

POWERING *an* ENERGY REVOLUTION

Fuel Cells Promise Improvements in
Transportation, Electronics and
Power Generation

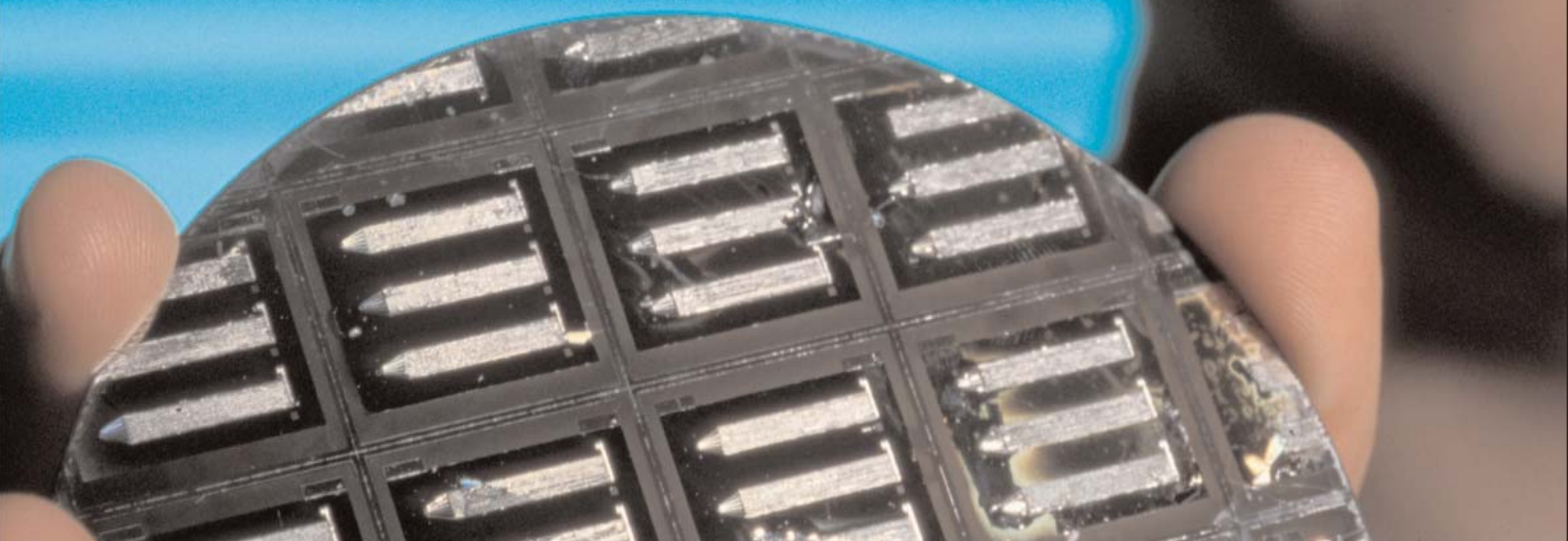


PHOTO BY GARY MEEK

FUEL CELLS

Imagine

cell phones that don't quit in mid-conversation because the batteries have died, laptop computers that run all day without power cords, efficient automobiles that emit virtually no nitrogen oxide or hydrocarbon pollutants, tiny self-powered sensors built on integrated circuits, soldiers of the future able to operate behind enemy lines without leaving a trail of spent batteries, and home electrical systems that keep working even if the power grid fails.

Above: Christopher Moore, a graduate student in Georgia Tech's School of Chemical Engineering, holds a silicon wafer containing micro fuel cells. The cells will convert methanol into electricity to power integrated circuits, which would also be fabricated on the silicon wafer.

The common denominator for these dreams is a 160-year-old innovation known as the fuel cell. By directly converting chemical energy to electrical energy, fuel cells promise a revolution in transportation, distributed power generation and electronic devices of all types.

As part of an integrated program, focused by the Center for Innovative Fuel Cell and Battery Technologies, Georgia Institute of Technology researchers are advancing a broad range of fuel cell technologies. With support from private corporations and federal agencies, these projects will help turn fuel cell visions into reality – some by the end of this decade.

