Oak Ridge National Laboratory

# REVIEW

• MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY •

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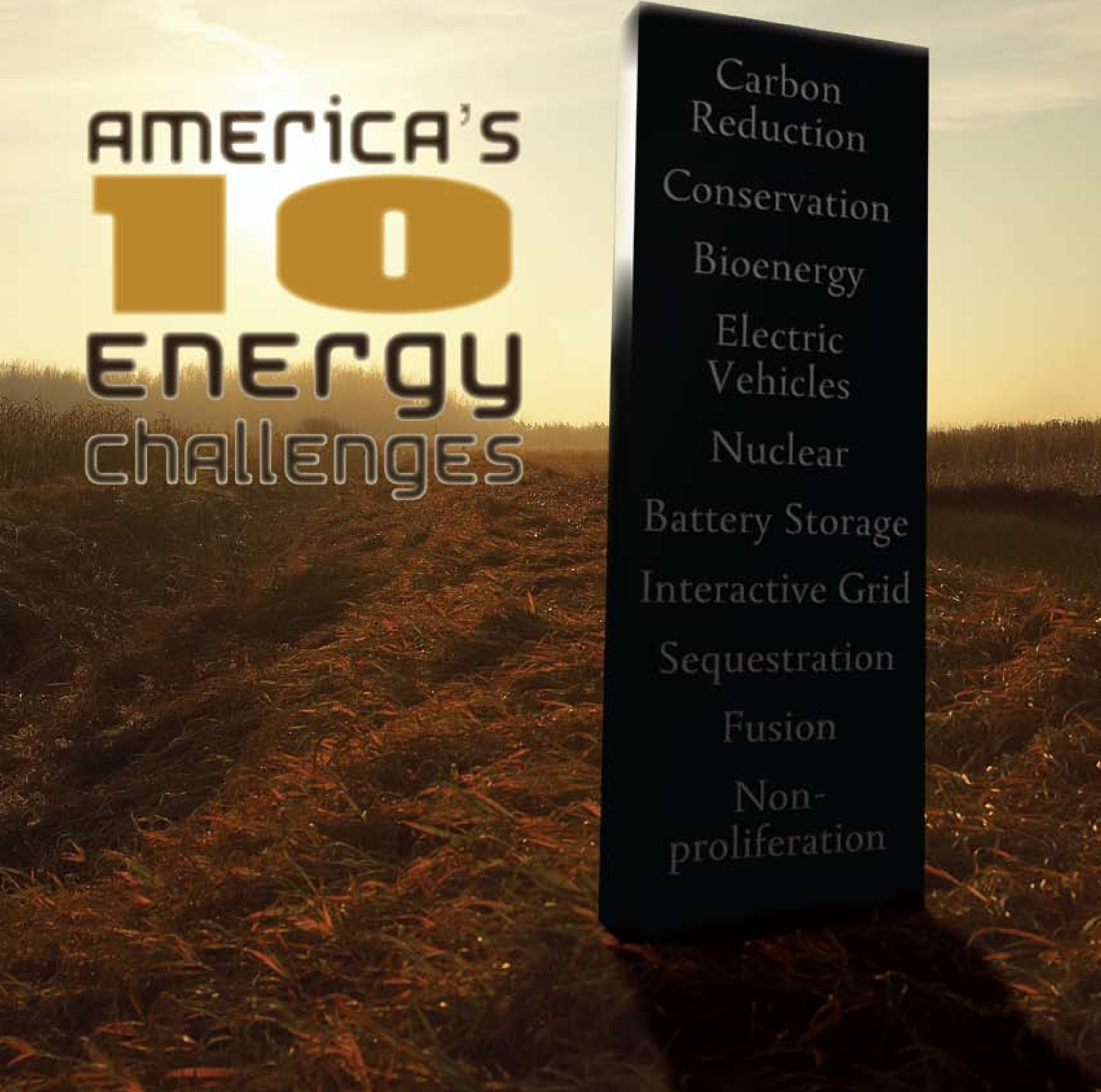
## America's 10 Energy Challenges



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Vol. 42, No. 2, 2009

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Solving the

# BIG PROBLEMS

Some four decades ago, ORNL Lab Director Alvin Weinberg was asked to explain the purpose of the national laboratories. One might have expected that Weinberg, a veteran of the Manhattan Project and one of America's foremost nuclear scientists, would respond with an answer that revealed the depth of his intellect and the extraordinary complexity of the laboratory he managed. He did—with a simplicity that captured both his brilliance and his vision for the unique collection of assets in America's system of national laboratories.

"Our purpose," Weinberg said, "is to solve the big problems." Standing less than five and one-half feet tall, Weinberg understood that America's future would confront the scientific problems that required facilities and capabilities beyond the ability of industry or even the best universities to provide. Grouped broadly within the three categories of energy, the environment and national security, these grand scientific challenges today constitute the research agenda for the Department of Energy's national laboratory system.

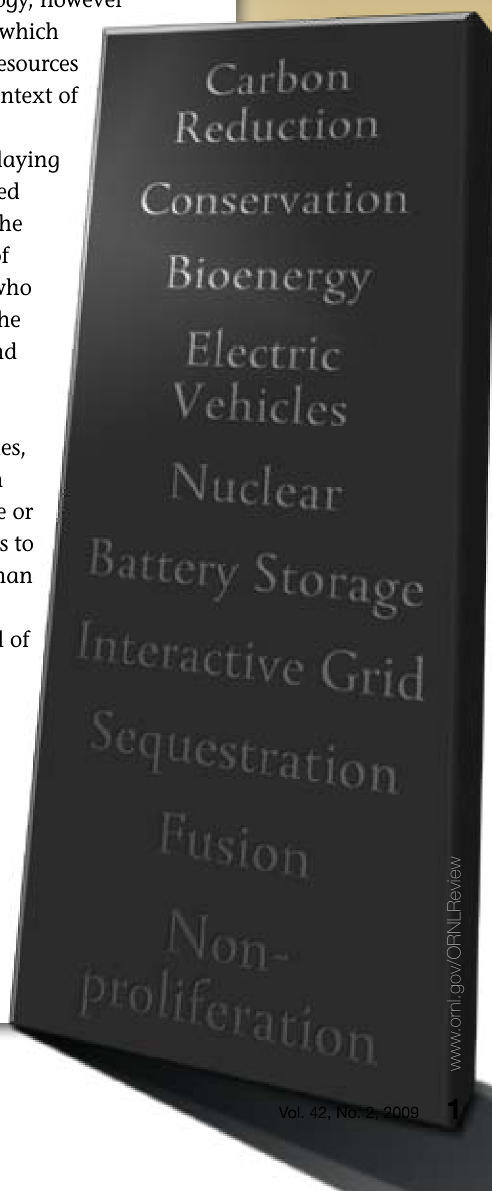
This issue of the *ORNL Review* examines ten of the world's most important energy-related challenges. Nine of these challenges are related directly to the twin goals of providing an adequate volume of sustainable energy while dramatically reducing current levels of carbon emissions. Indeed, one of the most pressing decisions facing policymakers is determining which combinations of new technologies offer the best chance of delivering on these goals. Each proposed technology, however promising, is accompanied by a level of uncertainty that complicates efforts to predict which combinations of discoveries will deliver the best long-term returns. The investment of resources required to develop these technologies would appear enormous unless viewed in the context of the stakes, both environmentally and economically, for America's future.

As the nation's largest energy research facility, Oak Ridge National Laboratory is playing a leading role in addressing each of energy's "10 Big Problems." Our strategy is grounded in the belief that no single technology and no single energy source can alone provide the volume of energy capable of sustaining both the quality of our lives and the viability of our planet. Indeed, this belief is now shared by the Administration and the Congress, who together have embarked upon the most dramatic program of scientific research since the Manhattan Project. Working through the Department of Energy, there is a collective and accelerated effort to attack each of the 10 Big Problems.

In some respects, this endeavor is like no other in American history. Success will depend, not just upon the delivery of a host of challenging new technological discoveries, but also upon the willingness of the American public to make fundamental changes in their daily activities. The development of dramatic new technologies for battery storage or the electric grid will be of little value if Americans prove unable to adapt their life styles to electric cars or to the idea that it will be cheaper to wash their clothes at night rather than in the afternoon.

At Oak Ridge, we are betting on the resilience of the American people, and mindful of Alvin Weinberg's confidence that we are capable of solving the big problems.

Billy Stair
*Director, Communications and External Relations Directorate*



# News & Notes

## ORNL to Host Tennessee Solar Initiative

*Tennessee Governor Phil Bredesen (left) and ORNL Director Thom Mason (right) at the announcement of the $62 million Solar Initiative.*

In a press conference held at the Tennessee capitol, Governor Phil Bredesen announced plans for a $62 million Solar Initiative that will be housed at Oak Ridge National Laboratory and the University of Tennessee. The Solar Institute will be dedicated to research in battery storage and thin-film photovoltaics, two areas key to the future of the solar industry.

Tennessee has been the site for two recent major investments by solar-industry manufacturers. Governor Bredesen is hoping to build upon this momentum by establishing Tennessee as a "thought leader" in the emerging renewable energy sector.

The Governor said the Solar Institute will marshal the state's research capabilities to improve the conversion of solar energy into electricity and to increase the capacity of solar batteries to store electrical energy. The project's ultimate goal is to expand the use of solar power by making it more competitive with fossil energy.

ORNL was selected to lead the effort in part because of the laboratory's capabilities in advanced materials research. The Spallation Neutron Source, the Center for Nanophase Materials Sciences, and the Leadership Computing Facility together give Tennessee a unique collection of assets needed to tackle a variety of materials-related issues.

The Governor's Solar Initiative also includes the construction of a five-megawatt "Solar Farm" that will be located adjacent to Interstate 40. The Solar Farm will sell green power to the Tennessee Valley Authority and use the revenues to fund future experimental solar panels for the Solar Institute.

The Solar Institute is the latest partnership between ORNL and the state of Tennessee. The state in 2006 invested approximately $70 million in a joint bioenergy project to develop cellulosic ethanol, in cooperation with the Department of Energy. The project included the construction of a bio-refinery to commercialize the new generation of ethanol produced at ORNL.

## Two Energy Frontier Research Centers at ORNL

Oak Ridge National Laboratory will be home to 2 of 46 new multi-million-dollar Energy Frontier Research Centers announced by the White House in conjunction with a speech delivered by President Barack Obama at the annual meeting of the National Academy of Sciences. The Energy Frontier Research Centers are being established by the Department of Energy at universities, national laboratories, nonprofit organizations, and private firms to address specific energy technologies.

"As global energy demand grows over this century, there is an urgent need to reduce our dependence on fossil fuels and imported oil and curtail greenhouse gas emissions," said Secretary of Energy Steven Chu. "Meeting this challenge will require significant scientific advances. These centers will mobilize the enormous talents and skills of our nation's scientific work force in pursuit of the breakthroughs that are essential to make alternative and renewable energy truly viable as large-scale replacements for fossil fuels."

