key, low-voltage affair. For R. ferrireducens to be useful on a large scale, engineers will have to find a way to ramp up the power, explains physicist John Stringer of the Electric Power Research Institute.

"Biologically based reactions tend to be on the slow side in terms of electricity generation," he says. "The overall flux of the reactions is relatively slow, because biological processes are relatively slow. We walk relatively slowly. Trees grow relatively slowly. On the other hand, a flame represents a fast reaction. The oxidation reaction that goes on in your bloodstream that allows you to live is going quite a lot slower than that."

Ramping up to a more powerful voltage and operating on a larger scale are engineering hurdles that may, in time, be overcome. For example, Lovley suggests that developing an electrode that can host a larger colony of bacteria may help. He's talking to University of Massachusetts materials researchers now about those possibilities.

Clearly, no one is talking about powering a household with iron breathers any time soon. Because of Lovley's unexpected finding, however, the number of researchers interested in electricity generation via bacteria promises to expand.

Leonard Tender, an electrochemist with the Office of Naval Research, says that when he looks at the ocean floor, he sees a battery: "It's an electron-rich environment down there. It started to look like a fuel cell to me. And if we put an electrode in sediment, lo and behold it worked. The way we understand it is that microorganisms strip away electrons from

Lab Persistence Pays Off

Lovley's fond of telling people that his microbial discovery was "just lucky."

"Not exactly," counters Kevin Finneran, the graduate student who actually did the legwork that isolated the organism.

"Derek has posters all over his laboratory," says Finneran. "One of them pictures Einstein and has one of his most famous quotes: 'Chance favors the prepared mind.'"

In September of 1999, his second year of graduate school, Finneran became one of several students tasked with the rather tedious process of isolating microorganisms in Lovley's laboratory. As part of a Department of Energy grant, soil samples from a Virginia aquifer were sent to Lovley's lab and it was Finneran's routine task to "feed" these various samples different nutrients, then record what happened.

"This is where luck meets slogging away in science," says Finneran, now a microbiologist with Geosyntec of Boxboro, Massachusetts.

During the routine "feedings," he noticed that one culture was processing the iron much more quickly than was typical. He told Lovley, who immediately understood that this unique behavior could turn out to be valuable. He and Finneran played around with the bacterium, learning as much as they could about how it functioned. The more they looked, the more they liked what they saw.

Finneran earned his doctorate before Lovley began to think about the bacterium's electricity potential, however, so it was another member of the lab team, Swades K. Chaudhuri, who found out how very well R. ferrireducens could accomplish that task.

"When Derek told me that," says Finneran, "I thought it was absolutely wild. Wow!" When asked whether Lovley was "just lucky," Finneran laughs. "When I left, the project didn't just languish," he says. "That's the way Derek is—if there's an interesting question, he'll put someone on it and get the questions answered."

"Derek's work has opened up a whole new world in science, in our understanding of what microbes are capable of," says Finneran. "Now, in his applied research, he's delving into environmental restoration using bacteria. It was really a lot of fun to be able to work with that group."
—W.W.

organic matter. These electrons have a great deal of potential energy."

"These microorganisms are starved for places to stick these electrons. They get very creative about where to put those electrons. We've found that if we stick those electrodes in, they'll use those."

What has scientists particularly excited is that some of these bacteria-based systems could turn out to be "self-renewing," says marine chemist Clare Reimers of Oregon State University. "The environment is resupplying the chemicals that you need to keep the system running. A hydrogen/oxygen fuel cell needs somebody to pump in hydrogen. You have to supply that fuel. With the systems that we're setting up in the ocean, you can think of the microorganisms as supplying the fuel, as they break down the material in the ocean."

Reimers initially hopes to develop sea-floor cells that will provide this "semi-perpetual" power for remote sensors that can do things like census whale populations or detect earthquakes. She even foresees bacteria-powered underwater vehicles. Theoretically, the bacteria would be fueled by gleaning the carbon-based organisms that drift down through the water column from the sea surface, somewhat the way baleen whales filter phytoplankton for energy.

Reimers can also see a land-based future for the technology, sometime in the future. "You may not power your whole home, but you can certainly augment and reduce the power that's driven by fossil fuels."

Lovley thinks the little bacterium will help to pave the way for a pretty interesting energy future. It's not quite Back to the Future, where you can stuff a banana into the fuel tank, says Lovley, but it's a step in that direction.