Already, fuel cells boast a 30-year history of powering space missions. They also now run small numbers of demonstration buses, automobiles and stationary power units. But before fuel cells can compete economically with today's electrical generation technology, internal combustion engines or even batteries, dramatic improvements must be made in performance and cost.

Why Fuel Cells?

First demonstrated in 1839, fuel cells produce electricity by separating the electrons of hydrogen from their protons. In the simplest form, hydrogen gas flows into an electrode (the anode), where a platinum catalyst separates the electrons from the protons. The positively charged protons pass through a membrane into another electrode (the cathode), where a catalyst helps them combine with oxygen to form water. The electrons flow along a collection plate to produce electrical current that can turn motors, power lights or produce heat.

Traditional power plants and engines burn fuel to extract its chemical energy, using hot gases to spin turbines, create steam or move pistons. Multiple conversions from chemical to thermal to mechanical to electrical energy waste power in these “heat engine” systems. But because fuel cells convert chemical energy directly to electrical energy, they can be up to three times as efficient as today’s engines and power plants at extracting power from fuels.

Fuel cells also provide environmental advantages by avoiding combustion pollutants.

Fuel cells running on hydrogen – a potentially renewable fuel – produce only water, heat and electricity. But because hydrogen is inconvenient to store and transport, hydrocarbon fuels – natural gas, methanol, ethanol, gasoline and even diesel – are increasingly being used to power fuel cells, though they also produce carbon dioxide and often require a chemical reforming step. Still, because fuel cells are more efficient than combustion at extracting power, their carbon dioxide emissions are lower per unit of power produced. And nitrogen oxide emissions – a key component of ozone pollution – are near zero.

A single fuel cell generates less than a volt of electricity. To produce useful voltages, multiple cells must be combined into “fuel cell stacks” producing the specific voltages required for an application. This modularity provides another fuel cell advantage.

Along with key support infrastructure, Georgia Tech researchers are currently working on several types of fuel cells.

Because they can use a wide range of fuels with high efficiency, solid oxide fuel cells may be the power source of tomorrow – though they’re too expensive today. Polymer electrolyte membrane (PEM) cells are the choice today for transportation and distributed stationary power, though their robustness still needs improvement. Direct methanol fuel cells, a variation on PEM technology ideal for compact power applications, use liquid

methanol, which is easy to transport but currently lacks the efficiency of other cells. Alkaline fuel cells, used primarily in space and military applications, are being considered for specialized commercial segments, while existing products for electric utility applications use primarily phosphoric acid or molten carbonate fuel cells.

Lowering the Temperature, Lowering the Cost

Solid oxide fuel cells offer important advantages over other fuel cell technologies, including high efficiency and flexibility to use a range of hydrocarbon fuels without a reforming step. But those advantages come with a cost: Solid oxide fuel cells operate at 800 degrees Celsius, requiring use of expensive ceramic materials or alloys able to withstand the heat. Their operating efficiency suffers dramatically at lower temperatures.

Meilin Liu, a professor in the School of Materials Science and Engineering, is working on electrode technology that will reduce or eliminate the low-temperature efficiency penalty. His group focuses on providing a larger reaction surface area by reducing the size of pores in which reactions take place and through which reactants flow. Increasing the surface area accelerates the electrochemical reactions that produce electricity, and Liu is using that to compensate for the loss of efficiency caused by lowering the temperature. His electrodes operate at 500 degrees C, allowing him to use less costly materials, such as stainless steel, without compromising performance.

“To efficiently release the electrical energy, we need the electrochemical reactions to occur very fast,” he explains. “One way to facilitate the electrochemical reactions is to increase the surface area of the electrode. We can do that by making very fine pores. But if the pore size becomes too small, gas transport into and out of the electrode becomes difficult.”

His “functionally graded” electrodes not only display high catalytic activities for fast electrode reactions, but also have optimum architecture for rapid gas transport, dramatically reducing the internal losses at low temperatures. Beyond cutting materials costs, lowering the temperature could also extend fuel cell life and improve reliability.

Ultimately, Liu sees solid oxide fuel cells powering individual homes, replacing the furnace and hot water heater – and allowing homes to operate apart from the local power grid. “You would get higher efficiency, so you would need less natural gas to produce the same amount of useful energy,” he notes. “The fuel cell would also produce much less pollution compared to a furnace.”