The 46 centers, to be funded at $2-$5 million annually for an initial five-year period, were selected from a pool of some 260 applications. Many

*Continued on page 3*

## Senate Energy Chair Visits ORNL


ORNL Director Thom Mason (left) accompanied Tennessee Senator Bob Corker, New Mexico Senator Jeff Bingaman, and Tennessee Senator Lamar Alexander on a tour of the laboratory.

New Mexico Senator Jeff Bingaman and Tennessee Senators Lamar Alexander and Bob Corker spent a day in Oak Ridge learning how ORNL will play a leading role in a number of energy-related projects. The three senators, accompanied by ORNL Director, Thom Mason, toured the Spallation Neutron Source, the Center for Nanophase Materials Sciences, and the National Center for Computational Sciences.

Mason noted that each of the visiting senators plays an important role in our nation's energy future.

Alexander, who hosted Bingaman at his nearby cabin in the Smoky Mountains, noted in a press conference that the New Mexico senator is very important to the people in East Tennessee. "He's chairman of the senate committee that has jurisdiction over the Oak Ridge National Laboratory and the facilities in Oak Ridge and of the Great Smoky Mountain National Park," Alexander said. He added that Bingaman is in a position to influence "the future of Oak Ridge and our competitive position in the country." Alexander also noted that Corker is a member of Bingaman's committee.

Corker said that Bingaman "has an understanding of issues surrounding energy." In recalling a recent visit to Sandia National Laboratories in Bingaman's home state of New Mexico, Corker noted that Oak Ridge National Laboratory has a number of partnerships with the New Mexico laboratory.

For his part, Bingaman said that he and Corker have spent considerable time deaing with the issues shared among ORNL and the Sandia and Los Alamos national laboratories. Bingaman noted that it's a particularly exciting time for people involved with national laboratories because "the country is as aware today of our challenges, economically and technologically, as it has ever been." He emphasized that the nation's national laboratories are a substantial part of the solution to these challenges.

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*Continued from page 2*

of the winning proposals came from teams that combined the capabilities of universities and national laboratories. Selection was based on a rigorous merit review process utilizing outside panels composed of scientific experts.

The two ORNL Energy Frontier Center projects are the Fluid Interface Reactions, Structures and Transport (FIRST) Center and the Energy Frontier Center for Defect Physics in Structural Materials. "Energy storage and material properties will be key pieces to solving the nation's energy puzzle," said Michelle Buchanan, ORNL Associate Laboratory Director for Physical Sciences. "ORNL has a unique blend of scientific expertise, facilities and leadership needed to address these challenges. We are honored to receive these awards and eager to go to work."

The FIRST Center, which DOE plans to fund at a level of $19 million, will bring together a multidisciplinary research team of labs and universities to provide unprecedented knowledge of how fluids and solid materials interface at a subatomic level. Understanding these interactions is the basis for improved batteries, solar panels, and fuel cells and also can impact other energy-related research applications, such as carbon dioxide sequestration and corrosion-resistant materials.

ORNL's second funded project, the Energy Frontier Research Center for Defect Physics in Structural Materials, will bring together researchers from ORNL, six universities, and Lawrence Livermore National Laboratory, to address the most pressing basic research challenges in structural materials for energy. DOE also plans to fund this center at a level of approximately $19 million.

The center's goal is to provide atom-by-atom control and manipulation of defects that currently limit material performance and durability. Center scientists also will seek new ways to develop materials with unprecedented strength, toughness, radiation damage tolerance, and self-recovery. Malcolm Stocks of ORNL's Materials Science and Technology Division is the center director.

Energy Frontier researchers in Oak Ridge will take advantage of new capabilities in nanotechnology, high-intensity light sources, neutron scattering sources, supercomputing, and other advanced instrumentation. The effort seeks to lay the scientific groundwork for fundamental advances in solar energy, biofuels, transportation, energy efficiency, electricity storage and transmission, clean coal, carbon capture and sequestration, and nuclear energy.

# Both Directions at Once

## PROBLEM:

### *Can America simultaneously achieve energy independence and address global warming?*

The challenge of controlling climate change is a goal that, to many, appears to be at odds with the equally important goal of energy security. However, the idea that the two goals are somehow mutually exclusive is not one accepted by ORNL energy researcher David Greene. “We don’t want to sacrifice one for the other,” he says. “We want—and we believe it possible—to achieve environmental goals and energy security goals at the same time.”

To help determine which technologies have the greatest potential for reaching these goals, Greene and a multidisciplinary group of researchers from across the laboratory conducted the ORNL Energy Assurance Study to determine (1) which energy goals are feasible, (2) the technologies needed to realize these goals, and (3) where best to deploy research and development efforts.

“The good news,” says Greene, “is that, with technology advances in most areas, the goals are achievable. More good news is that, if we can master carbon capture and storage and identify environmentally acceptable ways of producing domestic fossil fuels, then the conflict between climate and energy security goals will be very, very small.”

Greene contends the real challenge is to assure a high probability of success for 11 specific technologies. “This means that we must pursue all 11 as if we needed every one to succeed,” he says.

The Energy Assurance Study had two fundamental premises: First, we must control climate change and solve the global problem of oil dependence. Second, achieving these two broad goals at an acceptable financial cost will depend upon advanced technologies. The uncertainty lies in advancing any area of technology to the point of making a significant contribution. “The focus on this uncertainty enables our study to provide a different perspective on the importance of research and development,” Greene says.

## Defining the Goals

Greene notes that while many studies have focused on the feasibility and cost of achieving climate goals, only a few have considered the energy security side of the equation—and many of these studies have posited the impractical goals of an oil-free economy or the elimination of oil imports. “Both of these positions are too extreme and not reasonable,” Greene says. “We want to achieve a situation in which our economy and foreign policy are free from the undue influence of nations that supply oil, where we don’t worry about the price of oil any more than we worry about the price of copper.”

Greene and his colleagues have developed a model of the world oil market that enables them to project whether a particular set of strategies would result in oil independence. The model takes account of oil market uncertainty by simulating thousands of possible future scenarios. Using this model, they have determined that oil independence—defined as a situation in which it is 95% likely that the nation will spend less than 1% of its gross domestic product on oil in any given year—could be achieved by 2030 through improving America’s petroleum supply/demand balance by 11 million barrels a day.

Greene stresses that energy independence does not mean absolute independence from imported oil. “The key,” he says, “is shrinking U.S. potential economic vulnerability to a small and manageable problem.” This is done by decreasing demand through energy efficiency and increasing supply through the use of more environmentally benign fossil fuels. “Imports will certainly go down a great

deal," Greene observes, "but they need not be eliminated and are not the sole focus."

On the climate front, most studies estimate that the world will need to reduce greenhouse gas (GHG) emissions 50 to 80 percent—a significant range—by 2050 in order to stabilize atmospheric CO2 at levels that will avoid dangerous climate changes.

"In our study, we assumed that we want to do both of these things at the same time," Greene says. "Secondly, we recognized that not every technology we need will be available. Progress with every technology is not a sure thing. Even technologies we are fairly sure of are not a done deal."

## Assessing the Options

To develop a comprehensive picture of current and near-future policy options, ORNL scientists and engineers were asked to provide assessments of the technologies they thought would be the most effective in meeting the climate and energy goals.

"A study like this requires experts in every phase of the energy system—people who know the electricity grid, transportation, solar energy, nuclear energy, and so on," says Greene. "The credibility of the study really rests on those folks. Only a place like ORNL with a breadth of research and a high level of expertise can undertake a project on this scale."

The group's study examined these broad technologies:

- Carbon capture and storage
- Nuclear power
- Transportation energy efficiency
- Wind
- Buildings energy efficiency
- Solar
- Industrial energy efficiency
- Biomass
- Electric drive vehicles
- Advanced fossil liquid fuels
- Efficient electricity generation and transmission

The study's authors took a novel approach to determining which technologies would be available to address the problems. "People usually build scenarios," Greene said. "They assume we will have certain technologies and that these technologies will cost a specific amount of money. Based on this rigid scenario they determine what the future would look like." In contrast, the ORNL study approaches the problem from a different perspective: Inserting a level of uncertainty about which, if any, of these technologies will be available and in what year, the study seeks to understand the chances of solving the twin challenges of energy security and climate change. Perhaps even more intriguing, the study seeks to determine which of the 11 technologies are indispensable parts of the solution.

Using the data gathered from ORNL researchers, as well as from other studies by the International Energy Agency and the National Academy of Sciences, the technologies were analyzed in terms of their impact on U.S. oil dependence in 2030 and on global GHG emissions in 2050."

## Critical Technologies

The results indicate several combinations of technologies are capable of reaching the goal of oil independence in 2030. The team took encouragement from the fact that some of these combinations could also achieve up to a 70% reduction in GHG by 2050.

The group next looked at the combinations that solved both problems, seeking to identify which technologies were critical. "For example," says Greene, "what if wind power or nuclear remain at current levels?" Greene explains that, if policymakers want 95% certainty that the challenges of oil independence and GHG emissions can be solved simultaneously, the crucial question is, "How confident do we have to be that any single technology will be successful?" "It turns out that we need to be at least 50-50 or better on every technology," he says. "The message is that we really must work hard on developing all of these technologies to be sure that most of them will be available."

"The only technology that was absolutely essential to meeting the greenhouse gas goal was carbon capture and sequestration (CCS)," Greene says. "Similarly, advanced fossil technologies, like oil shale, coal to liquids, and environmentally safe oil drilling, were shown to be absolutely essential to meeting our oil dependence goal."

Other technologies, such as transportation energy efficiency, were also important, but only the removal of CCS and advanced fossil technologies resulted in zero probability of meeting GHG and energy independence goals.

The study made clear a final point: Time is of the essence. "We cannot just sit back and wait for someone to invent something to take care of the problem," Greene says.

"The success of our efforts to address climate change and energy security has a critical dependence on advancing technology," says Greene. "This study is just a starting point for understanding and measuring the importance of energy research to the lives of our children."

# Becoming Part of the Process

## PROBLEM:

### *Can we reduce power consumption without compromising our quality of life?*

*Home automation systems help consumers tailor their daily habits and energy consumption to match their needs and budgets.*

When ORNL scientist Jeff Christian declared in 2004 that houses could be designed to produce enough energy to pay for the power they consume, he had a lot of people shaking their heads in disbelief. Now that a growing number of zero-energy houses has sprung up in and around Oak Ridge, the same people are nodding their heads—this time in agreement.

The growing acceptance of zero-energy housing has inspired Christian to extend to the broader market the reach of both zero-energy homes and the technologies that enable these super-efficient houses.

A combination of new technologies, new habits and new policies will be required to make Christian's vision a reality. Consumers will need to be convinced to pay greater attention to their electricity consumption. Likewise, a commitment will be necessary from utilities to making smart grid capabilities available to consumers.

On the technology front, one of the most promising tools for reigning in out-of-control miscellaneous electrical use in homes is the home automation system. Many homeowners are surprised to learn that zero-energy houses are not solely dependent upon solar panels, high-tech gadgets and cutting-edge building techniques. The success of low-energy homes is made possible when people understand how and why they use energy. Researchers have found that the power required to heat, cool and provide hot water for most households accounts for only about one-half of energy consumption. The remaining 50 percent is used for a host of smaller activities, such as washing clothes, watching television and lighting rooms. Both halves of the energy equation can get a significant efficiency boost from the use of relatively simple home automation systems.

