Biofuel cells: can they fulfil their promise?

BARBARA HEYDONN AND ROSAMUND GEE

While scientists argue that biofuel cells represent a fundamental dislocation in power delivery, wide-scale commercialization appears to be some way off.

Biofuel cells are devices that use biocatalysts to convert chemical energy to electrical energy. Typically, these development systems harness energy from whole-cell organisms (microbial-based biofuel cells) or use enzymes from living organisms (enzymatic biofuel cells) in the electron-transfer chain between the fuel substrate and the electrode surface. Yet whilst the success of fundamental research is a reason for optimism, it’s evident that there is still a long way to go before biofuel cells can make the transition out of the laboratory and into mainstream markets.

Operating lifetime, complexity, durability and cost are just a few of the issues that will need to be tackled before the technology reaches end use. However, the biggest challenge facing developers may be imagining (and funding) the development of applications that can be enabled by this unique technology. The real promise of biofuel cells is not just to replace conventional power sources, but to enable totally new applications that simply can’t be performed today. With this in mind, at least two companies—Power2Gen (Summit, New Jersey) and Accuron (St Louis, Missouri)—have been formed to commercialize enzymatic biofuel cells. In the near term, both intend to develop portable power sources for consumer, industrial and military products such as laptops, cell phones, digital cameras, video cameras or power tools.

In the past, enzymatic systems have had short operating lives—often measurable in hours—and microbial systems have been considered too bulky and impractical. What’s encouraging, though, is that researchers are beginning to overcome these limitations through innovative design and the development of appropriate applications for the technology. There are a number of drivers stimulating this international R&D effort on biofuel cells:

- Demand for clean energy from renewable resources.
- Demand for small, lightweight power sources to provide power in remote areas or for small devices (such as biomedical implants). For the latter, biofuel cells may be the only technology capable of providing power at that scale.
- Biofuel cells have the potential to be less expensive than conventional fuel cells because they don’t require expensive catalysts and may use more effective configurations than the traditional design of an anode and cathode separated by a polymer/ceramic membrane.
- Biofuel cells could be fuelled more easily and safely than conventional fuel cells.

Although broad commercialization is not expected for at least 10 years, volume markets for biofuel cells could include everything from conventional battery replacement to novel applications.
Microbial or enzymatic? Microbial fuel cells use living microorganisms to produce electrochemically active substances. These fuel cells typically operate in one of four ways:

- **Fuel**, such as hydrogen, is produced in a biocatalytic microbial reactor, separated, and then fed to the anode of a fuel cell. Some scientists consider these systems biofuel cells, although the system is really operating as a bioreactor connected to what could be a conventional fuel cell.

- In a true biofuel cell, the electrochemical oxidation of hydrogen at the anode takes place in the presence of the biological components that generated the hydrogen. Typically, the reductive species that are generated by metabolic processes inside microbial cells are protected by a microbial membrane, which in turn limits electron transfer at the electrode.

- To improve the electron-transfer mechanism, most microbial fuel cells use mediators to help couple the intracellular electron transfer process with electrochemical reactions at the electrodes. In most cases, these systems operate under anaerobic conditions to encourage electron transport along the "artificial" electron relays.

- Some microorganisms—such as *flavobacteria* and *eubacteria*—produce electron carriers on their outer membrane. This characteristic allows electron transfer with the anode to take place without a mediator. The discovery of this type of microorganism is generally credited to Byung Hong Kim and colleagues at the Korea Institute of Science and Technology (Seoul, Korea), who received US Patent 5976719 for a mediator-less biofuel cell (2 November 1999). One class of microbial fuel cell attracting plenty of interest is the so-called biofilm—essentially, colonies of bacteria that occur naturally where a food source exists. Researchers are exploring ways to harvest electricity from these colonies, especially in nutrient-rich environments such as on the sea floor or in waste water. The main advantage of microbial fuel cells is that, as they are living systems, they tend to be self-sustaining and able to operate for long periods—in theory, for as long as the environment can be maintained. Some researchers argue that these systems tend to operate more like batteries than fuel cells, because it is difficult to maintain mediator concentrations as fuel is added or waste stream removed.

In contrast, enzymatic biofuel cells use enzymes from living organisms as biocatalysts, instead of whole living cells. Oxidative biocatalysts participate in oxidizing the fuel and transferring electrons to the anode; reducing biocatalysts participate in reducing the oxidizer at the cathode. Enzymatic biofuel cells can also require mediators to establish electrical contact and tend to have much higher current densities than microbial biofuel cells. Until recently, their operating lifetimes tended to be limited (days or weeks rather than months) com-
Artificial intelligence: a team led by Chris Melhuish at the University of the West of England is developing energy-autonomous robots powered by plant material and microbial fuel cells (left). The first stage of the EcoBot project involved the construction of a proof-of-concept sugar-eating robot (right).

pared with their microbial counterparts. That said, Shelley Minteer at St Louis University (St Louis, Missouri) appears to have made substantial progress on this score, reporting a biofuel cell that can generate 6-10 mW/cm² while operating under continuous use for six to 12 months (see below).

Generally speaking, research on enzymatic fuel cells is focusing on improved power densities and extended operating lifetimes, as well as cost reduction. Wiring enzymes to the electrode, genetically designing enzymes and eliminating mediators are all being looked at as ways to ramp the power density, while physical protection of the enzyme or the use of genetically tailored biomolecules could help to extend the operating life.