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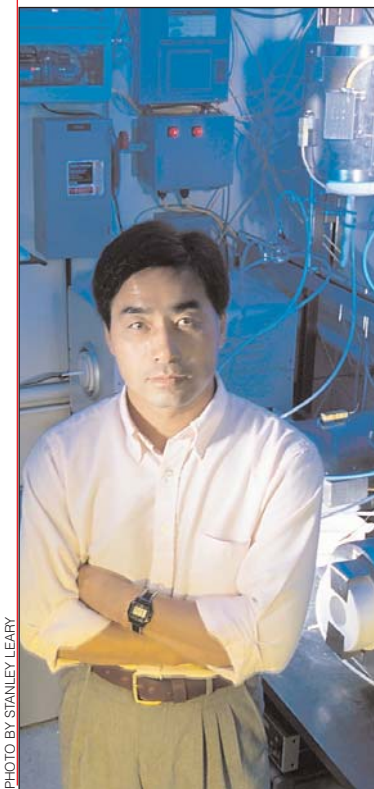
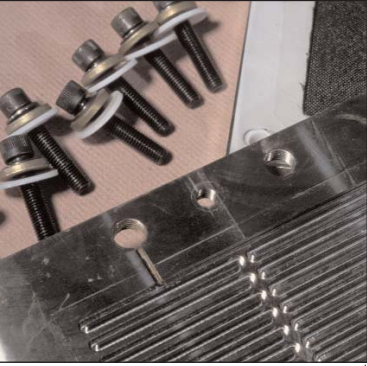


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Georgia Tech researchers have designed and fabricated a broad range of fuel cells. Shown are the stainless steel current collector and other components of a 100-watt fuel cell stack.

Solid oxide cells can directly use natural gas and methanol. With additional fuel reforming, they can also operate on gasoline or diesel fuel, which could make them ideal for transportation applications, where they would be more efficient than PEM cells.

But there is a long way to go before fuel cells can compete economically, says Liu, who is co-director of the Center for Innovative Fuel Cell and Battery Technologies. The capital cost for solid oxide fuel cells now tops \$6,000 per kilowatt, compared to \$400 for conventional power plants.

Liu's lab supports 11 Ph.D. students and seven post-doctoral students or visiting scientists with funding from several corporations and federal agencies, including the National Science Foundation (NSF), National Energy Technology Laboratory (NETL), U.S. Department of Energy (DOE), Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR).

Powering the Electronic Soldier

Sensors, electronic weapons and communications gear have become vital to soldiers in the field. The technology provides a key advantage, but also comes with a cost: power requirements that are becoming more and more difficult to meet with existing battery technology.

Miniature fuel cells could help meet the power needs of future soldiers, freeing them from the burden of battery packs and chargers, and the problems of spent batteries. Through funding from DARPA, a group of Georgia Tech researchers is developing a 20-watt, low-temperature solid oxide fuel cell based on advanced manufacturing technologies and Liu's new materials and functionally graded electrodes. The research team includes Joe Cochran, Jim Lee,

Meilin Liu,
Dave McDowell

and Tom Sanders

from the School of Materials Science and Engineering and the Woodruff School of Mechanical Engineering.

Researchers at the Georgia Tech Research Institute (GTRI) are addressing the system engineering issues surrounding compact fuel cells for soldiers and larger systems for transportation and distributed generation. "The fuel cell is more than a magical electrochemical stack that converts fuel to electricity," notes David Parekh, director of GTRI's Aerospace,

Transportation and Advanced Systems Lab and director of the Center for Innovative Fuel Cell and Battery Technologies. "You also have to provide fuel processing on the front end, and power electronics on the other end to convert direct current to alternating current or to regulate voltages for DC applications. And you have to integrate and manage all the components as a complete system."

GTRI contributes its long experience with engineering military systems to the initiative. Beyond Parekh, the GTRI fuel cell initiative involves more than a dozen full-time researchers, several technicians and numerous students. Building on Georgia Tech's broad capabilities, it has developed strategic partnerships with leading private sector producers of fuel cell technology, such as UTC Fuel Cells and Motorola.