Increasingly common, these systems provide a communication link between the household electrical system and the utility grid. Through this link, consumers have access to a detailed and real-time breakdown of how much electricity they are using for specific appliances at specific times. Equipped for the first time with this information, consumers can begin to tailor their daily habits, and their energy consumption, to both their needs and their budgets.

ORNL researchers are working on the next generation of household appliances, which will include the capability to receive pricing information from the grid, as well as alerts about when electrical demand is expected to be particularly high or low. Christian's team is partnering with General Electric, Whirlpool, and the Tennessee Valley Authority to install this new capability into their test houses—Habitat for Humanity homes occupied by families—with the eventual goal of showcasing the technologies in larger, high-performance homes.

"Consumer behavior has a major effect on power consumption," Christian says. "Utilities understand that, so they are making a substantial investment to install 'smart' meters in residential areas to enable automation systems to communicate with the utility."

One of the key drivers behind the move to smart meters is the adoption by many utilities of time-of-day pricing for electricity—that is, charging more for power during peak use hours and less during hours when the demand is low. "For example," Christian says, "in California the nighttime rate might be five cents per kilowatt hour, but in the late afternoon when it's really hot and people are demanding a lot of air conditioning, the peak rate might be as much as a dollar per kilowatt hour."

On the most basic level, home automation systems can save energy by using sensors to determine when people are present and then turning lights and televisions off when no one is in the room. With the latest technologies, consumers can go a step further and allow the utility company to control the power consumption of their major appliances.

"For example," Christian says, "with a home automation system, families can shut down their hot water heater for an hour or two during parts of the day when it's normally not being used. Consumers might choose to let the utility choose these times or choose the times themselves. Similar technologies could also enable consumers to set their dishwasher or washing machine

to start operating when electricity is cheapest. For instance, the dishwasher could be loaded after supper but be instructed not to start operating until 10:00 at night, when energy rates are lower—or the consumer might instead let the utility determine the most economical time to start.

"Giving the smart grid control of certain appliance functions has essentially zero impact on homeowners. The new technologies literally do not require them to do anything," Christian says. "However, people who want to adjust their behavior and control the appliances themselves can take even greater advantage of this system."

Christian points out that widespread use of new grid technologies would dramatically decrease the peak demand for power. This new aspect of energy conservation is an attractive alternative to building new power plants to support ever-increasing peak power demands. Confronted with the financial and political costs of building additional power plants, Christian says utilities are faced with the policy decision of whether it is better to take advantage of emerging smart grid technology than it is to add additional capacity to the grid. "If we can get a lot of people to participate, the potential for saving energy and saving money is huge."

When Christian says "lots of people," he means lots of people. The demonstration project he is currently pitching to utility companies around the country would involve equipping 200,000 homes with "smart" meters. Ideally, these would be zero-energy homes in order to have the greatest long-term impact on power consumption. "It really comes down to the electric utilities enabling consumers to take advantage of this technology," he says. "We can talk all day about fancy controls and fancy appliances, but the infrastructure has to be there first."

For example," Christian says, "in California, the utilities are making the investment to install thousands of meters every day." Building codes that recognize the benefits of this technology are being adopted, as well. "In Boulder, Colorado, the codes are graduated," he says. "If you want to build a house that is 5000 square feet or larger, then it must be a zero-energy house. If the new house is 4000 square feet, it must be a very efficient house, and so on. Even the smallest houses need to meet Energy Star standards that are established by the U.S. Environmental Protection Agency and the U.S. Department of Energy."

"I'm also encouraged by the government's plans to invest in upgrading the country's electric power infrastructure using smart grid technology," Christian says. "I hope the result has an impact on our lifestyle as big as the construction of the Interstate Highway System 50 years ago."

Christian acknowledges that the impact of any technology depends ultimately on whether consumers embrace it. "The issues of foreign oil dependence and climate change all come down to choices that individuals make," Christian says. "Zero-energy homes, smart grid technology, and home automation systems can enable consumers to reduce their energy expenditures without impacting their comfort or their lifestyles. This particular technology enables the customer to be part of the solution, rather than just complaining about the shortcomings of conventional power plants. Until recently, all we could do was buy or not buy power. In the world of tomorrow, we will become part of the process."

# ANXIETY ATTACK

## PROBLEM:

### *Can new batteries relieve anxiety over electric vehicles?*

The public anxiety that accompanied last summer's price spike of gasoline above $4 a gallon motivated many consumers to consider alternatives to gasoline-powered vehicles. As demand for gas-electric hybrids exceeded supply, both domestic and foreign auto manufacturers began accelerating plans for the first generation of all-electric vehicles.

While electric transportation alternatives are increasingly in fashion, the discussion will remain largely in the abstract until large numbers of vehicles are actually on the road. In the meantime, two fundamental technology challenges—the cost of electric vehicles and their relatively limited range—stand in the way of significant market penetration.

The batteries required for energy storage currently add thousands of dollars to the price of a hybrid or all-electric car. Even if cost is not a factor, many potential buyers are deterred by what the industry calls "range anxiety." Even the best battery systems on all-electric vehicles must to be recharged after about 100 miles of use. Like drivers a century earlier who worried about running out of gas, car companies must overcome similar anxieties of today's commuters and housewives who fear being stranded with a "dead" battery.

Developing technological solutions to these anxieties has become one of the key challenges for materials science researchers like ORNL's Energy Materials Program manager, Craig Blue. "Traditionally, ORNL's largest impacts have been in basic research," Blue says. "Now we're translating that capability into more applied areas. These areas include lightweight materials, like low-cost carbon fiber, and improvements in battery technology that will reduce cost and simultaneously improve range and reliability."

"A successful transition to electric vehicles will require battery technology based on higher performing materials, more cost-effective manufacturing methods, and better systems integration that will reduce cost and provide more usable energy with no compromise of safety," says Ray Boeman, ORNL's Transportation Program Director.

"If we can reduce the weight of a passenger vehicle by 40 percent through the use of lightweight materials such as carbon fiber composites," says Boeman, "we will translate that reduction into a 25 percent increase in fuel economy." Due to the added weight of batteries, the need for lightweight vehicles is critical," Boeman adds.

Carbon fiber appears to be the material with the greatest potential to reduce vehicle weight at a reasonable cost. However, carbon fiber is currently too expensive to be competitive with other materials in the mass market. "To reduce the cost, we are developing new ways of making carbon fiber, starting with new materials and new processes," says composites researcher Cliff Eberle.

Today, most carbon fibers are made from petrochemicals using processes that have changed little in decades. Because these chemicals are derived from oil, their price is volatile and has fluctuated by a factor of three over the last year. "We are investigating other materials with costs that are lower and less volatile," Eberle says.

One of these alternative materials is lignin, one of the most abundant polymers on earth. Lignin is also a low-cost byproduct of several industrial processes, like paper-making and the production of biofuels. Most importantly, lignin is a renewable product with no direct link to the price of oil.

Eberle and his colleagues at ORNL are working on a low-cost process to turn lignin into carbon fiber. "Traditionally carbon fiber is made using a fairly expensive, time- and labor-intensive heat treatment process," Eberle says. "We are experimenting with microwave-assisted plasma to create the carbon fiber faster while using less energy." Eberle believes his group will be able to process the carbon fiber in about a third of the time using half the energy of conventional methods. If successful, the new process would increase the throughput and reduce the cost.

Most of the expected weight-reduction benefits of low-cost carbon fiber would initially result from using carbon fiber for components such as body panels, fenders, doors, and hoods. In the longer term, Eberle also expects eventually to see carbon fiber components used in structural applications in the chassis and as driveshafts. Together, these new materials would lower the weight of the vehicle significantly.

In addition to increasing vehicle efficiency by reducing weight, ORNL's pursuit of new battery technologies and improved manufacturing processes holds out the promise of

A plasma conversion line of a pilot carbon fiber processing unit.

lower cost and greater range for electric vehicles. "I think the Department of Energy is looking to ORNL for insight as to where we should go next with lithium ion batteries, as well as with the next generation of electric vehicle batteries," says Blue. "Industry wants to increase the distance battery power can go, so we are working to improve the range and reliability of the current generation of batteries, as well as to reduce production costs. We are exploring ways of streamlining the manufacturing process to make batteries more affordable so they are attractive to a broader spectrum of the public."

ORNL materials researcher Claus Daniel says that, in the past, battery research was primarily concerned with electrochemistry. "Eventually, research determined that lithium-ion chemistries were the best for transportation applications because of their very favorable charge to weight ratio. Now our primary focus is taking this technology and addressing the fundamental issues of cost, reliability, and range."


*ORNL's pursuit of new battery technologies and improved manufacturing processes holds out the promise of lower cost and greater range for electric vehicles.*

Daniel believes these issues line up well with ORNL's historic strengths. "ORNL has a strong background in materials research, materials characterization, and process development." These capabilities, combined with the analytical capabilities of the Spallation Neutron Source and the laboratory's Center for Computational Sciences, provide ORNL an unprecedented ability to study the processes that cause batteries to degrade and to simulate structural and material alternatives that could result in longer battery life and greater reliability.

Daniel and his group are taking advantage of these unique capabilities at ORNL in collaborations with a number of academic and industrial research teams. The group is working with the University of Michigan to develop battery components that improve the performance and durability of lithium-ion batteries. They are also collaborating with battery manufacturers to incorporate into their products new types of electrodes and separator materials to boost reliability and reduce costs. This effort includes developing new manufacturing processes that can be used to scale laboratory prototype efforts up to commercial level.

Daniel and his colleagues are also employing cutting-edge techniques, like acoustic emission spectroscopy and X-ray diffraction, to gain a theoretical understanding of what causes materials inside a working battery to break down and eventually fail. "These tools give us the ability to measure the stress being experienced by battery components with X-rays and actually to listen to cracks forming in the components as they degrade," says Daniel. "By analyzing these noise events and correlating them with the X-ray diffraction data, we hope that we can determine what caused them to occur. My graduate student assistant, Kevin Rhodes, is doing a tremendous job with the collection and interpretation of those signals." This research is being conducted in cooperation with Edgar Lara-Curzio, Director of ORNL's High Temperature Materials Laboratory, and battery expert, Nancy Dudney.

Daniel hopes to use this information, along with traditional knowledge of fatigue properties of materials, to develop theories that explain how battery materials degrade and fail. "If we can do that, we can achieve a breakthrough in ways to create materials that last longer and work better," he says.

ORNL has worked closely with industry in the ongoing efforts to develop new battery technologies.

"We work with industry on almost every project," says Blue. "Much of our work culminates in new processes and parts.

Blue continues,"We can take advantage of the laboratory's basic research capabilities to give us the understanding of the materials. Then we can work with industry in the applied world. We like to believe that we are the best at what we do. The Laboratory has more than 140 R&D 100 Awards, 40 percent of which come out of the Lab's materials research programs."

