contract and lengthen in response to electrical signals, just as hair cells do.

Even so, proponents of the motility amplifier still haven't explained how prestin makes cells contract or precisely how the pumping cells account for the ear's prodigious ability to distinguish between tones. "When people make models of how you should use the electromotility, they include some sort of extra [frequency] filter," says Mario Ruggero, a neuroscientist at Northwestern. "I find that somewhat dissatisfying." Researchers working with nonmammalian vertebrates have also begun to question the piston model. The hair cells of birds, amphibians, and reptiles cannot pump, they point out. Yet these animals hear nearly as well as mammals do, albeit at lower frequencies. Seeking an amplifier common to all sharp-eared animals, these researchers point to the stereocilia.

The stereocilia can explain both the ear's fine tuning and other quirks of hearing in one mechanism. Over the past 2 years, Hudspeth and colleagues have developed a mathematical model in which the stereocilia tune the ear so that it is poised between two stable states, one quiet, the other ringing like a public-address system with the volume turned up too high. That on-the-brink point is called a Hopf bifurcation. In their most recent paper, Hudspeth and his team report that it puts the ear in a nonlinear dynamical situation—one in which the output is not simply proportional to the input. That nonlinear state explains why the ear amplifies softer sounds more intensely than loud ones, and why it is better at discerning their pitch. It also accounts for the third "combination tone" people sometimes hear when two tones are played at once.

Proponents of stereocilia, however, lack a key piece of their puzzle: In spite of overwhelming circumstantial evidence, no one has ever cloned the ion channel at the heart of the model or proved that it works as researchers claim. "We truly don't know that the stereocilia mechanism exists in the outer hair cells," Ruggero says.

The biggest challenge for either theory is to explain how mammals can hear at extremely high frequencies when other animals can't. If trapdoor amplification were the only mechanism at work, then you might expect all creatures with stereocilia to have similar hearing ranges. Yet bats can perceive pitches up to 100 kilohertz, 10 times higher than stereocilia-bearing nonmammals can hear.

Because only mammals have pumping outer hair cells, it might seem obvious that electromotility accounts for the mammalian ear's startling tonal range. But that idea seems to run up against basic physics. In experiments with cell cultures, Dallos's team has shown that prestin enables cells to change shape within microseconds, fast enough to amplify vibrations at 100 kilohertz. For the protein to react that quickly, however, the voltage difference between the inside and the outside of the cell must change by roughly a millivolt within microseconds. To make that happen, a hefty charge must flow onto and off of the cell. Yet such a charge can't shuttle back and forth fast enough to keep pace, Fuchs of Johns Hopkins says.

The debate over hair cells may turn on the ear of a mouse. By knocking out the gene for prestin, researchers could turn off the pistons in the mouse's outer hair cells. Such an experiment is the next logical step, all agree. If the ion channel of the stereocilia powers the mammalian ear, the knockout mouse should hear nearly normally. "The problem is going to be the other way around," Hudspeth says. "If the mouse doesn't have normal hearing, what does that mean?" Knocking out prestin may somehow interfere with the stereocilia, Hudspeth says, so a nearly deaf mouse won't settle the issue. In which case, you'll likely hear more about it, as long as your hair cells hold out.

—ADRIAN CHO

MATERIALS SCIENCE

New Tigers in the Fuel Cell Tank

After decades of incremental advances, a spurt of findings suggests that fuel cells that run on good old fossil fuels are almost ready for prime time

It's no wonder that miniature power plants called fuel cells are a perennial favorite in the quest for cleaner energy: They generate electricity from fossil fuels without burning them and spewing pollutants. But the technology's promise has always seemed just beyond reach. For one, most versions of fuel cells work best on pure hydrogen gas—a fuel, notorious for its role in the *Hindenberg* zeppelin's fiery demise, that's tricky to store and unwieldy to transport. And a leading alternative design—fuel cells that run on readily available fossil fuels—has lagged because these are prone to choking on their own waste.