"We have developed a symbiotic relationship with Motorola in developing power electronics targeted toward a direct methanol fuel cell the company is developing," says Allan Williams, a GTRI senior research engineer. "It's very much a two-way street. We help them develop aspects of their product, and they help us develop components of systems that interest us."

Parekh's group also focuses on a unique combination of fuel cells, batteries and capacitors to power small-scale sensing applications. The combination provides the best of all worlds – sustained power from the fuel cell, power storage from the battery and bursts of peak power from the capacitor for transmitting data. Unattended sensors, remote communications devices and unmanned aerial vehicles need such a combination.

"We saw several applications that required not only the ability to deliver power efficiently, but also to deliver large amounts of power instantaneously," Williams says. "We needed to not only have fuel cells, but also to overcome their inherent limits on delivering large amounts of power without building large cells. By bringing the fuel cell together with the electrochemical capacitor, we were able to meet that need."

Parekh's group has also investigated tiny hybrid systems based on as few as one fuel cell and one tiny coin battery that could be optimized based on power and size needs.

In another project, research engineer Gary Gray is working on the problem of properly controlling moisture in PEM fuel cells. "The polymer electrolyte is only conductive when it has a certain amount of water absorbed into it," he explains. "Water management in this system is really critical because if you let it dry out, the whole stack loses power. But if too much water accumulates, you have trouble getting the hydrogen and oxygen in."

A tiny tube extends from a single silicon die containing a micro fuel cell. In laboratory testing, the tube will carry methanol fuel to the cell for conversion to electricity. The electricity will power an integrated circuit built on the same silicon die.

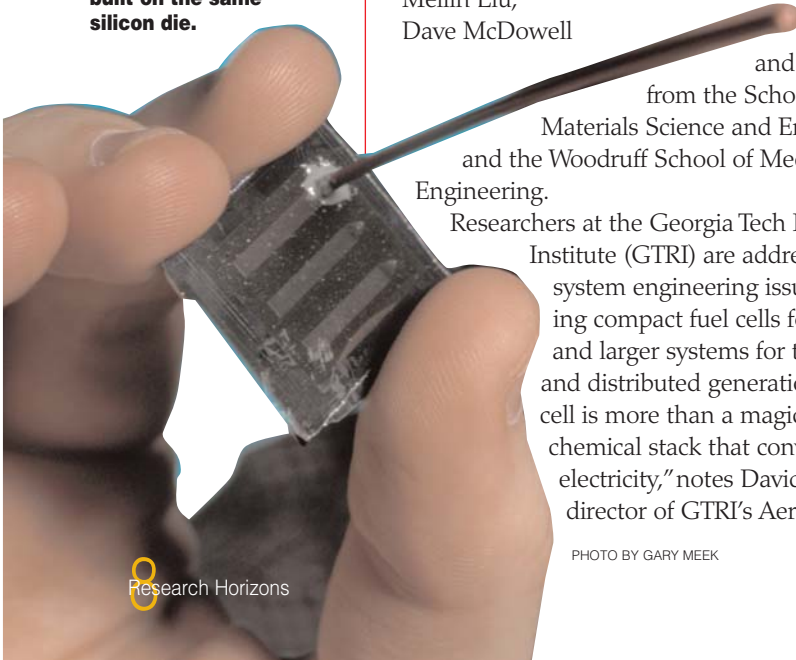


PHOTO BY GARY MEEK

Gray hopes to develop a novel water and gas flow modulation system based on testing done with a 100-watt fuel cell stack built in GTRI. The system also includes a fuel reforming system that produces hydrogen from methane.

Micro Fuel Cells Integrated on a Chip

The smallest part – in physical dimensions – of the Georgia Tech fuel cell program is a project to incorporate a tiny fuel cell into a microelectronic package that would include an integrated circuit and sensor. The system might operate unattended for up to a year, sniffing for dangerous gases or listening for vibrations from approaching vehicles.

The micro fuel cell would operate on a solution of methanol and water, using a unique membrane developed by researchers at Case Western Reserve University.