**The question for Blue and his colleagues—and for the automotive industry—is whether these capabilities will relieve the collective anxiety of the American public.**

# FOOD or FUEL?

## PROBLEM:

### *Can ethanol reduce oil imports without compromising food supplies?*

The Department of Energy's accelerated effort to develop a new generation of cellulosic ethanol provides a textbook example of the challenge posed by the collision of competing policy priorities. At ORNL's Bioenergy Science Center (BESC), a consortium of researchers is making progress toward the twin goals of reducing oil imports without compromising the world's supply of food.

While researchers pursue a variety of promising transportation technologies on the horizon, plant-based biofuels, like ethanol, have a more near-term potential to significantly reduce U.S. dependence on imported oil. However, when dramatic price spikes of gasoline temporarily increased demand for ethanol, many viewed ethanol, and the use of valuable farm land for the production of crops to make ethanol, as the cause of sharp world-wide increases in the cost of food. The perception remained despite several studies that suggested overall energy and petroleum costs, and not simply ethanol production, were the major causes of inflationary pressures on food prices.

Faced with the need to protect world food supplies, the BESC is focusing on new ways of developing ethanol from biofeedstock crops such as switchgrass and poplar trees. The primary difference of this approach is that it does not use conventional ethanol-producing food crops such as corn, which contain large volumes of starch. This starch is easily broken down into sugar and then fermented to ethanol. In poplar and switchgrass, most of the sugar is contained in the cellulose that makes up stalks, stems and leaves.

"Breaking starch down into sugars is a relatively easy process that occurs in our stomachs," says BESC scientist Brian Davison, "but cellulose is put together in such a way that only a very limited number of microbes can break it apart. Understanding the complex process of breaking cellulose into its component sugars is the fundamental challenge of the BESC research.

Based upon about 18 months of progress, Davison is confident of gaining access to the cellulosic sugars. He believes the more important questions yet to be resolved are whether cellulosic biofuels can be produced economically and sustainably in sufficient volume to alter current consumption levels of gasoline.

### A competitive cost

The price of oil fluctuated wildly, moving up and then back down three-fold during 2007-2008. Cellulosic ethanol is not competitive with oil priced at $30-50 per barrel. One of the BESC's goals is to find a way to convert cellulose to ethanol at less cost than gasoline—or at least be competitive enough for a marginal price difference, justified in terms of improved energy security and a reduction of fossil fuels emissions.

Davison is convinced that the cost efficiencies needed to make cellulosic fuels economically viable are realistic. "We're not there yet," Davison says. "Despite the current deployment of cost of first-generation technology, the costs need to be reduced to make ethanol a large-scale industry. The creation of this second-generation technology is one of the main missions of the BESC."

Davison notes that BESC has made rapid progress in the quest to identify highly productive plants and highly efficient microbes. Working in the National Renewable Energy Laboratory in Boulder, Colorado, BESC researchers have established a high-throughput screening process that has analyzed thousands of plant samples to see how much sugar is released when the samples are broken down by various microbial enzymes. "This process has shown that the natural variation in sugar release among poplar trees was greater than we expected," he says. "Our task now is to identify which genes allow higher levels of sugar release, so we can start eliminating and altering genes to maximize the process."

ORNL's team has made progress on the microbial side of the equation as well. According to BESC director Martin Keller, "Microbial strain development is coming along nicely. The center has a couple of different candidates at Oak Ridge and at our partner sites that show potential for consolidated bioprocessing." While some microorganisms consume biomass and others produce ethanol, the goal of consolidated bioprocessing is to identify or create an organism that does both in a single step. Such a discovery would save time and significantly decrease the cost of the ethanol production process.

The center is now working with two groups of microbes capable of breaking down cellulose and fermenting the resulting sugars. "If the microbe can ferment the sugars, I'm confident we can genetically tweak the process to produce increasing volumes of ethanol," Davison says. "We know some of these organisms make ethanol—not as much as we want, and not just ethanol. However, if a microbe makes three or four things and we only want one, genetic engineering can produce the one we want."

Despite his confidence, Davison notes that recently discovered organisms like the ones the BESC has been working with are often much more difficult to genetically engineer than microbes that have been studied for decades. "I am confident we can get the results we want," he says, "but I would hedge on how long it will take. We still need to understand how these microbes simultaneously undertake this enzyme production, degradation and fermentation in a single package."

## The potential impact

The most convincing evidence that cellulosic ethanol has the potential to make a significant impact on the nation's transportation energy supply comes from the landmark "Billion Ton Study," produced in 2005 by researchers from ORNL's Environmental Sciences Division and the U.S. Department of Agriculture.

The study's conclusion—that in the United States "significant amounts of land could shift to the production of perennial crops if a large market for bioenergy and bio-based products emerges without impacting baseline projections for food and feed demands,"—had a transformative effect on both U.S. energy policy and the willingness of industrial partners to invest in emerging ethanol technologies.

## A sustainable strategy

Davison expects cellulosic ethanol to be a sustainable option but cautions that researchers first need to address issues such as soil fertility, which crops work best, and preferred agricultural practices.

Fortunately, both switchgrass and poplar are well-suited to a range of climate conditions and soil types. Neither requires a great deal of water, and both can be grown on "marginal" land that normally would not be used to grow food crops.

Research on poplar and switchgrass at ORNL has demonstrated that these perennials are actually better for the soil than food crops. "In some cases," Davison says, "they are even better for the land than letting it lie fallow because they store more carbon in the soil."

Still, there are critics who will argue that, until scientists can disprove with certainty the potential of detrimental side effects, the appropriate policy is to do nothing. In the absence of an alternative proposal, Davison contends we cannot continue on the current path indefinitely, so we must do something better.

BESC is now fully operational and funds more than 300 scientists working in locations around the country to develop sustainable energy alternatives. "Research is progressing extremely well in all areas," Keller says. "We have developed a multi-disciplinary partnership among national laboratories, academia, and industrial partners."

This broad-based arrangement has enabled the center to draw on the strengths of each organization to advance new concepts and new strategies dedicated to finding solutions to one of America's most important scientific challenges. With growing confidence, they believe they can unlock the code to one way of meeting America's energy needs without compromising the environment or the world's increasing precious supply of food.

*ORNL's Bioenergy Science Center is focusing on new ways of developing ethanol from crops, such as switchgrass and poplar trees—a strategy aimed at reducing oil imports without compromising the world's food supply.*

# TOO MUCH GAS

## PROBLEM: *Can carbon sequestration reduce global levels of carbon dioxide?*

Long before global warming was a serious part of the political debate, ORNL researchers were logging greenhouse gases, tracing the carbon cycle, and tracking the effects of climate change. Oak Ridge researchers also were seemingly ahead of their time in developing and testing strategies to stabilize levels of carbon dioxide ($CO_2$) in the atmosphere. Today, equipped with comprehensive climate data and increasingly sophisticated computational models, climate scientists are able to predict, with increasing accuracy, trends in climate change and gauge the potential effectiveness of remediation efforts with unprecedented levels of certainty and detail.

Among these remediation strategies is carbon sequestration, a method of capturing and storing $CO_2$, the most common greenhouse gas. $CO_2$ is introduced into the atmosphere by activities, such as burning fossil fuels and various agricultural practices. Unlike some other atmospheric gases, $CO_2$ absorbs energy from sunlight, rather than reflecting it back into space. The process warms the $CO_2$, which in turn heats the surrounding atmosphere. Reduced to its most simple form, the earth's rising average temperature is linked to the growing volume of $CO_2$ produced by human activity.

**The primary challenge of biosequestration is figuring out how we can persuade this natural system to increase its appetite for $CO_2$.**

According to the United Nations' Intergovernmental Panel on Climate Change, human activities now add 10 billion tons of $CO_2$ to the atmosphere every year. Projections that include a growing population, increased energy usage, and improved living standards, suggest that $CO_2$ emissions could rise to 20 billion tons annually by 2050. According to Gary Jacobs, head of ORNL's Environmental Sciences Division, the planet may be exceeding that trajectory already. "If our current trajectory continues through 2100," he says, "we will be looking at plausible severe warming on the order of about 6° C. An average increase of that magnitude could result in some regions, particularly in the northern latitudes, warming by as much as 10 to 15° C."

Climate simulations indicate that such levels of warming would have extreme consequences, including more frequent and severe droughts, floods, and storms. A significantly warmer climate would also have a negative impact in some regions, such as northeast India, on water resources, creating the possibility of famine and large-scale population migrations.

The goal of Jacobs and his staff of climate researchers is to develop strategies to help avoid such extreme scenarios by stabilizing the level of $CO_2$ in the atmosphere in the relatively near future. "If we had a magic wand and could stop all emissions today," says Jacobs, "we would still see warming on the order of a degree because so much $CO_2$ is already built into the climate cycle. The challenge of climate science is to figure out where we can put away, or sequester, several billion tons of $CO_2$ every year." Global climate models indicate that sequestration on the billions-of-tons scale would be enough to begin to stabilize atmospheric levels of $CO_2$ and at least slow the pace of global warming.

Jacobs anticipates that sequestration efforts will be ramped up in conjunction with increased use of technologies, such as nuclear, solar and wind, that do not produce $CO_2$ emissions. "The hope is that as these new energy technologies come into play, their increased efficiency will generate more power with less $CO_2$ to worry about," he says.

ORNL's carbon sequestration research is concentrated in three main areas: ocean sequestration, carbon capture and storage, and biosequestration.

ORNL's ocean sequestration research is focused in two categories. One approach is to fertilize the ocean's natural carbon cycle by seeding the water with iron to stimulate plankton growth, thereby pulling more $CO_2$ out of the atmosphere. When the plankton die, they sink to the bottom and are buried by sediment, along with the $CO_2$ they consumed. The other ocean-based approach involves injecting captured $CO_2$ deep into the sea where, because of the extreme pressure and cold temperatures, the gas would settle into dense pools and remain indefinitely.

Carbon capture and storage targets the source of the problem by concentrating the $CO_2$ emitted from coal- or gas-fired power plants and creating a supercritical fluid that can be stored below ground in geological formations, such as saline aquifers and abandoned oil wells. "Conceptually, we could store hundreds of billions of tons of $CO_2$ in these structures," Jacobs says.

However, despite the promise of ocean-based and geologic sequestration technologies, neither seems poised to be widely implemented in the near future. "Both ocean and geologic storage require a cost-effective means of separating and capturing the $CO_2$," Jacobs says. Large-scale demonstration projects are not scheduled for several years, so full implementation would likely be considerably later. "To get to point where we can annually sequester a couple of billion tons of $CO_2$ 'soon' would require major acceleration of R&D, demonstration projects, and long-term policy decisions that would incentivize utilities and others to make large-scale infrastructure investments," he says. "In addition, ocean sequestration would require international discussions on the possible impacts of the technology."

