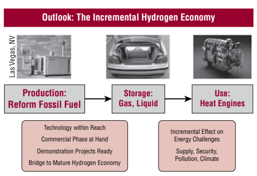
Argonne NATIONAL LABORATORY

Volume 6, No. 1
Summer 2006

TransForum™

News From Argonne's Transportation Technology R&D Center

www.transportation.anl.gov



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VIEWPOINT

Two Hydrogen Economies Needed to Address World Energy Challenges

Not one, but two hydrogen economies are needed to adequately address the world's energy challenges and provide the greatest advantages – a near-term, incremental hydrogen economy within technological and commercial reach and a mature hydrogen economy, in which basic research breakthroughs are within reach. ***Page 2***

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RESEARCH REVIEWS

Argonne Engineers See into the Future of Hydrogen Internal Combustion Engines

Images of hydrogen combustion have been captured for the first time in an internal combustion engine operating at real-world speeds and loads by engineers at Argonne. DOE EERE Assistant Secretary Andy Karsner with Steve Chuslo, also from EERE, tour Argonne's energy efficiency labs and facilities. ***Page 3***

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Market-Ready Hydrogen Sensor Promises "Ultra" Performance

A tiny new hydrogen sensor developed by Argonne researchers can sense hydrogen at extremely low concentrations — as low as 25 parts per million — and very rapidly (in less than 70 milliseconds) without elaborate amplification of the signal. Based on nanostructured self-assembled palladium thin films, it is a true example of a ready-for-market product of nanotechnology. ***Page 4***

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Hydrogen + Advances in Fuel Cell Technology = Clean, Efficient Transportation

Hydrogen is an ideal energy carrier for fuel cells, which offer a clean, efficient power source for transportation. Argonne works closely with the U.S. Department of Energy (DOE) to develop materials, processes, and systems for polymer electrolyte and solid oxide fuel cell systems, as well as hydrogen production, delivery, and storage options. ***Page 5***

THE UNIVERSITY OF CHICAGO

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Two Hydrogen Economies Needed to Address World Energy Challenges

Hydrogen is a compelling replacement for fossil fuels used in transportation for its clean, efficient propulsion of cars and light trucks using fuel cells whose only exhaust is ordinary water. A hydrogen economy that meets all our transportation fuel needs would greatly reduce emissions of pollutants that are harmful to human health and greenhouse gases associated with climate change. It would also save energy in the process.

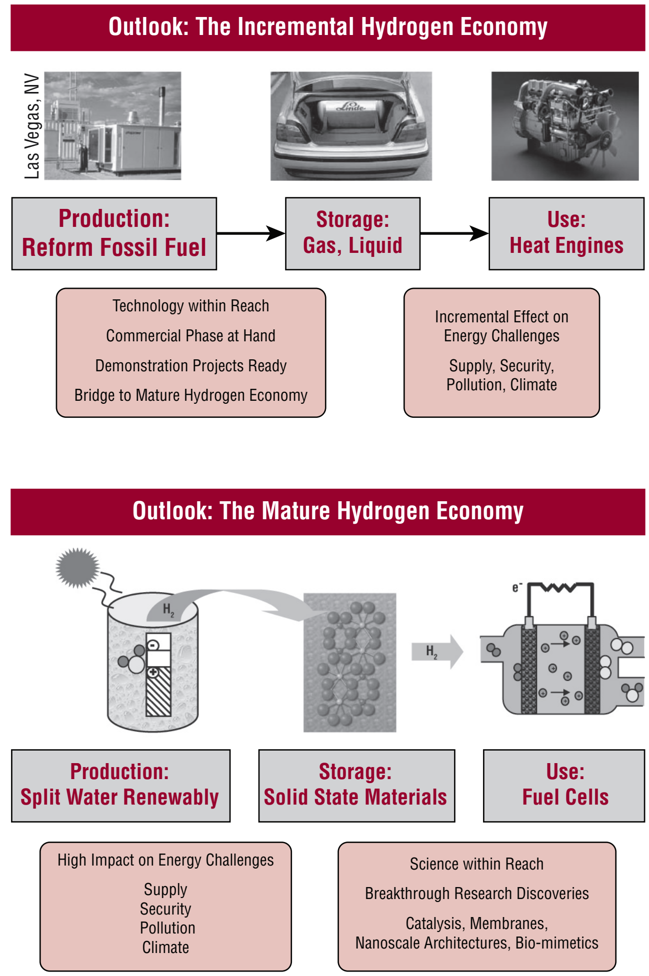
In fact, George Crabtree, Argonne Senior Scientist and Director, Materials Science Division, contends that two hydrogen economies actually are needed to adequately address these challenges and provide the greatest advantages.