At last, however, researchers have made critical strides in developing commercially viable fuel cells that extract electricity from natural gas, ethane, and other fossil fuels. Conventional ceramic cells, known as solid oxide fuel cells (SOFCs), work this magic by converting, or reforming, the hydrocarbons to hydrogen inside the cells. That demands ultrahigh temperatures, which in turn requires expensive heat-resistant materials. But scientists have found a way to bypass this costly reforming process: a new generation of SOFCs, including one featured on page 2031, that convert hydrocarbons directly into electricity. And even the standard reforming SOFCs are on a roll. A recent demonstration of a system large enough to light up more than 200 homes showed that it is the most efficient large-scale electrical generator ever designed.

"I think we've turned the corner," says Mark Williams, who oversees fuel cell research at the National Energy Technology Laboratory in Morgantown, West Virginia. Versions of ceramic fuel cells, experts hope, will power everything from individual homes to municipal electrical grids. The market for the devices, says Subash Singhal, who heads fuel cell research at the Pacific Northwest National Laboratory in Richland, Washington, could reach billions of dollars over the next 10 to 15 years. Says Kevin Kendall, a solid oxide fuel cell expert at Birmingham University in the United Kingdom: "Suddenly things are happening that weren't possible 10 years ago."

That's rapid progress indeed for a technology now entering its third century of de-

Model of efficiency. This new fuel cell assembly converts a higher percentage of fuel to electricity than any power plant ever built.

CREDIT: SIEMENS WESTINGHOUSE POWER CORP.

velopment. Today's hydrogen-powered fuel cells operate on much the same principles as the first cell invented in 1839 by Sir William Grove, a Welsh judge. They're configured like a battery, with a negatively charged electrode, or cathode, and a positively charged anode separated by a membrane that allows only certain ions to pass through. When hydrogen gas is infused into the space surrounding the anode, a catalyst splits the molecules into protons and electrons. The liberated electrons flow into the anode and out of the cell as electric current that can run attached devices or be fed into electrical grids, before completing the circuit by returning to the cathode. The protons, meanwhile, are impelled through the membrane to the cathode, where they combine with oxygen from the air and electrons from the external circuit to form water and heat.

Solid oxide cells are like hydrogen cells in reverse. In SOFCs, oxygen grabs electrons streaming into the cell via the cathode, creating negatively charged oxygen ions. These ions migrate across a ceramic membrane, typically a substance such as yttria-stabilized zirconia (YSZ) that conducts oxygen ions well. At the anode, the oxygen ions react with a variety of hydrocarbons to produce electricity, water, and carbon dioxide.

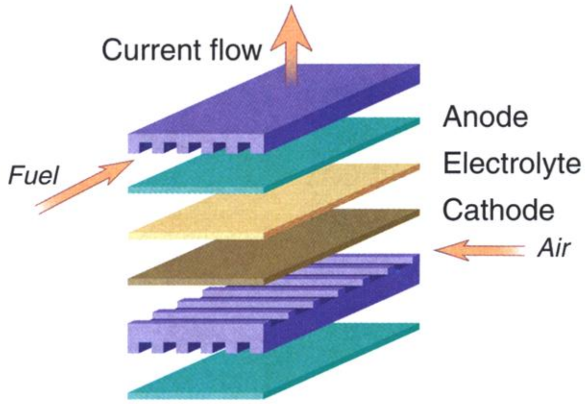
The problem is that besides ripping apart hydrocarbon chains, SOFC nickel anodes often weld together carbon atoms in the hydrocarbon shards instead of allowing them to bind with oxygen to form CO_2. These sooty fragments tend to stick to the anode. "That more or less destroys your fuel cell," says Scott Barnett, an SOFC expert at Northwestern University in Evanston, Illinois.

Unless the hydrocarbon feedstock is reformed first, the carbon deposits will accumulate at temperatures—around 1000°C—typically needed to jiggle the oxygen ions enough to force them through the ceramic membrane to the anode. To make it easier for oxygen ions to get to the anode, Barnett and his colleagues used an atomic spray-painting technique to grow YSZ membranes just 5 millionths of a meter thick, much thinner than the standard 150-micrometer membranes. Oxygen ions could slip through this ultrathin membrane at temperatures closer to 600°C. But nickel anodes are dormant at these temperatures, so Barnett's group had to be doubly innovative: They also developed a nickel-spiked cerium-oxide anode that works at lower temperatures than nickel alone.