Still, Jacobs remains undeterred. "The biosequestration option—enhancing the natural uptake and storage of $CO_2$ in vegetation, plants and soil—is technically less challenging and provides near-term options for removing 1 to 2 billion tons of $CO_2$ per year. On a global scale, we lose every year roughly 1.5 billion tons of carbon back into the air through land use change, be it through deforestation, agricultural practices, development, or just poor land management." Fortunately, natural systems take up about 3.5 billion tons of $CO_2$, so they provide a net sequestering of 2 billion tons per year. Jacobs indicates that the primary challenge of biosequestration is figuring out how we can persuade this natural system to increase its appetite for $CO_2$. "Could we go from two tons to five?" he asks. "Can we get to 10? I certainly think we can get to five—possibly 10, but it would take significant management of global land resources at unprecedented levels."

Several options exist to achieve higher rates of biosequestration through land management. One is promoting low-till or no-till agriculture, because tilling the soil deeply releases the $CO_2$ that has been absorbed from the air by the plants and deposited in the soil by their roots. "That's not science as much as just good land management practice," explains Jacobs. "Globally, more carbon resides in the soil than in the vegetation."

"In Milan, Tennessee," he continues, "there is a switchgrass farm where we are studying the uptake of $CO_2$ in the soil. The soil in the fields accumulates a lot of carbon, so understanding how it is accumulated and how long it stays in the soil is important." For example, Jacobs and his team have found that if the switchgrass is harvested too early, or if the farmer tries to squeeze two plantings into a single season, then relatively little $CO_2$ and nitrogen are deposited into the soil. "It's better environmentally to let the switchgrass go through a frost and die—and then cut it so all of the $CO_2$ has been deposited below ground."

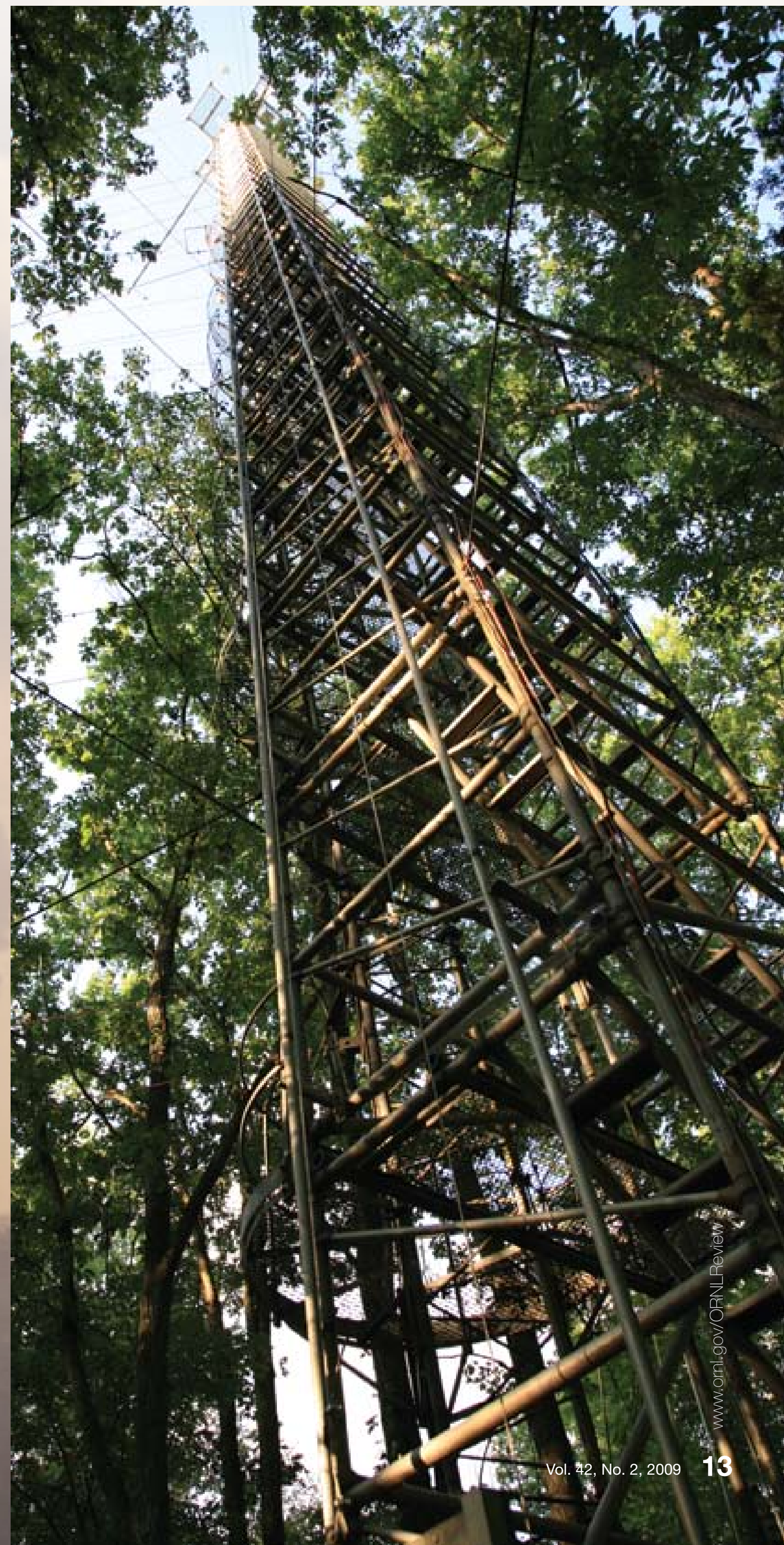
"We can also put a lot of carbon in trees," Jacobs says. "An opportunity arises if we receive an offset by using the trees to generate power or for fuel. So not only do we pull carbon out of the environment, we also replace other emissions from fossil fuel sources."

Jacobs notes that 30-50 percent of the land mass on earth is currently managed for agriculture, homes, and commercial activity, so thinking about biosequestration on a global scale is not unreasonable. "Where environmental science can really make a contribution is in understanding where the carbon can be stored on a biological or molecular scale," he says. "However, as land use changes—as we go from grasslands to trees or from deserts to grasses—the reflectivity of the land changes, and that, in turn, changes climate. If we alter present patterns on a large enough scale, we can change the hydrologic cycle locally, which can potentially modify climate trends on a global scale."

"So, in environmental sciences, we do fundamental studies on how to store carbon," Jacobs says. "Then our computational scientists and their improved earth system models provide us with the opportunity to analyze how these sequestration options stabilize the climate, how quickly that happens, and what new climate state we will inherit.

Jacobs and his colleagues have the most unique perspective, using biology at the molecular scale in the effort to tackle one of the biggest problems facing humankind.

*The biosequestration option—enhancing the natural uptake and storage of $CO_2$ in vegetation, plants and soil—provides near-term options for removing 1 to 2 billion tons of $CO_2$ per year from the atmosphere.*



# The Nuclear Option

## PROBLEM: *Can new technologies deliver a nuclear future that is safe and affordable?*

Alarmed by the prospect of global warming and impatient with the economic disruption and unpredictability of global energy markets, polls have revealed a gradual increase in support among the American public for nuclear power. Although recent surveys suggest that as many as two-thirds of Americans favor expanding the nation's nuclear power base, much of the support remains tentative. Despite their desire for a carbon-free source of energy, for many, their comfort level with nuclear power rests with concerns about whether advances in nuclear technology have successfully addressed the issues of safety and affordability.

Sherrell Greene, Director of ORNL's Nuclear Technology Programs, sees nuclear power as one of the few near-term options for generating the volume of low-carbon power required for the world's largest economy. In fact, Greene views nuclear power as the bridge to a low-carbon future. "Today we have 104 nuclear power plants operating in the United States," says Greene. "These plants are responsible for 70% of the low-carbon electricity we produce and are operating efficiently and safely."

"A little known fact is that we are getting more energy out of these plants than we would have thought possible three decades ago," adds Kelly Beierschmitt, Executive Director of the lab's High Flux Isotope Reactor. "That increased volume of energy is not a result of building more plants. The increase comes from making nuclear power plants more efficient and reliable."

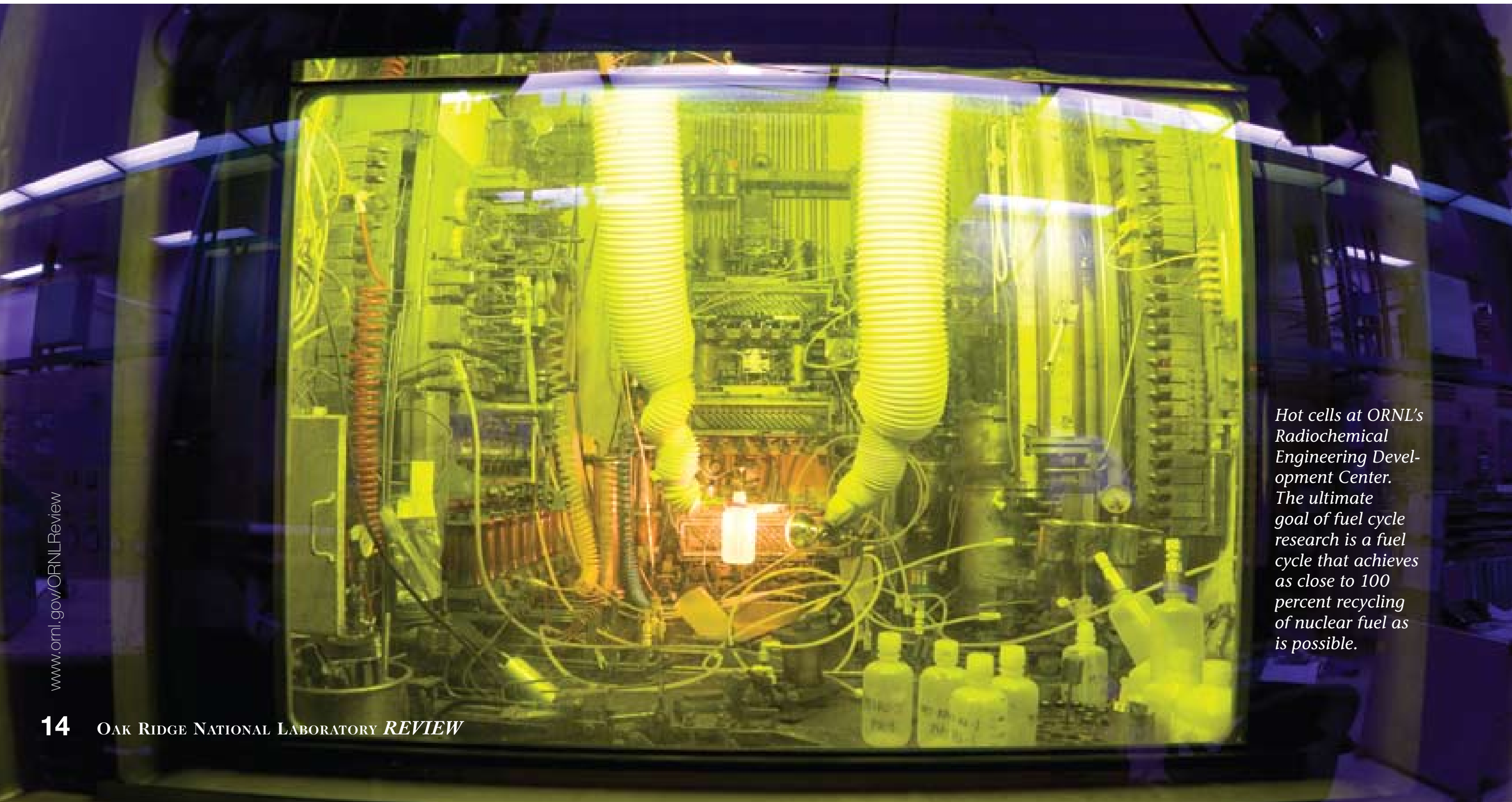
Reliability, to the surprise of skeptics, is one of nuclear power's major selling points. Greene notes that the availability of nuclear plants in recent years has been more than 90 percent. That performance compares favorably with other carbon-free energy options, such as solar panels and wind turbines that generate far less power and often do not exceed 30 percent availability.