First, a near-term, incremental hydrogen economy will be established using technology within commercial reach. "The incremental economy will make hydrogen from fossil fuels as we do now, store hydrogen as liquid or compressed gas, and burn hydrogen in internal-combustion engines or turbines for generating electricity. The energy impact will be minimal. It will use the same amount of fossil fuels, have little impact on efficiency, and provide the same CO_2 output. However, it rolls out the hydrogen economy, establishing an infrastructure and teaching us how to use it," he says.

"But to get the full energy benefits, we need a mature hydrogen economy, as opposed to an incremental one," Crabtree explains. "To develop it, we need basic research to learn how to produce hydrogen by splitting water renewably, store hydrogen in solid compounds, and react it in fuel cells. This second economy is independent of fossil fuels. Hydrogen fuel cells will offer twice the efficiency of internal-combustion engines."

Crabtree notes that Argonne is currently working on the technology advances needed to achieve the incremental hydrogen economy as well as the basic research breakthroughs needed for the mature hydrogen economy. Before the two hydrogen economies can become a reality, however, scientists face research challenges in catalysis, membranes, nanoscale architectures, bio-inspired production, in situ experiments, and theory/simulation.

Advances being explored to promote the incremental economy include new and improved ways of reforming fossil fuel (see related article on pp. 5-6), storing hydrogen as a gas or liquid, and enhancing combustion in heat engines. New basic research initiatives are laying the foundation for the mature hydrogen economy. For example, Argonne scientists have discovered a route to significantly enhance the catalytic activity of platinum (Pt) in hydrogen fuel cells. They found that alloys like platinum cobalt (Pt_3Co) are more active than pure Pt for reacting hydrogen and oxygen to produce water at the fuel cell cathode. Alloying tunes the strength of the oxygen bonds and thus the catalytic activity through a volcano-shaped peak. The catalytic activity at the peak for Pt_3Co is a factor of two larger than for Pt without alloying.



The Two Hydrogen Economies

Ultimately, the success of the two hydrogen economies depends on whether emerging hydrogen technology will provide more value than today's fossil fuels. While the market will ultimately decide the fate of the hydrogen economies, government can play a critical role in introducing hydrogen technology. The large R&D investments, the uncertain outcome for new approaches, and the long timeline to payoff often deter market investment. As a result, early government investments in setting goals, offering research support, and sharing risk are essential to cultivating viable, market-driven incremental and mature hydrogen economies.

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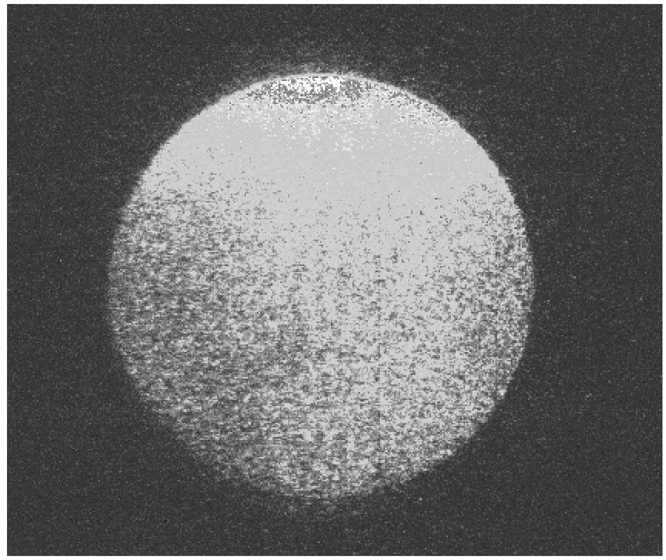
Argonne Engineers See into the Future of Hydrogen Internal Combustion Engines

Images of hydrogen combustion have been captured for the first time in an internal combustion engine operating at real-world speeds and loads by engineers at the U.S. Department of Energy's (DOE) Argonne National Laboratory. This window into the inner workings of a hydrogen-powered engine is helping to optimize the engines for use on the streets.

