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

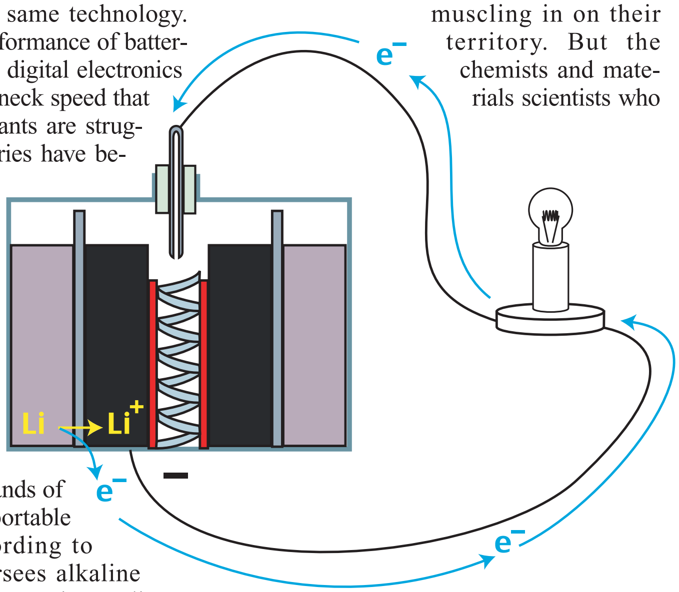
BATTERIES

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.

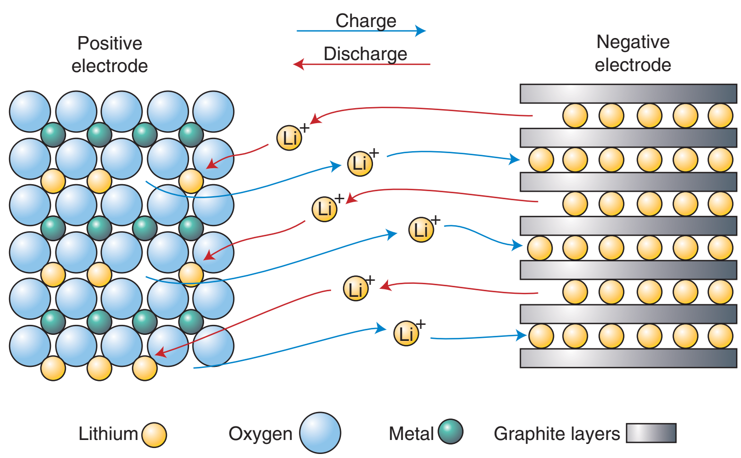
ILLUSTRATION: C. SLAYDEN

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 graphite anode, migrate through the electrolyte, and form chemical complexes with the metal oxide within tiny channels in the cathode's physical structure. Applying an opposing voltage forces the ions back to their starting point, recharging the battery. Lithium's high reactivity and the need to exclude moisture mean that lithium batteries are very expensive to make, however.

To justify the costs, designers want to boost the batteries' performance still further. Their first target for improvement is the anode. Graphite is good for this job because lithium slips easily between its parallel sheets of carbon rings. The problem is that it takes six carbon atoms to accommodate one lithium ion, wasting space. "We'd like to develop materials that can pack more lithium into a given volume," says Gerald Caesar, who manages battery and fuel-cell research for the Advanced Technology Program at the National Institute of Standards and Technology in Gaithersburg, Maryland.



Migrating species. In a lithium ion battery there is no redox reaction. Ions shuttle between cavities in the graphite cathode and metal oxide complexes in the anode.

To accomplish this, researchers are looking for metallic composites that absorb lithium ions. At T/J Technologies in Ann Arbor, Michigan, for example, chemists have found that nanoparticles of various lithium-tin alloys can absorb and release 2.5 times more lithium than a given volume of graphite. Batteries made with tin-alloy anodes store nearly three times more charge than those with a graphite anode, and the tin-based materials cost far less than graphite, too.

Another line of attack is to improve the electrolyte, which must exclude even the smallest trace of water to avoid explosion. "There are so many problems with today's nonaqueous electrolytes that it's amazing that lithium ion batteries are as good as they are," says Brookhaven's McBreen. One of the main problems is that positively charged lithium ions and their negative co-ions in the electrolyte do not separate well in nonaqueous solvents, so the lithium ion ends up dragging its co-ion like a ball and chain. "The harder it is for lithium to move from one electrode to another, the poorer the performance of the battery," says McBreen, whose group has developed different additives to ease that congestion. One, a fluorinated isopropyl boron compound, enhanced the conductivity of the standard ethylene carbonate–dimethyl carbonate electrolyte 100-fold by binding to the co-ions, thereby giving the lithium ions more freedom to move. A battery made with this electrolyte kept its performance over 50 discharge-charge cycles. Longer term tests are now under way.