Reliability aside, no one should mistake Greene's enthusiasm for nuclear energy with disdain for other sustainable energy sources. "We will need a broad variety of energy options to reduce consumption and increase our production of clean energy," Greene says. "When I look at the scenarios for economic growth in the United States, I conclude that every viable solution includes a substantial contribution of nuclear power. Although other energy options may lie over the horizon, nuclear power is the only large-scale, low-carbon energy source deployable right now."

Greene sees four major challenges along the road to an expanded nuclear power infrastructure:

### (1) Maintaining the integrity and extending the life of existing commercial reactors

Greene maintains that ORNL is well positioned to provide leadership in maintaining the health and extending the life of our existing nuclear reactors as long as possible. "Nuclear materials research is one of the signature capabilities of this laboratory. It is an important capability to



*Hot cells at ORNL's Radiochemical Engineering Development Center. The ultimate goal of fuel cycle research is a fuel cycle that achieves as close to 100 percent recycling of nuclear fuel as is possible.*

have when it comes to extending the life of existing reactors."

Nuclear plants that were originally licensed for 40 years are now being considered for 20-year extensions. Currently, 52 of the 104 nuclear reactors in the United States have been granted 20-year extensions to their operating licenses. It is assumed that all but a few of the remaining plants will eventually apply for extensions as well.

**When I look at the scenarios for economic growth in the United States, I conclude that every viable solution includes a substantial contribution of nuclear power.**

The key to extending the life of nuclear reactors is monitoring and maintaining the integrity of the materials used in their construction. To help accomplish this, ORNL materials researchers have developed techniques for testing materials in the field using very small samples. For example, a sample of base metal from a reactor vessel can be used to help determine its condition and integrity.

Other lab-developed monitoring techniques include "health monitoring" instrumentation and sensors that provide an overall picture of the health of reactors as they operate.

### 2) Developing a range of nuclear power plants in terms of size

Greene contends that in addition to more nuclear plants, America needs a greater variety of plants to suit economic and geographical realities. "Henry Ford used to say you can have any color Model T as long as it's black. Well, today you can have any size nuclear power plant you want as long as it's over a gigawatt in size."

Greene notes that the country will need a small- to medium-sized nuclear power plant option—one that provides 300MW of power or less—for a variety of reasons. "One is the large capital cost," he says. "All gigawatt-class plants—coal or nuclear—are getting prohibitively expensive—from $4000-$8000 per kilowatt. That's a massive lift in a market where most power generators are capitalized below $20-$25 billion. Asking a company that has an asset value of $20 billion to go out and purchase a $6-$8 billion power plant is unreasonable.

"We also need small- to medium-sized plant options so we can put plants in locations that are near the demand for power but may not be suitable for larger plants because of the capacity of the electrical grid or limited availability of water,"

### (3) Developing non-electrical applications

Just as a range of power plant sizes would broaden the applicability of nuclear power, so would the development of nuclear plants dedicated to non-electrical applications, such as providing high-temperature process heat for industrial applications.

"Most power plants that use a steam cooling system—nuclear, coal, or otherwise—lose approximately two-thirds of their energy as waste heat," says Greene. One of the scientific challenges is that the current generation of reactors operates at relatively low temperatures—not high enough to support petrochemical processing and similar industrial applications. Our goal is to build higher temperature reactors to support industrial applications."

The laboratory's advanced materials expertise could also be applied to the development of other power plant components, such as the heat exchangers needed to transfer thermal energy from nuclear plants to nearby industry. To further explore the potential for non-electrical applications of nuclear power, the lab recently completed a study of the feasibility of coupling a small nuclear power plant to a biofuels production plant.

### (4) Designing advanced reactors and closing the fuel cycle

A new generation of nuclear plants that incorporates advanced designs and fuel cycles that reduce the production of long-lived radionuclide waste elements in the spent fuel is needed.

Current practice at nuclear power plants is to use fuel assemblies for four to six years and then remove them and store them. "When we do that," says Greene, "we throw away more than 90 percent of the fuel's original energy value."

Greene outlines three main goals in recycling nuclear fuel. "We would like to recover and reuse the uranium, potentially recover the plutonium for use as mixed oxide fuel, store the short-lived fission products, and mix the long-lived waste products back into reactor fuel to transmute them into shorter-lived radionuclides."

"The ultimate goal would be to achieve an economical, environmentally sustainable fuel cycle that achieves as close to 100 percent recycling of nuclear fuel as possible," Greene says.

Beierschmitt notes that, "The nation no longer has a dedicated experimental fast reactor, but our High Flux Isotope Reactor can produce fast neutron fluxes in the core that are approximately equal to those produced at the last operating fast reactor."

A large part of the research done at ORNL's nuclear facilities focuses on the fast reactor technology needed to close the fuel cycle by reprocessing spent fuel in ways that would minimize waste and eventually allow the industry to "burn-up" the heavy actinides that pose long-term storage problems.

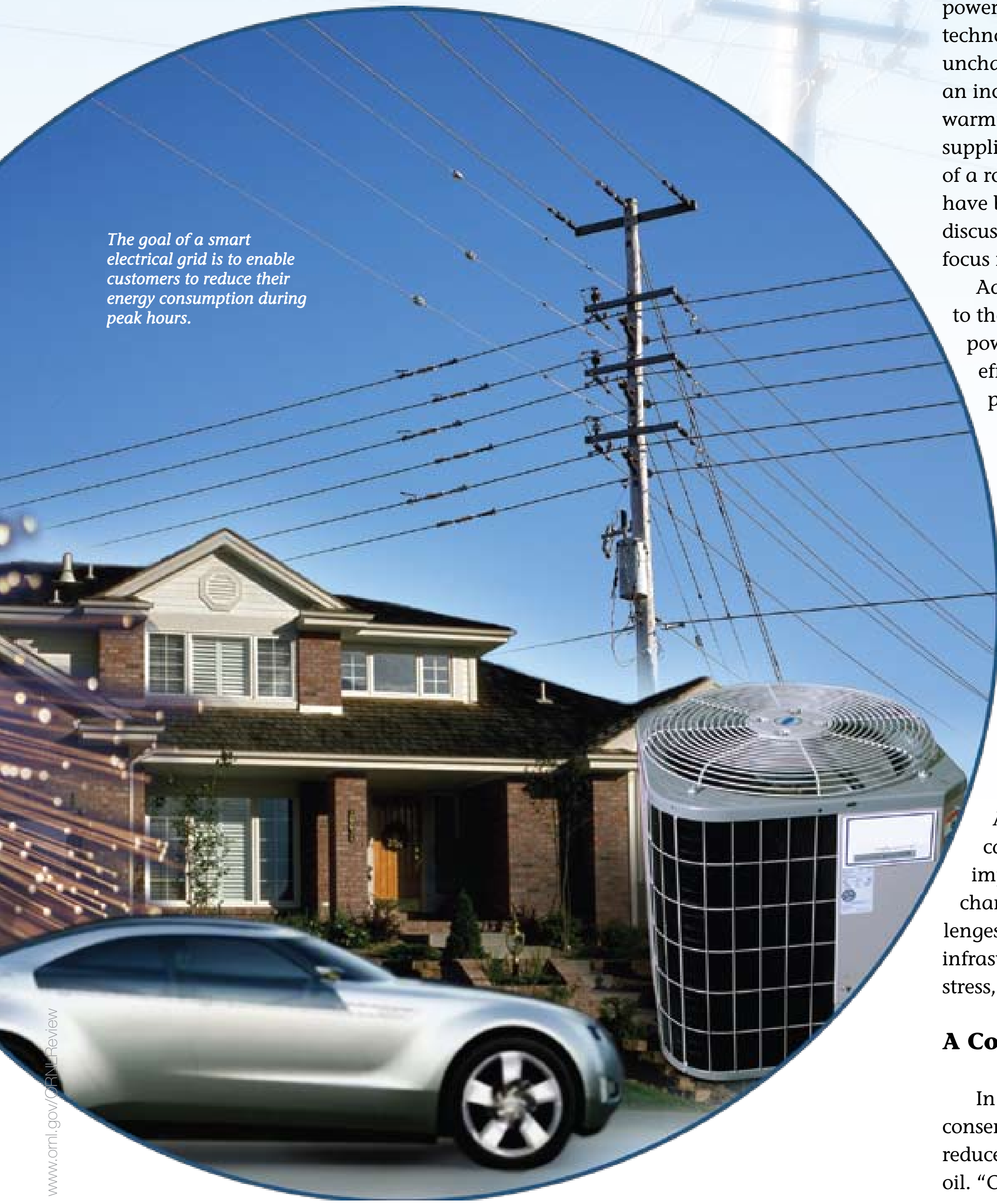
"That's a big part of our program here," Beierschmitt says, "doing that design work for the next generation of fast reactors. There are a lot of players involved in this effort—from engineers developing the processing equipment to materials researchers fabricating targets for burn-up. Computational researchers are also involved—creating simulations to help us understand the physics behind how fuel is burned in current reactors and to validate models that will help us design the next generation of reactors."

Beierschmitt sums up a complex issue succinctly. "Nuclear power is the simplest path to getting carbon-free megawatts on the grid." Less simple is how fast the American public can get comfortable with the idea that nuclear power will be an increasing part of their energy future.

# Breaking the Grid Lock

## PROBLEM:

### *Can a modern electrical grid change American habits of energy consumption?*



*The goal of a smart electrical grid is to enable customers to reduce their energy consumption during peak hours.*

As innovation has transformed much of the global economy, America's electric power grid has remained based upon technologies that have been virtually unchanged for decades. In parallel with an increasing public awareness of global warming and the need for sustainable supplies of energy, the potential benefits of a robust, intelligent, interactive grid have become a centerpiece of policy discussions and an emerging research focus for the Department of Energy.

Advocates of grid modernization point to the need to accommodate diverse power generation sources, ensure more efficient and more reliable service, and provide consumers with the information necessary to manage household energy consumption.