"Hydrogen-powered internal combustion engines (ICEs) are a low-cost, near-term technology," explains mechanical engineer Steve Ciatti, who is the project's principal investigator. "They can be the catalyst to building a hydrogen infrastructure for fuel cells."

Some automakers are already viewing hydrogen ICEs as a near-term bridge to the use of fuel cells in vehicles, according to Ciatti. Both Ford and BMW already have demonstration fleets gathering data.

"Hydrogen ICEs can ease the transition to fuel-cell powered cars," Ciatti says. "We're envisioning a two-step conversion to hydrogen. Using hydrogen ICEs as a stop gap will give consumers a chance to adapt to a new hydrogen economy in steps as the new infrastructure is phased in. With these engines, they will still pump fuel into their cars."



This full-combustion image of OH shows the number of H + O = OH* reactions that occur inside a direct-injection hydrogen engine. It provides a qualitative assessment of where (areas in white, red, and green) and how rapidly those combustion reactions occur. The image was taken at 3,000 RPM and with 6 bar indicated mean effective pressure (IMEP), which is about 75% load. The engine was fueled by gaseous hydrogen using a port fuel injector.*

By using imaging tools and other standard engine measurement devices on a Ford Motor Co. single-cylinder, direct-injection hydrogen engine, Argonne mechanical engineers Ciatti, Henning Lohse-Busch, and Thomas Wallner are optimizing engine operation and identifying the root causes of combustion anomalies, such as pre-ignition and knock. These problems are more pronounced at high speeds and high loads. Argonne researchers observe 50 performance measurements during each engine test.

Researchers use ultraviolet imaging to capture images inside the running engine. "Hydrogen's visible radiation signature is barely discernible, so we focused on the chemical reactions of hydrogen and oxygen, called OH* chemiluminescence, in the engine," Ciatti says. These reactions emit photons in the ultraviolet energy range, and that light is captured and analyzed with specialized optics.

"Hydrogen ICEs are a lot like gasoline engines, except the fuel is gaseous instead of liquid," Ciatti adds. Hydrogen has wide flammability limits, so the engine does not need a throttle, a device that chokes the air/fuel mixture to control the engine power and hampers efficiency (a standard car today is 25 percent efficient; a hydrogen car will be close to 45 percent efficient), nor do they require exhaust after-treatment when operating correctly.

"The unique properties of hydrogen fuel (wide flammability limits and ignition characteristics) are exciting because you can do things with hydrogen that you can't do with hydrocarbons," Ciatti says. "For example, you can use direct injection (spraying the fuel directly into the combustion chamber), so the efficiency goes up and the power density goes up, but unfortunately, the complexity goes up as well."

Researchers are also determining the most efficient and cleanest way to run the engine without knock or pre-ignition, another technical challenge. Because of its nature, hydrogen easily combusts, so researchers are experimenting with a multiple-injection approach. They are injecting hydrogen directly into the cylinder once or twice during each combustion cycle, depending upon operating conditions. The goal is to determine the optimum timing and amount of hydrogen injected during each cycle. The wrong mixture of hydrogen causes engine operation and emission problems. The researchers are also experimenting with prototype injectors. Making them is a materials science and engineering challenge because the operating atmosphere is unusually hot and under high pressure. Sealing and cooling the injector become critical tasks.

"Working with a single cylinder allows us to isolate problems so we don't have four cylinders to track through to see where and how problems started," explains Ciatti. "We plan to solve problems in the single cylinder and then try them out in a four

Top: DOE EERE Assistant Secretary Andy Karsner experiences "driving" a vehicle on Argonne's four-wheel-drive dynamometer in August 2006. This unique DOE facility can test a wide variety of advanced vehicles, including those with hydrogen engines and fuel cell vehicles.

Bottom: EERE's Andy Karsner (r- center) and Steve Chuslo (r) learn about hydrogen engines with Argonne's Larry Johnson (l-center) and Don Hillebrand (l).

cylinder," says Ciatti. The mechanical engineering team has installed and is commissioning a 2.3-liter four-cylinder Ford hydrogen engine. Eventually, the team will integrate the four-cylinder engine into a flexible hybrid vehicle to test how the engine operates as part of a vehicle in Argonne's Advanced Powertrain Research Facility.

