Micro fuel cells stack up well against batteries on paper. But the devices still face engineering, financial, and even political hurdles

Shrinking Fuel Cells Promise Power in Your Pocket

TECHNOLOGY

The future of consumer electronics hinges on finding compact, long-lasting sources of power. As devices become ever smaller and more ravenous for electricity, they have already outstripped technology's ability to keep pace. This special Focus package explores how so-called micro fuel cells might solve the problem, and how makers of conventional batteries hope to adapt their products to compete in the power struggle.

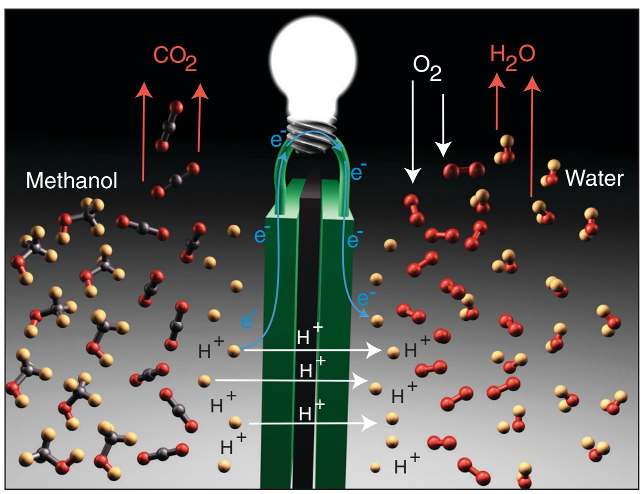
▶ **FUEL CELLS**

BATTERIES

Modern conveniences can be so inconvenient. A billion of us now cart around laptops, cell phones, and other portable electronic gadgets. But as nifty as these accessories are, they have us perpetually prowling for outlets to recharge their ever-fading batteries. And the problem is only getting worse. Packed with energy-hogging color screens and video and data transmission capabilities, next-generation devices threaten to drain batteries in just tens of minutes instead of the few hours they take today. "Even with improvements, batteries cannot keep up with the needs," says Hyuk Chang, a principal researcher with Samsung Advanced Research Institute in Suwon, Korea.

Until now consumers haven't had much of an alternative. But that's about to change. A bevy of companies are closing in on commercialization of micro fuel cells, small devices that convert chemical fuels such as hydrogen or methanol directly into electrical power. Packed with energy, these chemical fuels promise to power devices up to 10 times as long as batteries on a single charge. For laptop users, that means no longer running out of juice on a long flight; for cell phone fanatics, it means 20 hours of nonstop gabbing. And even when the juice does run low, fuel cells can be recharged instantly just by adding more fuel. When it comes to powering advanced portable electronics, "fuel cells seem to be a front-runner in a field where there are very few choices," says Dennis Sieminski, business development manager of AER Energy Resources Inc., a battery development company in Smyrna, Georgia.

Among fuel cell makers, the race is just heating up. Companies including Motorola, Samsung, and Manhattan Scientific introduced new prototype micro fuel cell devices in the past year. And these and other companies expect commercial versions of the devices to begin hitting stores in the next 2 years. The early devices, company officials say, will likely be small, cigarette pack–sized modules that serve as backup power supplies for devices slotted with conventional rechargeable batteries. But by 2007, many experts believe, chemical power will have begun systematically replacing conventional plug-and-play electric rechargeables altogether—if, that is, micro fuel cell makers can overcome a few none-too-small barriers, including high cost and concerns over the danger of carrying combustible fuels aboard airplanes.



Power play. By cleverly reshuffling atoms and electrons, fuel cells convert hydrogen-rich fuel into electric current.

Charging to market?

For years, companies have been competing furiously to create macrosized fuel cells to power cars and generate electricity for homes and offices. Large cells still represent the biggest potential markets for the technology, says K. Atakan Ozbek, who heads energy research at Allied Business Intelligence Inc., a technology research company in Oyster Bay, New York. But the micro fuel cell market is nothing to sniff at. Battery makers, for example, sell some $5 billion a year of rechargeables alone, and cell phone makers distribute close to 400 million new phones a year. If micro fuel cell makers manage to capture even a fraction of those markets, they'll quickly find themselves doing big business.