Integrating all three devices into one package potentially makes fabrication more efficient and allows different components to work together. For instance, air brought in to operate the fuel cell could also cool the integrated circuit and provide the flow for the gas sensor, notes Paul Kohl, a professor in the School of Chemical Engineering. Metal layers deposited for the integrated circuit could also produce the fuel cell electrodes.

But co-fabricating the components on a silicon chip adds to the design challenge. Traditional microelectronics fabrication techniques operate at temperatures that would damage the polymer membrane of the fuel cell. Building air channels small enough goes beyond what is known about small-scale fluid flow. And to avoid using precious electricity for pumping, a micro-scale clock spring may be used to maintain pressure inside the fuel tank.

Beyond the fabrication challenges, Kohl and his team must also overcome limitations in fuel cell efficiency. Because methanol can cross over from

the anode to the cathode, existing methanol fuel cells use dilute fuel – which limits power production to as little as two-tenths of a watt in a cell this small. Boosting the methanol concentration would produce more power, or allow use of a smaller fuel tank.

“We have to get all the materials and components to work well together,” Kohl notes. “We also have a multi-dimensional challenge of how to design an efficient cell. There are a lot of trade-offs.”

Sponsored by DARPA, the project also includes Peter Hesketh, a professor in the School of Mechanical Engineering, and Christopher Moore, a graduate student in the School of Chemical Engineering. Beyond the sensor, Kohl hopes the micro fuel cell technology will ultimately have applications in larger equipment such as cellular telephones or laptop computers.

Cutting Catalyst Cost Through Fractals

Fuel cell technology works best and pollutes least when powered by pure hydrogen, but hydrogen is inconvenient to transport and store. So there is strong interest in hydrocarbon fuels – such as gasoline or methane – from which hydrogen can be produced through a catalytic reforming process. But the cost of catalytic metals – platinum or palladium – poses a serious obstacle in the drive to make fuel cells economical.

Andrei Fedorov, a professor in the School of Mechanical Engineering, hopes to cut the amount of catalyst needed by as much as 70 percent by putting the particles only where they do the most good.

“Intuition tells you that you want to have the maximum catalytic surface area,” he notes. “But you actually need to have it only at strategic places on the surface. We are placing the catalysts in such a way that we can use much less of the expensive materials while not compromising the reaction chemistry.”

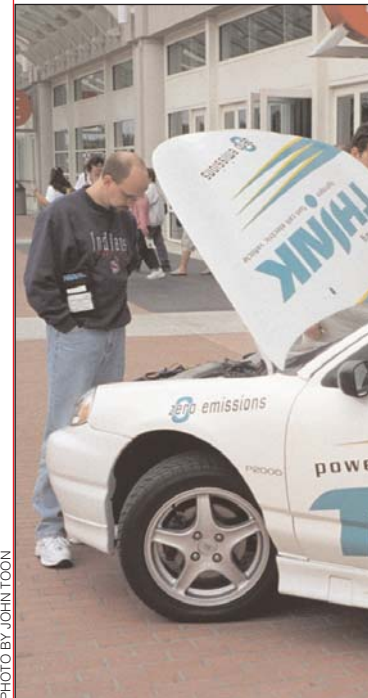


PHOTO BY JOHN TOON

In California, automobile manufacturers and fuel companies are working together to demonstrate transportation uses of fuel cells. Visitors to the National Science Teachers Association annual meeting in San Diego had an opportunity to drive and examine this prototype fuel cell vehicle.

Center for Innovative Fuel Cell and Battery Technologies

Georgia Tech's Center for Innovative Fuel Cell and Battery Technologies pursues a four-part mission: (1) to be a catalyst for developing revolutionary fuel cell and battery technologies, (2) to create partnerships with leading industry and government organizations to advance the technology, (3) to educate industry professionals, university students and budding K-12 scientists, and (4) to serve as a magnet for economic development.

Center Director David Parekh and his colleagues seek to develop a broad suite of key technologies needed to enable major advances for the fuel cell and battery industry. “Companies out of necessity are going to have to freeze the concepts they are bringing to market and focus development narrowly along their product lines,” he notes. “We want to focus longer term on embryonic technologies that could produce broad advances. There are pieces of the technology that all of them will need, whether it's advanced materials, power electronics, fuel processing or distributed generation protocols. There is a real opportunity for Georgia Tech to develop innovations that could address those needs.”