Tom King, director of ORNL's Energy Efficiency and Electricity Technologies Program, has spent years studying both the potential benefits of transforming the nation's power grid and the challenges that will have to be overcome prior to meeting the energy demands of the coming decades. Echoing his ORNL colleague David Greene (see "Both Directions at Once," page 4), King summarizes America's challenges into two distinct categories: energy security and the impact of energy options on climate change. "Solutions to both of these challenges will place a burden on an electric infrastructure that is showing signs of stress," King says.

### A Convergence of Issues

In the area of energy security, consensus exists about America's need to reduce sharply current levels of imported oil. "One nearest-term option may be the growing convergence of the electric delivery and transportation systems," King says, "The growing use of hybrid electric vehicles will combine, over the next decade, with the introduction of plug-in electric vehicles. Depending upon when and how fast these vehicles charge, their collective impact on the grid could be significant."

The second challenge, and one related to energy security, is how to generate adequate energy while simultaneously decreasing the negative impact of energy production on the environment. King believes that electrification of the transportation system could meet roughly one-half of the $CO_2$ reduction goals for transportation. Such a dramatic increase in electric vehicles, however, would result in a corresponding increase in the demand on power plants to charge the vehicles' batteries. "Much of this demand is likely to be met by a greater penetration of renewables into the energy market to address the environmental concerns," says King. Although a good thing, these variable and intermittent resources can pose problems for the grid. Utilities will need to understand the potential impacts of these new energy sources on the electric delivery system before making long-term investments."

For example, when we look at energy security and climate challenges, each technology pathway has major impacts on the grid. "Many advocate a reduction in the use of coal," says King, "but such a decision must come with a clear understanding of other energy alternatives. Increasing our use of renewable energy sources is a desirable option, but we must be realistic in projecting the ability of renewable sources to meet future energy demand."

One as yet unresolved issue related to renewable energy sources is the effect of power inverters on the grid. Inverters are used to convert the electricity generated from solar panels, for example, into power that can be transmitted across the grid. Wind and solar energy farms require the intensive use of power inverters. Experience has shown that, when large numbers of inverters are on the distribution system, they can interact in ways that can create stability challenges to the grid.

"We have to understand what those consequences could be," King says. "Safety and reliability require that a plan to generate significant amounts of energy from renewable technology must ensure that all of the system's components are compatible before deployment. The technology pathways needed to address these problems will demand a robust electrical infrastructure."

Over the past two or three decades, a general uncertaintly about the direction of regulatory policy led to a lack of investment in new grid technologies. King emphasizes that closing this technology gap means more than just building more transmission towers. It also means making the grid "smarter."

## Reshaping Behavior

By King's definition, a smart grid combines a two-way communication infrastructure with a power delivery system that can handle a range of new generation technologies, such as renewables, monitoring devices or fault current limiters. The smart grid would also enable customers to be more responsive in energy management.

"A smart grid is much more than placing a new meter on the side of a home in hopes of reducing demand," King says. "The goal is to enable more customers to understand how they consume energy and to respond to price signals in a way that reduces peak consumption."

"Many consumers have little appreciation for how much it costs if their kids leave the lights on," says King, "or for the financial impact of running the refrigerator or setting the thermostat in the summer at 72°F instead of 76°F. Currently there is no easy way for the American consumer to understand the relationship of use and cost of energy."

"Over the next five years," King says, "the market will make available to consumers a variety of in-home monitoring devices that will indicate in real time how much electricity is being used, along with the precise cost. In other words, turning off a light will reveal the immediate savings. Only a real-time monitoring system that is visible to the consumer will provide the motivation needed to alter behavior to the extent required to produce a significant reduction in energy consumption."

At present, most regions of the United States have fixed-rate pricing for electricity, meaning the cost is the same regardless of when the power is used. King foresees an accelerating trend toward time-of-use, or real-time, pricing to provide a strong financial incentive for consumers to move some of their power usage, like washing clothes or dishes, to off-peak hours. Time-of-use pricing would help utilities level daily demand on the grid and greatly reduce stress on the system during peak heating and cooling hours in the summer and winter. Equally important is the fact that utilities would be under less pressure to build new power plants to accommodate peak periods of demand.

King believes that development of a capacity for the grid to store power, perhaps by batteries positioned at substations, could be an additional way of reducing stress on the system, both at the bulk transmission level and at the distribution level. "As America moves toward increased market penetration of renewables," says King, "the ability to integrate technologies like wind or solar with storage devices would be transformative. Such concepts are high risk, but they are also high reward and are likely to present a variety of research opportunities for the laboratory in the near future."

"The goal of providing energy security in an environmentally benign way is among the biggest challenges facing humanity," King says. "Energy will continue to be a critical component of almost everything we do that sustains our quality of life. Meeting $CO_2$ reduction goals represents a new dimension of this challenge."

Unknown is whether the scientific community can develop revolutionary technologies, like an interactive electrical grid, that will be accepted by a public accustomed to an unlimited supply of affordable energy. Even less clear is whether sufficient time exists to find the answer.

# What's In Store

## PROBLEM: *What happens to renewable power when the wind doesn't blow and the sun doesn't shine?*

One of the most critical scientific challenges confronting American energy security is the elusive ability to integrate plentiful, yet intermittent, power sources, such as wind and solar, into the electrical grid. The Department of Energy estimates that by 2020, wind and solar power could account for more than 20 percent of the nation's generation capacity. Equal to America's existing inventory of nuclear power, the goal will only become a reality if researchers can develop new energy storage technologies capable of capturing excess energy at peak generation times and storing it for use when generation from these renewable sources is low or non-existent.

Tom King, Director of ORNL's Energy Efficiency and Electricity Technologies Program, notes that the electrical grid differs currently in one significant way from other energy distribution systems, such as oil and natural gas, in that electricity cannot be stored cost effectively. "At present, generation must be balanced with consumption," King says. "In simple terms, if I turn on the light, more power needs to be generated. If I turn off the air conditioner, less power needs to be generated. America has operated for more than a century with the ultimate just-in-time process."

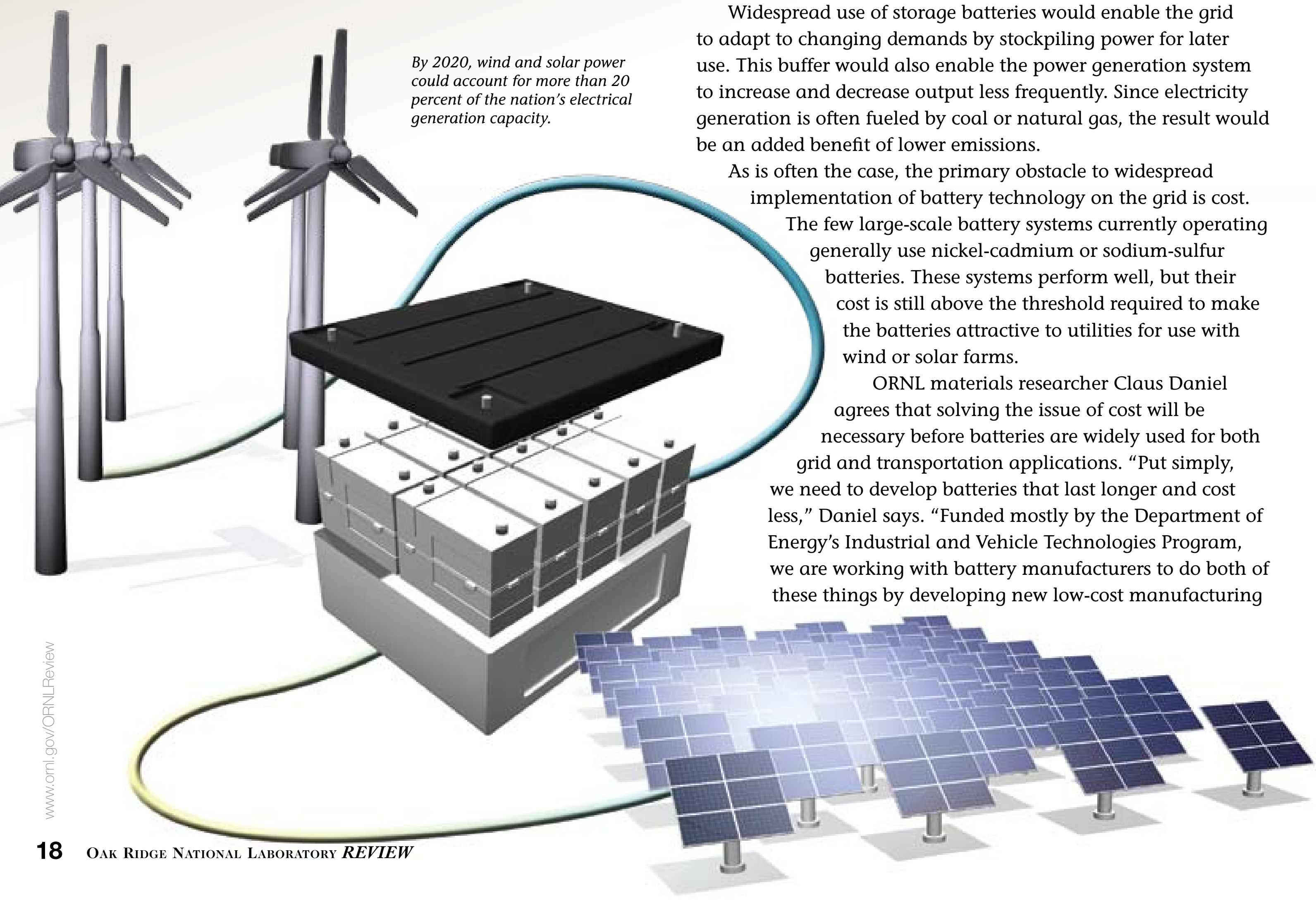
The only large-scale power storage strategy currently in use is "pumped hydro," a system that every night uses excess energy from hydro-electric dams to pump water uphill to reservoirs when demand is low. The next day, when demand rises, the stored water is released and routed through turbines to generate electricity. "The Tennessee Valley Authority has a pumped hydro system that can generate 1500MW of power," King says. "That's like having an extra nuclear power plant."

While pumped hydro is an option only where hydroelectric dams already exist, similar levels of electrical energy storage can be achieved with the use of massive batteries. "Having that much storage at multiple points on the grid would fundamentally transform the way electricity is delivered," says King. "If every substation had a low-cost storage battery, the country could have a more reliable electrical system."

Widespread use of storage batteries would enable the grid to adapt to changing demands by stockpiling power for later use. This buffer would also enable the power generation system to increase and decrease output less frequently. Since electricity generation is often fueled by coal or natural gas, the result would be an added benefit of lower emissions.

As is often the case, the primary obstacle to widespread implementation of battery technology on the grid is cost. The few large-scale battery systems currently operating generally use nickel-cadmium or sodium-sulfur batteries. These systems perform well, but their cost is still above the threshold required to make the batteries attractive to utilities for use with wind or solar farms.