They certainly compete well on paper. Methanol, the most common fuel for small cells, has more than 10 times the energy density of a material in a lithium ion battery. If a fuel cell turned just half of the energy in 30 grams of methanol into usable energy, it would put out 80 watt-hours of electricity—compared with fewer than 7 watt-hours for a conventional mobile-phone battery. And consumers on the go are willing to pay extra for power that lasts longer and can be instantly recharged, Ozbek says. As a result, "micro fuel cells will be the first ones that most consumers see on the market," he predicts.

But like all fuel cells, the miniature versions face numerous hurdles on the way to market. Most micro fuel cells are packed with precious-metal catalysts that make them costly to produce. They run on flammable chemical fuels. Because they typically perform best at high temperatures, they must be well insulated to protect the electronics they power—not to mention anyone carrying them around. And the devices are a long way from proving themselves as reliable and versatile as plug-and-play batteries.

Large or small, fuel cells work by converting chemical energy into current. The reactions take place inside a chamber containing two electrodes separated by an electrolyte that keeps the chemical reactants apart (see figure above). Hydrogen atoms are fed into the chamber at the negatively charged electrode (anode), where catalysts

ILLUSTRATION: C. SLAYDEN

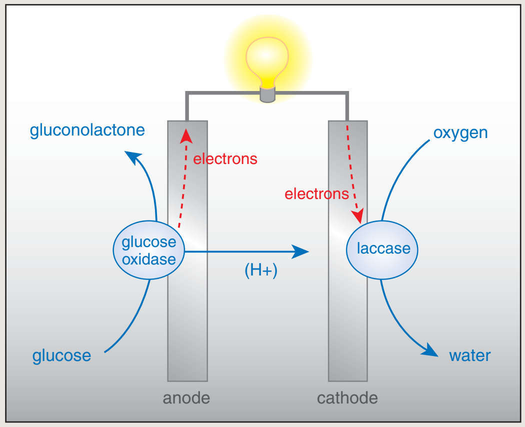
Biofuel Cells

While companies are battling to shrink fuel cells down to cell phone size, nature has already done them one better. Enzymes in creatures from bacteria to people extract energy from compounds such as glucose to power life. Now researchers are looking to borrow a page from biology's manual to create rice grain–sized fuel cells that run on chemicals inside our bodies. Such cells, they say, could someday power futuristic implantable sensors that monitor everything from blood glucose levels in diabetics to chemicals that signal the onset of heart disease or cancer.

Researchers can already make glucose-detecting sensors as small as a millimeter across. "But you cannot make a submillimeter-sized battery at a reasonable cost," says Adam Heller, a chemical engineer and biofuel cell pioneer at the University of Texas, Austin. "That's where we see the use for miniature biofuel cells."

Biofuel cells are much further from commercial development than their larger cousins. But recent progress has been heady. Last August, for example, Heller and his Texas colleagues reported in the *Journal of the American Chemical Society* that they had created a miniature glucose-powered cell that puts out 600 nanowatts of power, five times the previous biofuel cell record and enough to power small silicon-based microelectronics. Heller's lab has already developed millimeter-sized glucose sensors, which are currently being commercialized by a company called TheraSense in Alameda, California. And the new biofuel cells may one day keep such implantable sensors running for days to weeks at a time.

Like traditional fuel cells, biofuel cells use catalysts at two oppositely charged electrodes to strip hydrogen atoms of their electrons and then combine the leftover hydrogen ions with oxygen to form water (see figure). The siphoned-off electrons are then used to do work. In traditional fuel cells, reactants at the two electrodes are kept apart by a thin plastic membrane. But such membranes would be impractical to make on the size scale of biofuel cells, so Heller and other teams have settled on another approach: They use enzymes to carry out the reactions and tether those enzymes to the two different electrodes to ensure that the proper reactions occur at the right spots. At the negatively charged electrode, or anode, copies of an enzyme called glucose oxidase strip electrons from hydrogen atoms on glucose, converting the sugar molecule to gluconolactone and a pair of hydrogen ions. These ions then travel to the positively charged electrode, or cathode, where an enzyme called laccase combines them with oxygen and electrons to make water. The tethers are made of osmium-containing polymers that ferry electrons between the electrodes and enzymes.



Lifelike. By drawing fuel from the body and processing it with enzymes, researchers hope to build fuel cells that imitate the power plants in living organisms.

Heller's cells do have their drawbacks. Because laccase enzymes typically work best in environments much more acidic than the neutral pH of blood, laccase-based fuel cells implanted in the body likely wouldn't produce much power. "Nature didn't evolve proteins to work with circuitry," says Tayhas Palmore, a chemist at Brown University in Providence, Rhode Island.