This research is funded by the DOE's Office of Energy Efficiency and Renewable Energy, FreedomCAR and Vehicle Technologies Program. Argonne researchers are collaborating with Sandia National Laboratories, Ford, BMW, and the European Hydrogen Internal Combustion Engine (HyICE) initiative.

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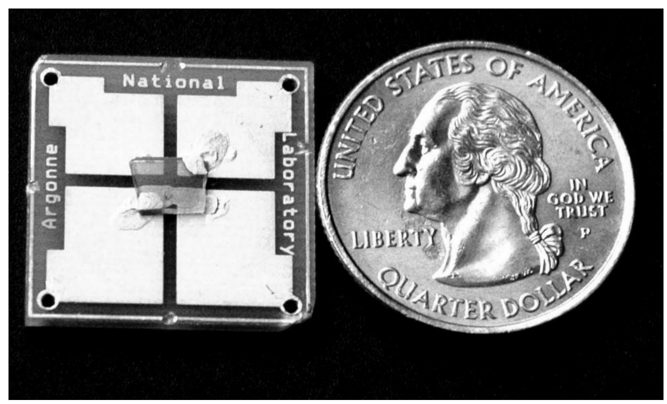
Market-Ready Hydrogen Sensor Promises "Ultra" Performance

"Ultra" means "beyond the ordinary" – and Argonne's new ultrafast and ultrasensitive hydrogen sensors deliver on that promise. Michael Zach, a Glenn Seaborg Postdoctoral Fellow in Argonne's Materials Science Division (MSD) and his colleagues Tao Xu and Zhili Xiao, also of MSD, have produced the tiny new sensors, which are based on nanostructured self-assembled palladium thin films.

The ultrafast and ultrasensitive sensors discovered at Argonne are true examples of a ready-for-market product of nanotechnology. "Our discovery is an enabling technology that will provide a fundamental safety component for our emerging hydrogen economy," states Zach. "They are much faster, more sensitive, simpler, and less expensive than any other existing hydrogen-sensing system. They also have low power requirements and require only simple monitoring of resistance, making them robust for many applications," he explains. The sensors can be manufactured by using easy, scalable techniques for mass production, which minimizes their cost.

As our nation pursues new fuels and technologies, hydrogen-based technologies will become more widespread in transportation – but using hydrogen involves safety considerations different from those of other fuels. Therefore, the need for cost-effective and reliable hydrogen sensors is growing, and Argonne's sensor may well set an industry standard for sensor performance in transportation and other applications. The sensor developed by Zach and his colleagues can sense hydrogen at extremely low concentrations – as low as 25 parts per million – and very rapidly (in less than 70 milliseconds) without elaborate amplification of the signal. Using only processes that are compatible with mass production and routinely used in the semiconductor industry, they have created the world's fastest



Argonne's novel hydrogen sensor.

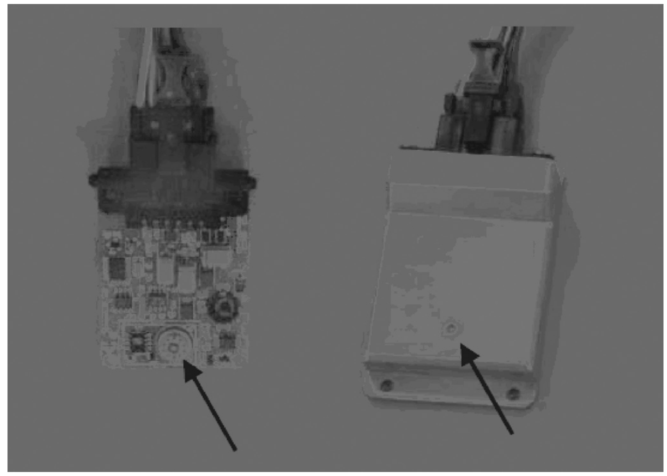
commercially producible hydrogen sensor. This simple, robust technology eliminates the need for heavy, bulky, and energy-demanding methods for detection. "And by adding electronic devices to activate safety systems when thresholds of hydrogen concentration have been reached, our technology can truly make a hydrogen economy safer than our fossil-fuel-driven economy," predicts Zach.