Snapshots of a community

Notwithstanding the current constraints on technology transfer, there’s a wide-ranging R&D effort on biofuel cells in progress at universities and research institutions around the world. The following highlights are not meant to provide a comprehensive overview of that activity, but they do serve to highlight the diverse nature of the work that is under way.

University of Massachusetts, Amherst (Amherst, Massachusetts). Under the leadership of microbiologist Derek Lovley, the team has reported how methanogenic ferredoxin (a bacterium commonly found in marine sediments) can metabolize sugar into electricity. According to a paper in Nature Biotechnology, the bacterium "can oxidize glucose to carbon dioxide and quantitatively transfer electrons to graphite electrodes without the need for an electron-shuttling mediator". Although it’s a long way to commercialization, the concept could one day be used to convert sugars in household rubbish and sewage directly into electricity. Another possibility is power generation for monitoring equipment on the ocean floor.

Brown University (Providence, Rhode Island). Separation of the fuel-containing fluids is a big problem for developers of microbial fuel cells with most designs relying on ion-conducting membranes that deteriorate over time. Brown has come up with a neat way round this problem. Specifically, by taking advantage of fuels of redox-active and insulating, they have been able to keep the fuels separate without a membrane. They have also overcome some of the deficiencies associated with membrane-less fuel cells — early prototypes had a tendency to short-circuit under pulsed flow — by incorporating a branched channel featuring six enclosed electrodes in the design.

Pennsylvania State University (University Park, Pennsylvania). Bruce Logan is one of the leading researchers active in this field. Back in February, his team published details of a microbial fuel cell that can generate electricity while simultaneously cleaning waste water. The researchers produced between 10 and 30 mW/m² (of electrode surface) while removing up to 78% of organic matter from the waste stream. The prototype fuel cell is a small plastic cylinder (6 inches long, 2.5 inches in diameter) containing eight graphite rods that act as anode. The rods are surrounded by electrodes and a central positive electrode composed of plastic, carbon and platinum. When waste water flows through the cylinder, bacteria stick to the graphite rods, channeling electrons into the rods as they consume organic material. As the electrons travel through the graphite rods to the platinum rod, they complete the circuit.

University of the West of England (Bristol, UK). Scientists are developing robots whose power derives from biological fuel cells that run on glucose and contain microbes such as E. Coli — to break down carbohydrates and release hydrogen atoms. The fuel cells also incorporate chemicals to drive a series of reduction and oxidation reactions that strip electrons from the hydrogen atoms and deliver them to the anode — a process that creates a voltage to power a circuit.

University of California, Berkeley (Berkeley, California). Scientists discovered that when glucose combines with the microorganism Saccharomyces cerevisiae (baker's yeast), it generates electricity that a miniature fuel cell can harness and distribute. In laboratory experiments, a prototype device generated 300 µV for 24 h. That sort of voltage, if sustained, is sufficient to power implantable medical devices such as next-generation pacemakers.

St Louis University (St Louis, Missouri). Last year, a team led by Shelley Minteer unveiled an ethanol-based enzymatic biofuel cell in which the enzymes are immobilized in a modified ion-exchange polymer membrane that attaches to the electrode. The design contrasts with earlier enzymatic biofuel cells, which contained enzymes in solution with the fuel (and as a
result suffered from low power densities and short enzyme lifetime.

The membrane lowers the acidity to near-neutral pH with a porous structure that traps and holds the enzymes while allowing the smaller fuel molecules to pass through. Minter and his graduate student, Nick Akers, have founded a start-up company called Aerasin to commercialize the technology.

University of Texas, Austin (Austin, Texas). This team is developing biofuel cells to drive medical sensor-transmitter systems in the body. The goal is to realize simple cells that can produce a few microwatts of power, operate for three to seven days, and cost less than $1.50 to produce. Current work is focused on designs that eliminate the need for a membrane by making the enzymatic electrocatalysis of the anode and cathode all-reductive towards their respective reactants. The scientists are also seeking to eliminate the need for a casing and seal by tailoring the electrolyte to operate under physiological conditions.

University of Oxford (Oxford, UK). Scientists at the university's inorganic chemistry laboratory have developed an enzymatic fuel cell in which a hydrogenase electrode replaces the conventional platinum-based fuel-cell anode. When the hydrogenase electrode is coupled to a cathode that incorporates the fungal enzyme lactase (which catalyzes the reduction of oxygen to water), the biofuel cell generates a small, but measurable output.

RITE: Research Institute of Innovative Technology for the Earth (Kizu-cho, Japan). In collaboration with consumer electronics giant Sharp Corporation, RITE is working on microbial fuel cells that consume glucose from liquefying and refining kitchen waste to generate hydrogen. The approach involves extending the bacteria's lifetime and hydrogen-production capability. Potential applications include domestic electrical appliances in the home.

In summary, while these groups and many others continue to innovate on the materials, components, and systems-level aspects of biofuel cells, technology transfer and volume commercialization remain medium-term prospects at best. On the flip side, the early-stage research clearly demonstrates that biofuel cells have the potential to one day compete with conventional power sources or enable new applications. Watch this space and expect a few surprises along the way.

Further reading

Barbara Hepworth is a senior consultant specializing in fuel cells at SRI Consulting Business Intelligence (SRI-BI), Menlo Park, California, US. Reach her at Barbara.Hepworth@sribi.com or 650-870-1653. Further information on SRI-BI’s fuel-cell programme can be found at http://sribi.com.