But Palmore has been working to improve matters here as well. At a fuel cell conference in Washington, D.C., last month, Palmore reported that her group had used standard molecular biology techniques to reengineer the laccase enzyme so that it retains about 50% of its activity at physiological pH. And Palmore and her colleagues are now working on incorporating the reengineered laccase into a prototype fuel cell that could extract power from circulating fluids such as blood.

All biofuel cells still face considerable challenges, however. Most important, blood and other complex bodily fluids contain numerous compounds that can deactivate or block the enzymes essential to fuel-cell function, causing them to stop working within hours or days. But if researchers can improve their stamina, biofuel cells could pave the way to a new generation of implanted devices powered by the body itself.

–R.F.S.

strip them of their electrons. The electrons are siphoned off to an electrical circuit where they are used to do work. The leftover protons, meanwhile, are drawn through the electrolyte—typically a plastic mesh that blocks free electrons from passing to the other side—to the positively charged electrode (cathode). There they combine with electrons returning from the circuit and oxygen molecules from air to form water, which is usually vented off as steam.

Future co-pilot? Fuel cells will have to get much smaller to replace batteries in devices such as PDAs.

CREDIT: (BOTTOM) MOTOROLA LABS

Although such hydrogen-consuming fuel cells can be extremely efficient, pure hydrogen must be stored in pressurized tanks—a drawback that makes it a "nonstarter" as the fuel source in mini fuel cells, says Kurt Kelty, who directs business development at Panasonic's Battery Research and Development Center in Cupertino, California. The alternative most micro fuel cell companies prefer is methanol. This liquid fuel has a high energy density and is plentiful and cheap, explains Mark Hampden-Smith, a vice president for catalyst supply company Superior MicroPowders in Albuquerque, New Mexico. The catalysts used in methanol fuel cells can also strip hydrogen atoms from methanol without the need for another step. What's more, he explains, in a fuel cell methanol breaks down into CO_2 and water vapor without any leftover byproducts that could foul up the fuel cell over time.

Reactions and regulations

Getting methanol fuel cells to work at high efficiency, however, hasn't been easy. One problem lies in the fuel itself. Methanol can cross through the plastic electrolyte to the cathode, where it will block the reactions that form water, thus reducing the overall efficiency of the cell. To lessen the problem, researchers often dilute the methanol with water. Yet this solution creates problems of its own, as it tends to lower the overall power output of the cell.

Numerous groups are working overtime

to come up with membranes less permeable to methanol. At a meeting last month in Washington, D.C.,* researchers at DuPont, which produces the most popular electrolyte membrane, called Nafion, reported developing a pair of new thin plastics that drastically lower the amount of methanol that crosses to the wrong side of the cells. The two membranes reduced methanol crossover by 60%, one of them while allowing a cell to operate at a 60% higher power output, DuPont's Raj Rajendran reported.

Researchers at the Japanese electronics giants NEC and Sony, meanwhile, are turning to all-carbon fullerenes for their electrolytes. Last year Sony, for example, reported creating a new electrolyte membrane using soccer ball–shaped C_{60} molecules. The fullerenes proved much less permeable to methanol, allowing Sony researchers to run their fuel cell without spiking the methanol with water.

Researchers at Motorola are making progress on a very different solution to methanol crossover. They're using advanced semiconductor manufacturing techniques to create a separate miniature fuel reformer that strips methanol of its hydrogen atoms, which are then sent to a fuel cell. Because methanol never enters the fuel cell itself, the cell can be made with a simpler design, says Jerry Hallmark, an electrical engineer who heads Motorola's fuel cell effort at Motorola Labs in Tempe, Arizona. Motorola hopes that, once perfected, the reformers could be stamped out at low cost just as microchips are today. Other teams, including groups at Manhattan Scientifics, Mechanical Technology, and Los Alamos National Laboratory, are also looking to lower costs by creating chiplike cells. "I think it's still early days" for these devices, says Hampden-Smith. "But it's definitely a promising strategy."

No matter which approach manufacturers settle on, the technology could still find itself derailed by factors well beyond their control. Precious metals such as platinum and palladium, which are used as catalysts in both fuel cells and reformers, could jump in price if consumers suddenly demand hundreds of millions of devices a year, Hampden-Smith cautions. Security concerns might also bar the way. For now, methanol and other liquid fuels cannot be taken aboard commercial aircraft. Hallmark is leading industry negotiations with the U.S. Department of Transportation to allow properly packaged fuel canisters on planes, but he acknowledges that last year's terrorist attacks in the United States could make his efforts a hard sell. "If the consumer cannot carry a fuel cell cartridge, then you have no product," Ozbek warns.