■ For more information, you may visit the Center's Web site at www.fcbt.gatech.edu or contact Parekh at 770-528-7826, or by e-mail at david.parekh@gtri.gatech.edu.



PHOTO BY GARY MEEK

Gary Gray (left) and Comas Haynes analyze fuel cell components under development in the Georgia Tech Research Institute. Behind them is a reformer that produces hydrogen from natural gas.

“As we get into fabricating fuel cells in large volumes, that is going to drive the cost down just like it did with integrated circuits. I believe we will make fuel cells very competitive economically. And that will happen in the next five to 10 years.”

The science of fractals may guide placement of the catalytic particles, an approach Fedorov and his students are studying through computer models and for which they hope to have experimental verification soon. Their placement technique could also help cut the costs of fuel cells themselves, which also use costly catalysts.

With support from Air Products and Chemicals, Inc., Fedorov's group also explores the unique issues involved in small-scale fuel reforming systems that might be used in laptop computers or cellular telephones. “There is a lot of difference between a large system and a small system in the kinetics of reactions, mitigation of heat transfer and mass transfer,” he says. “There is a lot of room for imaginative solutions here.”

He expects such portable electronics to be an important early application for fuel cells because the disadvantages of their existing power source – batteries – are well known. “Lowering the costs will make fuel cells more attractive than batteries within the next decade, with some applications for fuel cells powering portable electronics available in two or three years,” he predicts.

Modeling Guides Experiment

New technologies must ultimately be proven experimentally, but computer models can help researchers choose the most promising path and evaluate options. Which materials would be best for specific conditions? What combination of fuel cell stacks and traditional gas turbines would provide the optimal mix of power and reduced emissions? How will fuel reforming systems, fuel cells and power conditioning systems work together? When should a fuel cell stack be shut down for maintenance?

Bill Wepfer, Comas Haynes and their graduate students work closely with Georgia Tech's experimental researchers to provide that kind of guidance, using a detailed knowledge of thermodynamics, heat transfer and energy.

“Our models can tell other researchers what properties are needed in new materials, and what kinds of systems will produce what kinds of outputs,” says Wepfer, a professor in the Woodruff School of Mechanical Engineering and chair of the school's graduate studies department. “Modeling complements prototype testing because once you do the systems tests and calibrate your models, you can use the modeling to tremendously enhance the understanding and save time from routine testing.”

Haynes, a GTRI researcher, is applying unique Lagrangian modeling techniques to study the impact of transients on the electrochemical and

thermal characteristics of fuel cells. The modeling gives clues about what might happen under difficult conditions, such as when a generator must shut down suddenly or a load increases rapidly. It can also help predict the useful life of fuel cells by looking at the kinds of materials failures likely to occur and their impact on performance.

The Fuel Cell Road Ahead

With increased funding from Washington and growing corporate investment, fuel cell research and development is accelerating. In California, automobile manufacturers and fuel companies work together to demonstrate transportation uses of fuel cells. Large equipment companies like UTC Fuel Cells and Siemens Westinghouse have already demonstrated stationary fuel cells that operate reliably for five years or more, and many other companies like Motorola, Honeywell and Delphi are investing for their market areas.

How long will it be before we replace the furnace with a fuel cell, drive fuel cell cars or refuel our fuel cell-powered phones instead of recharge them?

“There are fundamental materials science and chemistry discoveries ahead that will lead to the kinds of reductions in cost and improvements in performance that will make fuel cells a reality,” says Wepfer, who has been working on energy systems since the 1970s. “A lot of organizations, both in government and the commercial world, are investing in fuel cells.”

He believes Georgia Tech is uniquely qualified to contribute to fuel cell development because of its broad-based expertise in materials, chemistry and chemical engineering, and manufacturing – all disciplines needed to make key advances.

Meilin Liu expects to see significant commercial use of the technology within a decade, perhaps sooner, thanks to economies of scale.

“As we get into fabricating fuel cells in large volumes, that is going to drive the cost down just like it did with integrated circuits,” he says. “I believe we will make fuel cells very competitive economically. And that will happen in the next five to 10 years.” **RH**

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