Here's a possible scenario: As hydrogen leaks from a damaged, malfunctioning, or improperly sealed automotive system, it will normally quickly dissipate to below the 4% lower limit of flammability. By using a sensor system that can detect a minor leak at one one-thousandth of a flammable concentration, it could alert the driver via a dashboard indicator light long before a more significant leak would develop. Says Zach, "If there's a more significant leak, or if hydrogen is leaking into an enclosed space where the concentration could build to greater than 4%, a very dangerous situation is about to occur. It's imperative to have an extremely rapid sensor that can shut off hydrogen at the tank in less than 100 milliseconds. When such safety devices are used, we can make hydrogen-powered vehicles much safer than the gasoline-fueled vehicles in use today."

Argonne's novel technology has sparked considerable interest from industry – companies interested in the technology range from start-ups to major international automobile manufacturers. For example, Argonne has teamed with Makel Engineering (Chico, California) to commercialize these sensors. "No other commercial technology works as fast, is as sensitive, or is as efficient as Argonne's technology, and those are some of the reasons why Makel Engineering has signed an exclusive license agreement with Argonne," asserts Zach.

Makel, a leader in high-quality hydrogen sensing for NASA's shuttle missions and other notable applications, will be employing Argonne's sensor design in a package developed for the automotive industry. This package combines robust signal processing, threshold detection, and redundant engineering to ensure safety. Combining Makel's proven electronic packages with Argonne's nanotechnology-based sensing elements will yield a simple, cost-effective, and highly marketable hydrogen-sensing unit. Makel has also secured funding for product development through Ohio-based Edison Materials Technology Center (EMTEC). "EMTEC will help to develop market-ready products based on Argonne's technology that will be widely commercialized in our automobiles and the fuel cells powering our homes," Zach notes.

With its ultrafast and ultrasensitive hydrogen sensor, Argonne is helping the nation meet its energy needs safely, cleanly, and responsibly. According to Zach, "Makel Engineering's confidence in Argonne's technology and EMTEC's product development expertise will help us deliver the technology needed to help ensure a safe and prosperous future."



Makel Engineering's electronics package for Argonne's sensor. Makel has developed a robust electronics package that is completely compatible with Argonne's sensor technology. The image on the left shows the circuitry that has been developed to provide threshold detection and continuous monitoring of the sensor condition. The arrows show the location of Argonne's sensing element. The image on the right shows the finished product, complete with the wiring harness and the packaging needed for installation in automobiles.

Argonne's extraordinary sensor was recognized with an R&D 100 award in 2006. The sensor's research was sponsored by DOE's Office of Science and Office of Basic Energy Sciences, State of Illinois, Makel Engineering, and Edison Materials Technology Center.

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Hydrogen + Advances in Fuel Cell Technology = Clean, Efficient Transportation

Hydrogen is an ideal energy carrier for fuel cells, which offer a clean, efficient power source for transportation. Argonne works closely with the U.S. Department of Energy (DOE) to develop materials, processes, and systems for polymer electrolyte and solid oxide fuel cell systems, as well as hydrogen production, delivery, and storage options.

Specifically, Argonne researchers are focusing on:

- Advanced fuel processing in integrated fuel cell power systems;
- Improved, lower-cost materials for fuel cells;
- Enhanced fuel cell designs; and
- Hydrogen production pathways, delivery system alternatives, and storage.

To support these R&D initiatives, Argonne's Fuel Cell Test Facility offers independent, standardized testing and evaluation of all fuel cell types for DOE and fuel cell developers. The only such facility in the national laboratory system, it is one of the few in the nation that can test full, automotive-sized systems.

Fuel Processing Innovations

Until hydrogen is readily available, fuel cells could operate on conventional fuels, such as natural gas, propane, gasoline, and diesel, or alternative fuels, such as methanol, ethanol, and biodiesel. Such fuels can be converted to hydrogen or a hydrogen-containing gas mixture through a series of chemical reactions in fuel reformers (also known as fuel processors).

Several Argonne R&D initiatives in fuel processing are under way. In one effort, a team of scientists and engineers has developed and patented a compact fuel processor that reforms conventional fuels into a hydrogen-rich gas to power fuel cells. The device is energy efficient, capable of rapid start-up and shut-down, and dynamically responsive to load changes. Sud-Chemie (Louisville, Kentucky) has licensed the reforming catalyst technology.