Ultimately, for reasons of cost, weight, longevity, and safety, manufacturers would like to do away with liquid electrolytes. Dozens of groups worldwide are racing to develop suitable conductive polymers. An intermediate step, made by researchers such as Kyoung-Hee Lee and his colleagues at Samsung SDI in Chungchongnam-Do, Korea, is to form a hybrid: cross-linked polymers in the presence of a liquid electrolyte. The Samsung team found that such materials were 100 times as conductive as the liquid electrolyte alone. Test batteries made from the flexible gellike electrolyte were, in Lee's words, "very encouraging as candidates for a practically useful lithium ion cell." Teams at Brookhaven and the University of Rome are also working on mixed polymer-liquid electrolytes.

Removing liquid altogether has proven difficult because it's not easy getting lithium ions to move smoothly through a solid polymer. But it is proving worthwhile for specialist applications. Quallion, a maker of specialist batteries in Sylmar, California, is trying to develop lithium ion batteries the size of a large grain of rice to power implantable nerve stimulation devices to treat conditions such as Parkinson's disease and urinary incontinence. Robert West of the Organosilicon Research Center at the University of Wisconsin, Madison, is helping the company with electrolytes. West says that conductive silicon-and oxygen–based polymers known as polysiloxanes are soft and pliable at room temperature, and they have among the highest free volumes of any polymer, "which means there would be plenty of room for lithium ions to travel between electrodes."

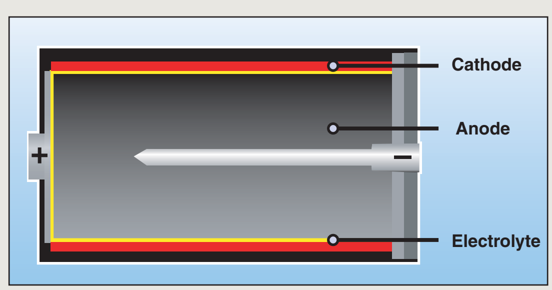
West and his team have now prepared several polymer electrolytes that Quallion has incorporated into prototypes. The best polymers have proved almost as conductive as liquid electrolytes. Quallion is now working out how to make commercial quantities of the tiny batteries. "We're dealing with an entirely new set of physical parameters in trying to make a battery this small," says Wendy Wong, project manager at Quallion.

Further in the future, battery designers would like to up the lithium stakes by

Inside a Battery

A typical AA battery is a miniature power plant that uses a chemical reaction to create an electric current. Every battery has a positive and a negative electrode immersed in an electrolyte that will conduct electrons or transport ions between them. Chemical reactions between ions in the electrolyte and the different metals of the two electrodes cause electrons to accumulate in the negative terminal, or anode. Connecting the two electrodes via an external circuit (which contains the device that needs current, such as a portable DVD player) allows the electrons to flow through the circuit from the anode to the positive electrode, or cathode. The more the battery is discharged, the more the anode becomes oxidized and the cathode becomes reduced. Eventually, one of the electrodes will no longer be able to react. Then the redox reaction stops; the battery is dead. In rechargeable batteries, applying an external voltage across the electrodes runs the redox reaction in reverse.

–J.A.



ILLUSTRATIONS: (TOP TO BOTTOM) C. SLAYDEN; J. MOGLIA moving from lithium ions to anodes made of lithium metal, which would pack even more power into a given volume. Again, finding a suitable solid electrolyte is the key. Chemists Mason Harrup, Thomas Luther, and Frederick Stewart of the Department of Energy's Idaho National Engineering and Environmental Laboratory in Idaho Falls have created solid electrolytes using phosphorus-and-nitrogen–based polymers known as polyphosphazenes, which can easily pass lithium ions between their chemical groups. By combining the polymer with a ceramic, compressing it, and then spinning the mixture into a thin film, the researchers made sheets of solid polymer flexible enough to wrap around a metallic lithium anode. When combined with a commercially available cathode, the result is a battery with "outstanding power-to-weight performance over a very large number of discharge and recharge cycles in a flexible package," Harrup says. Such a flexible battery would allow device manufacturers to cram the power source into odd-shaped nooks and crannies.