For micro fuel cells to make it to market, tricky engineering challenges could prove the simplest problems to solve.

–ROBERT F. SERVICE

* The Knowledge Foundation Fourth Annual International Symposium: Small Fuel Cells for Portable Power Applications, 21–23 April.

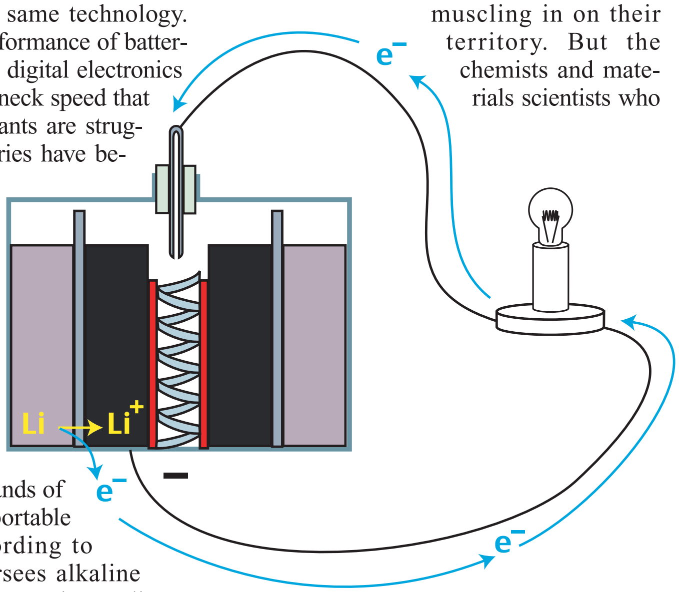
TECHNOLOGY
BATTERIES

The Battery: Not Yet a Terminal Case

The power demands of portable electronics may seem insatiable, but the venerable battery still has a few tricks to keep it a key player in the digital revolution

The alkaline power packs that today you pop into your electronic gadgets may not look much like the column battery developed by Alessandro Volta 200 years ago, but they are essentially the same technology. And even though the performance of batteries has improved greatly, digital electronics is evolving at such breakneck speed that these chemical power plants are struggling to keep up. "Batteries have become the showstopper in today's wireless world," says Krishna Shenai, a power engineer at the University of Illinois, Chicago. "They don't provide enough power, they're too heavy for the power they do provide, and they don't last long enough to meet the demands of the next generation of portable digital devices." According to John Hadley, who oversees alkaline battery research at Rayovac in Madison, Wisconsin, "there are personal electronic devices that have already been developed but that need better batteries from us before consumers will be satisfied with them."

It seems inevitable that fuel cells will soon take over many of the jobs that batteries now do (see p. 1222), and increasingly photovoltaic cells and even clockwork are muscling in on their territory. But the chemists and materials scientists who work in the field say they still have a few tricks up their sleeves. Complex ceramic electrodes and solid electrolytes made from conducting polymers may keep rivals at bay for years yet. "I don't think we've really scratched the surface of what it's possible to do with battery chemistry, and yet we're already far ahead of where we were just a few years ago," says chemist Jim McBreen of Brookhaven National Laboratory in Upton, New York.



Current fashion. In a pure lithium battery, metal ions in the outer cathode are oxidized, releasing an electron into the circuit and freeing a lithium ion to migrate to the anode.

ILLUSTRATION: C. SLAYDEN

The battery industry's secret weapon is lithium, a material with one of the largest electromotive forces in nature that is one of the lightest metals known. The big problem with lithium metal is that it is also immensely reactive. It catches fire when exposed to even the smallest amount of moisture and will oxidize virtually any liquid electrolyte.

Despite these challenges, the first generation of this type of battery, known as lithium ion batteries, are already in use in watches, flash cameras, and the newest rechargeable batteries. These batteries pack three times more energy into a given volume than a conventional alkaline battery and can be recharged an almost unlimited number of times. Unlike conventional batteries (see sidebar), lithium ion batteries don't use a redox reaction to generate electricity. Instead, lithium ions shuttle back and forth between the anode and cathode, forcing electrons to move with them.

In currently available lithium ion batteries, the anode consists of ultrapure graphite, which absorbs lithium ions, one per six-carbon ring. Oxides of cobalt, nickel, or manganese form the cathode. When the battery discharges, lithium ions exit the