Argonne researchers are also exploring technology to reform diesel fuel for use in fuel cell applications. For instance, tractor-trailer trucks soon could be using diesel to create the hydrogen needed for clean, quiet, fuel-cell-powered auxiliary-powered units (APUs). The APU would generate power for air conditioners and other hotel loads when the main engine is shut off. The researchers are collaborating with three university teams to address materials and fuel processing issues.

Argonne's Fuel Cell Test Facility, operational since 1998, has capabilities for evaluating full-size automotive fuel cell stacks and complete reformer/fuel cell systems with power rating of up to 80 kW. Shown here: Engineers check a proton-exchange-membrane (PEM) fuel cell stack before starting a test.

In yet another effort, Argonne is developing a ceramic membrane to efficiently and inexpensively extract hydrogen from fossil fuels. The membrane operates at higher temperatures and under low-humidity conditions to reduce system cost, size, and complexity.

More Durable Materials

A major hurdle to commercializing polymer electrolyte fuel cell systems, especially for automotive use, is the high cost of the cell's platinum electrocatalysts. To address this barrier, Argonne chemists are working on low-cost, non-platinum electrocatalysts (employing bi-metallic base metal/noble metal systems) for the oxygen-reduction reaction. These durable materials would be stable in the fuel cell's operating environment and retain high electrochemical activity over the fuel cell's design lifetime.

Better Fuel Cell Design

Improved fuel cell system design results in better operation and lower cost. GCtool and PSAT modeling software, created at Argonne, enables researchers to easily evaluate a myriad of fuel cell system designs, energy storage requirements, fuel economy, etc.

For solid oxide fuel cells, TuffCell, a novel design and fabrication process, decreases the stack cost and improves the mechanical strength, thermal cyclability, and seal durability. The design supports the cell on a rugged, inexpensive metal. TuffCell offers promise in APU applications for heavy-duty vehicles, enabling truck drivers to meet anti-idling legislation while improving their overall fuel economy.

Hydrogen Production, Delivery, and Storage

Argonne transportation analysts are evaluating various production and delivery system combinations to identify the best in terms of cost, safety, and energy efficiency. Their efforts were recognized in May with a DOE Hydrogen Program R&D Award "In Recognition of Outstanding Achievement in Delivery Analysis." (See FasTrax.) Researchers also are focusing on carbon-based materials for storage and analyzing hydrogen storage systems. A novel group of hydrogen adsorbent materials (nanostructured polymer and carbon) were developed with highly ordered layer structure on interstitial spaces at the nanometer scale. These materials were found to absorb significant quantities of hydrogen non-dissociatively via an enhanced van der Waals interaction.

The R&D initiatives described in this article are sponsored by DOE's Offices of Science, Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy.

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Looking Down the Road

We've decided to take a slightly different approach with this issue of *TransForum*. All the articles focus on one key research area that is expected to bring unprecedented change to the transportation industry. That very important area is – as you may have surmised – hydrogen.

The challenges associated with meeting the world's energy needs and the increasing demands for "clean" energy sources – sources that do not add more carbon dioxide and other pollutants to the environment – have resulted in increased attention worldwide to the possibilities of a "hydrogen economy" as a road to a secure energy future. In fact, two hydrogen economies – one incremental, the other mature – may be needed to successfully achieve this desired destination. (See *Viewpoint.*)

Some of the architects of that future are working right here at Argonne. From conducting fundamental basic research in catalysis to capturing images of hydrogen combustion in an internal combustion engine to developing ultrafast sensors for hydrogen vehicles, our scientists and engineers are working with our partners on the dramatic breakthroughs needed to achieve the lower costs, higher performance, and greater reliability that are needed for a competitive hydrogen economy.

Please read their stories and contact us if you would like more information about their work or are interested in partnering with Argonne to help build a more secure energy future.

Larry Johnson
Director
Argonne Transportation Technology
R&D Center

FASTRAX

Michael Wang was honored as the runner-up in the "New Methods and Tools" category of the prestigious Society of Automotive Engineers' (SAE's) International Environmental Excellence in Transportation (E2T) Awards. The awards were presented during the SAE Government/Industry Meeting in Washington, D.C. on May 8–10. Wang, of Argonne's Center for Transportation Research, received the award for developing the GREET software tool, used to evaluate the energy and emission impacts of advanced vehicle technologies and new fuels. The model considers the full fuel cycle – from well to wheels – and helps researchers in the transportation industry to evaluate and pursue more energy-efficient and environmentally friendly vehicle and fuel technologies. Since its release, GREET has become a familiar and respected analytical tool. As a licensed software product available free of charge to the public, GREET has more than 3,000 registered users worldwide.