The lower operating temperature has two payoffs: It reduces carbon crud buildup and cuts down heat stress on the apparatus itself. That means engineers should be able to build fuel cell components from steel rather than expensive heat-resistant alloys, says Singhal. And that, in turn, should lower the cost of the devices.

Other designs are breaking ground, too. In the 16 March issue of *Nature*, Raymond Gorte and his colleagues at the University of Pennsylvania in Philadelphia describe a different way of reducing carbon buildup. Instead of a nickel-containing anode, they developed one from copper laced with either cerium or samarium oxide that doesn't promote the formation of carbon-carbon bonds. They also slimmed down their YSZ membrane—to about 60 micrometers—to enable the cell to run at around 700°C. By going to an even thinner YSZ membrane like that used by the Northwestern group, Gorte says, the researchers should boost their cell's performance even further.

The most novel approach so far comes from a team in Japan. On page 2031, Takashi Hibino of the National Industrial Research Institute of Nagoya and his colleagues at Nagoya University describe a unique fuel cell design in which the hydrocarbons and air are pumped into a single chamber, where they surround the electrodes and electrolyte membrane, which is a single wafer made primarily of cerium dioxide. One side of the membrane is dabbed with nickel and serves as the anode, while the other side, the cathode, is a ceramic composite of samarium, strontium, cobalt, and oxygen. The cathode passes extra electrons to the oxygen to form oxygen ions, which migrate through the membrane to the anode. There the oxygen ions react with carbon monoxide and hydrogen—the two molecules produced when gaseous hydrocarbons are broken down by the anode—to form CO_2, water, and electricity.



Stacking the deck. Using layers of fuel cell elements, planar setups should generate more power per unit space than other designs.

Hibino's team found that their fuel cell works well at around 500°C. Besides deterring hydrocarbon buildup on the anode, the samarium-doped cerium oxide membrane at cool temperatures is a far better oxygen-ion conductor than the standard YSZ membrane. Singhal warns, however, that it may take years of engineering tinkering to scale up this and other cutting-edge SOFC designs for industrial use.

Further along in the pipeline are the fuel-reforming SOFCs. The 900-pound gorilla in this arena is a fuel cell, developed by Siemens Westinghouse, that reforms natural gas into hydrogen. After 3 decades of engineering improvements, Westinghouse has unveiled a new design that uses hot, pressurized exhaust gases from a network of fuel cells to drive a microturbine generator, which produces electricity on top of that already generated by the cells themselves. In a test of their 220-kilowatt cogeneration system this spring, the company reported converting nearly 60% of the energy in natural gas to electricity—an efficiency higher than that achieved by any power plant ever built, according to Williams. And that, he says, "is a remarkable achievement." Westinghouse intends to build a larger version—packing around 1 megawatt—that could replace conventional power plants. And because the cogeneration cell emits only a fraction of the sulfur, nitrogen oxides, and CO_2 of a conventional coal- or gas-powered plant to yield a proportional amount of energy, says Williams, it would be more benign to the environment.

As promising as the cogeneration cell sounds, the design may be the first and last of its kind. That's because other companies are hot on the trail of a potentially more promising approach: "planar" SOFCs made up of stacks of fuel cells, each consisting of thin electrode slabs with electrolyte membranes in between. Such stacking should generate as much as 10 times the power put out by an equivalently sized SOFC of the Westinghouse design, says Williams. Proponents of the planar technology argue that this could drop the price of a kilowatt of generating capacity from $1000—Westinghouse's target for its cogeneration—to $400, in the ballpark of power plants that run on natural gas.

At the moment, planar SOFCs are small-scale demos putting out tens of kilowatts. That may not last long, as the U.S. government is stepping up its backing of this and other SOFC technology. Earlier this month, the Department of Energy launched a new program—the Solid State Energy Conversion Alliance—to grease the wheels for commercializing such fuel cells. The aim of the $35-million-a-year program, says Singhal, is to get companies to blend recent advances in SOFC materials and design with low-cost manufacturing techniques honed in the semiconductor industry and elsewhere. If successful, he says, within a decade fuel cells that run on natural gas and other abundant fossil fuels should be on the market. Until there's an infrastructure for storing and distributing hydrogen gas, that should make SOFCs the biggest game in town.

–ROBERT F. SERVICE