Ultimately, the needs of electronic devices will outstrip the ability of batteries to adapt, but battery designers are darned if they're going to give up yet. Says Caesar: "There's only so many chemistries that you can use to make a battery, and we're trying to milk them for all they're worth."

–JOE ALPER

Joe Alper is a writer in Louisville, Colorado.

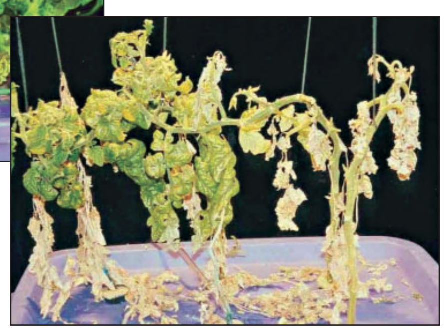
PLANT GENETICS

Finding New Ways to Protect Drought-Stricken Plants

With drought an ever-present threat, researchers are identifying genes that can help plants tolerate arid conditions in hopes of using them to produce hardier crops

Dry fields and stunted plants from Maine to Georgia show that the eastern United States has been hit with the worst drought in more than a decade. In the grain-farming and live-stock-grazing states of Montana, Nebraska, and Wyoming, ranchers are also confronting parched soils. Even the Midwest, home to 20% of the world's fresh water, is in trouble: Areas only 65 kilometers from the Great Lakes have dangerously low water tables.

The global picture is just as bleak. Historically arid regions in Africa and the Middle East are expanding, and shortages of fresh water are appearing in places, such as the Asia-Pacific rim and Northeast Brazil, that once never doubted their water supplies. "Worldwide, drought is the biggest problem for food production," says Jeffrey Bennetzen, a molecular geneticist at Purdue University in West Lafayette, Indiana. And that makes the quest for drought-resistant crops even more urgent, he says.



Salt lovers. Tomato plants carrying a foreign gene that protects their cells from salt-induced dehydration (*above*) thrive in a 200-millimolar salt solution, whereas unaltered plants (*right*) wither.

CREDITS: E. BLUMWALD/UNIVERSITY OF CALIFORNIA, DAVIS

In the last decade or so, researchers in the developing world have successfully coupled molecular marker technology, which allows a more precise identification of strains carrying desired traits, with classical plant breeding to yield more drought-tolerant varieties. For example, 1 year ago, South Africa's Ministry of Agriculture announced the release of maize ZM521, which produces yields up to 50% higher than those of traditional varieties under drought conditions. Many organizations, including the Consultative Group on International Agricultural Research, the International Maize and Wheat Improvement Center, and the European Union, contributed to the development of ZM521.

More recently, plant researchers in the United States and Europe have taken a newer tack, focusing on identifying specific genes that help plants cope with arid conditions and, it turns out, with other stresses, such as cold temperatures and the high salt concentrations often found in irrigated soil. Indeed, from a plant's perspective, frost injury, which involves water leaving cells and forming ice crystals in intercellular spaces; salinity damage, which occurs when roots can't extract enough fresh water from salt-laden soils; and drought injury are all forms of dehydration. "If you increase a plant's tolerance to dehydration, it doesn't matter whether the stress comes from cold or drought, it will often help the plant survive," says plant molecular biologist Michael Thomashow of Michigan State University in East Lansing.

Researchers are now attempting to beef up the ability of crop plants to withstand dehydration by transferring in some of the genes they've identified. They've achieved some successes, albeit modest ones, with cotton and tomatoes, and they hope to extend the work to the most important cultivated crops: cereal grains.

The Rockefeller Foundation in New York City, among others, wants to guarantee that such advances also benefit developing countries. Two years ago the foundation approved a 10-year global effort for up to $50 million to improve drought tolerance in maize for Africa and in rice for Asia. Given the resistance that greeted plants genetically altered to resist pests or herbicides, it remains to be seen how well accepted drought-resistant plants produced by the same technology will be.

Complex adaptations

Over the years, researchers have found that plants have evolved several mechanisms to guard against drought damage. One is by producing "osmoprotectants," compounds that shield proteins and membranes from the damaging effects of dehydration by forming a protective shell on their surfaces or by removing destructive hydroxyl radicals that would otherwise chop up proteins. Not all crop plants make osmoprotectants, which include sugars such as trehalose and certain amino acids and amino acid derivatives.

Almost 10 years ago, Hans Bohnert of the University of Illinois, Urbana-Champaign, decided to see whether the genes for osmoprotectants could be inserted—and made to function—in plants that don't normally carry them. He took a gene that produces the