Argonne's GREET software model also received an honorable mention in the 2006 Federal Laboratory Consortium (FLC) Awards – one of the most prestigious awards for excellence in technology transfer – that recognize outstanding work in transferring federally developed technology to the marketplace. Developer **Michael Wang** credits his colleagues in Argonne's Center for Transportation Research and GREET users with its success. The FLC is a nationwide network of federal laboratories that provides a forum to develop strategies and opportunities for linking laboratories' technologies and expertise with the market. More than 700 major federal laboratories and centers, along with their parent departments and agencies, are FLC members.

Senior executives at General Motors (GM) praised **Bob Larsen** of Argonne's Center for Transportation Research during the 2006 Challenge X Competition awards ceremony. Mark Maher, GM's Executive Director for Vehicle and Powertrain Integration, asked all GM staff to come on stage to recognize Bob's role in making the collaboration between industry and government such a success for nearly 20 years. Bob noted, "The greatest satisfaction is knowing that the thousands of engineers whose lives were changed by this series of vehicle competitions will be the ones who bring the technology that we developed and demonstrated into series production to benefit our nation and its people."

Argonne's **Jim Miller** testified at a public hearing of the Energy Subcommittee of the U.S. House of Representatives Committee on Science June 5 in Naperville, Illinois. The topic of the hearing, chaired by 13th Dist. U.S. Rep. Judy Biggert, was "Ending our Oil Addiction: Are Advanced Vehicles and Fuels the Answer?" Miller manages Argonne's Electrochemical Technology Program and is an authority on energy storage and conversion technologies, with particular expertise in fuel cells and batteries. Along with other experts, Miller discussed the challenges to widespread use of advanced flex fuel, hybrid, and fuel cell vehicles, and alternative transportation fuels such as ethanol, electricity, and hydrogen. He also addressed the research and incentives that can help overcome these challenges. Flex fuel, hybrid and plug-in hybrid vehicles were on display at the Naperville Municipal Center, where the hearing was held.

Marianne Mintz, Jerry Gillette, and **Amgad Elgowainy** of Argonne's Center for Transportation Research were co-recipients of a DOE Hydrogen Program R&D Award "In Recognition of Outstanding Achievement in Delivery Analysis" at DOE's Hydrogen Program Annual Merit Review in May.

Three articles on lithium-ion battery chemistry authored by Argonne's Chemical Engineering Division researchers **Ilias Belharouak, Khalil Amine, Jun Liu,** and **Christopher Johnson** were among the top 25 downloaded articles from *Science Direct* from July to September 2005. The articles are titled *New Active Titanium Oxyphosphate Material for Lithium Batteries, High-Temperature Storage and Cycling of C-$LiFePO_4$/Graphite Li-ion Cells, and Synthesis and Electrochemical Analysis of Vapor-Deposited Carbon-Coated $LiFePO_4$.* All three articles are published in *Electrochemistry Communications.*

PUTTING ARGONNE'S RESOURCES TO WORK FOR YOU

Industrial technology development is an important way for the national laboratories to transfer the benefits of publicly funded research to industry to help strengthen the nation's technology base. The stories highlighted in this issue of *TransForum* represent some of the ways Argonne works with the transportation industry to improve processes, create products and markets, and lead the way to cost-effective transportation solutions, which in turn lead to a healthier economic future.

By working with Argonne through various types of cost-sharing arrangements, companies can jump-start their efforts to develop the next generation of transportation technologies without shouldering the often prohibitive cost of initial R&D alone. Argonne has participated in dozens of these partnerships and has even been involved in helping to launch start-up companies based on the products and technologies developed here.

If working with world-class scientists and engineers, having access to state-of-the-art user facilities and resources, and leveraging your company's own capabilities sound like good business opportunities to you, please contact our Office of Technology Transfer and see how we can put our resources to work for you.

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***Trans**Forum* Volume 6, No. 1, Summer 2006

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TransForum is published by the Transportation Technology R&D Center, Argonne National Laboratory. Publishing support services are provided by Argonne's Technical Services Division. Art direction/design by Michele Nelson.

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