ORNL materials researcher Claus Daniel agrees that solving the issue of cost will be necessary before batteries are widely used for both grid and transportation applications. "Put simply, we need to develop batteries that last longer and cost less," Daniel says. "Funded mostly by the Department of Energy's Industrial and Vehicle Technologies Program, we are working with battery manufacturers to do both of these things by developing new low-cost manufacturing



*By 2020, wind and solar power could account for more than 20 percent of the nation's electrical generation capacity.*

processes and better quality control practices for battery components. This capability is enhanced by our ability at ORNL to use computer simulation to narrow down the parameter space that defines the best solution to a processing challenge. The relationships our staff enjoys with automotive and industrial companies are key to our current success."

ORNL's extensive experience with process development and materials characterization enables the laboratory to help industrial partners scale new processes for industrial production. "Some of the battery manufacturers have new materials that show tremendous performance on the bench scale," says Daniel, "but it can be difficult to scale to mass production of these materials and systems. We can use our experience to help them overcome these problems."

Some of the most innovative research in this field is focused on improving battery reliability by understanding—at a microscopic level—how batteries charge and discharge. "One of the factors that limits the lifetime of batteries is mechanical degradation of the electrodes," says Daniel. "For example, when we charge a lithium-ion battery, lithium ions enter the anode (the negative terminal of the battery), expanding it by 10 percent, in the case of carbon anodes. When the battery discharges, the ions leave and the anode shrinks." Repeated expansion and contraction can cause cracks in the anode that eventually lead to degradation and capacity fade. One of Daniel's Ph.D. students is developing an in-situ characterization technology to investigate this degradation and understand it better.

## America has operated for more than a century with the ultimate just-in-time process.

To understand this and other degradation mechanisms, ORNL materials researchers Karren More and Niels DeJonge have designed a system that enables a working battery to be examined in an electron microscope. DeJonge had previously developed a way use the microscope to image biological samples in a liquid environment. "We are using that same idea to image the operation of a small liquid battery cell at very high resolution," Daniel says. "We are hoping to see exactly how battery materials interact with the liquid electrolyte, how they degrade, and how dendrites—irregular deposits on the electrodes that can cause short circuits in batteries—are formed."

"This research should help us understand what goes on at the material interfaces and how battery components break down," says King. "If so, researchers can develop ways to extend the life of the materials and create more durable and cost-efficient batteries." King and his colleagues plan to extend this line of inquiry using ORNL's unique neutron scattering capabilities. "The goal is to extend the life of the systems, in effect, to get more charges and discharges," says King. "In the same process, a second goal is to determine if we can reduce the cost of the systems by using lower-cost materials."

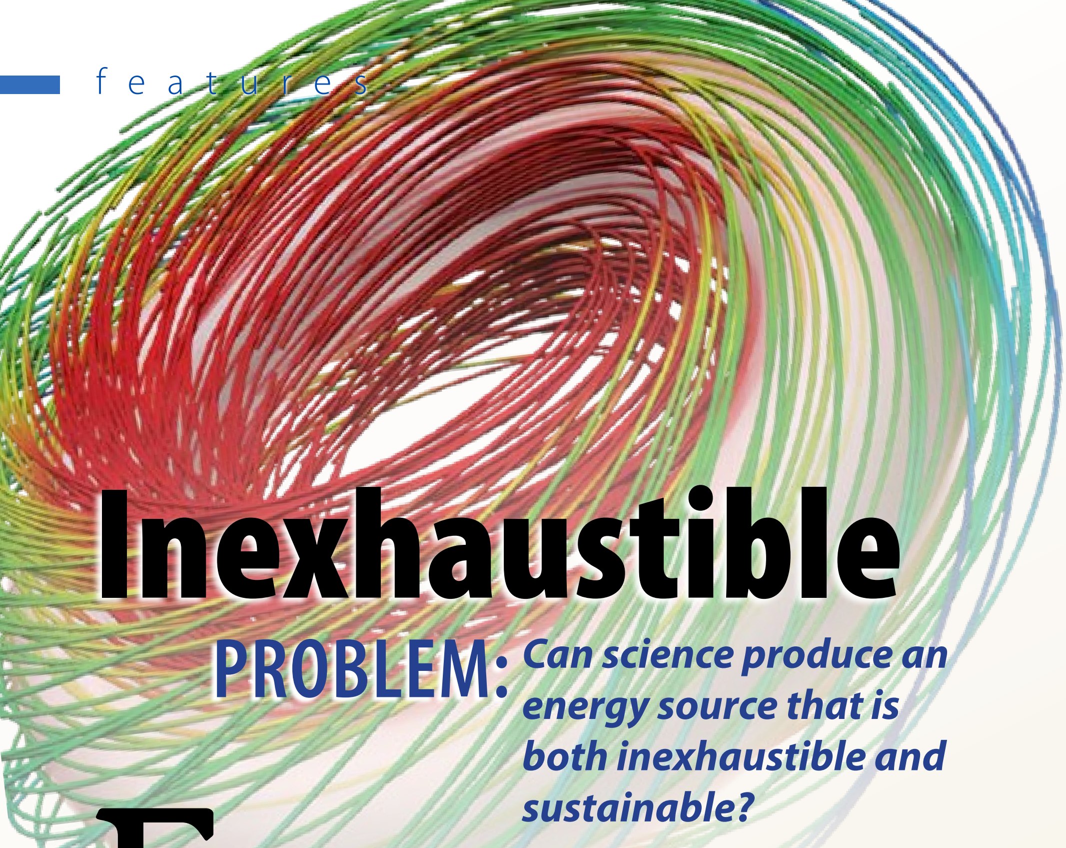
Researchers are also looking at ways to increase the power-density of battery systems—storing more energy in a smaller battery. This effort has important implications for both grid storage batteries and for batteries used in electric vehicles. King believes the development of high-power, high-energy-density batteries on the vehicle side will feed into the electricity delivery side—and vice versa.

Encouraged by the American Recovery and Reinvestment Act, King anticipates a wave of grid-related storage research. He expects millions, if not billions, of dollars of research and development.

If the funding becomes available, there are several areas to which King would like to give more attention, including modeling and simulation of battery systems and research and development related to low-cost manufacturing processes. King hopes to incorporate some of this research, with demonstration projects, into ORNL's Sustainable Campus Initiative. Preliminary plans include solar-covered parking areas for plug-in electric vehicles that are linked to innovative energy storage devices. King believes such a project would provide an opportunity to study user behaviors, charging and discharging of the vehicles, and impacts to the electric distribution system. He wants to gather data on when vehicles charge and how fast they charge—with an eye toward reducing vehicle charging rates on hot afternoons to divert power to building cooling systems. In other words, he hopes to learn how to control the use and generation of electricity.

"The challenges are imposing, but the opportunities are huge to make genuine progress and make a lasting contribution for the country."

*Solar-covered parking for plug-in vehicles would provide an opportunity to study user behavior, battery performance, and impacts on the electrical grid.*



# Inexhaustible

## PROBLEM: *Can science produce an energy source that is both inexhaustible and sustainable?*

For approximately 50 years, domestic and international policymakers have been presented with periodic proposals for nuclear fusion, a technology that some advocates have claimed could be a "silver bullet" answer to the world's increasing demand for clean energy. Indeed, nuclear fusion has been touted by segments of the international scientific community as a genuine solution to a large portion of the world's increasing demand for energy. From their perspective, fusion energy is both safe and environmentally benign. Equally important, the fuel source used by fusion is virtually inexhaustible.

To skeptics, the promise of fusion energy represents a technology that for decades has always been "thirty years away" from deployment. For the first time, the thirty-year prediction may be realistic. Supported by an unprecedented international research effort, the first fusion reactor designed to produce more energy than it consumes is being constructed in Cadarache, France, by a coalition of nations that includes the European Union, Japan, China, India, South Korea, Russia and the United States. The experimental reactor, called ITER, is scheduled to go online in 2018.

The American contribution to the multi-billion-dollar research and development effort is being spearheaded by the U.S. ITER Project Office at ORNL. "Oak Ridge was chosen to lead the ITER project largely for two reasons," says Deputy Project Manager, Carl Strawbridge. "ORNL has a depth of management expertise in distributed partnerships from our recent experience in designing and building the Spallation Neutron Source, In addition, at ORNL, Princeton Plasma Physics Laboratory, Savannah River National Laboratory and their associated research institutions, we have a collective wealth of technical expertise in the area of fusion energy—particularly in several specialized technologies where the U.S. is the world leader."

Strawbridge notes that ITER is an enormous management challenge, not only because of the project's global scope but also because all of the member countries have major responsibilities to deliver complex components on time and within budget. "The failure by any country to deliver," he says, "has a ripple effect on the entire project. We are just now discovering how challenging it can be to put a system together with nations that have different cultures, different currencies, and different areas of technological capabilities."

Strawbridge describes ITER as "an advanced prototype of a production fusion reactor that will test the feasibility of using this technology on a commercial scale." When completed, ITER is expected to produce 10 times more energy than it will use to maintain the thermonuclear reaction.

The long-term benefits of commercializing fusion power could be worth the short-term frustration of building the reactor. Unlike oil, the fuel used by fusion is essentially unlimited. "Deuterium, a stable isotope of hydrogen found in water, is the primary fuel," ITER Chief Technologist Stan Milora says. The other essential fuel is tritium. Fusion reactor designers take advantage of the neutrons the reactor produces by lining its walls with components that contain a form of lithium. The lithium combined with a neutron makes tritium. "The production of tritium can be self-sustaining in that respect," Milora says "There is enough lithium to last for thousands of years."

Compared with other large-scale power generation methods, fusion power has essentially no negative impact on the environment. Unlike both coal and nuclear, fusion power emits no greenhouse gas and leaves behind no long-term waste products. "The materials that we will use to build the reactors are called low-activation materials," Milora says. "When the materials need to be replaced, they will be much less radioactive than components from nuclear fission reactors. That means we can bypass the controversial issue of how to store highly radioactive reactor parts." Milora believes the absence of emissions and legacy wastes means that fusion reactors "could be built in any country, with the fuel available to all nations"

The anticipated amount of power produced by ITER will be much greater than in previous experimental fusion machines," Milora says. "The Joint European Torus had fusion gains of about one half. ITER's gain is predicted to be about 20 times larger. The increased efficiency will come from making the plasma hotter and denser and maintaining it at a higher pressure. That will be accomplished by making ITER much bigger than its predecessors."

Although ITER is strictly an experimental reactor, the project is being designed on a scale similar to a future commercial, power-producing fusion reactor. When fully functional, plans call for ITER to produce about 500MW of power. Milora expects that if ITER proves feasible, future production reactors of comparable size would produce as much as 2.5GW of power. To boost the power output by a factor of five in the same space, researchers will have to devise a way to increase the pressure of the plasma by a factor of about two. "That's a challenge on the physics side," Milora says, "because the plasma is essentially contained by magnets that balance the plasma pressure. As the pressure is increased, that delicate balance will be harder to maintain."

Maintaining control of the plasma is one of the two big challenges confronting the ITER research staff. "The plasma has a very complex shape," Strawbridge says. "Controlling it is a very dynamic process. Monitoring the diagnostics associated with the plasma, understanding how it's behaving, and ensuring that it's stable are critical." The other challenge involves materials technology—developing components that can tolerate both the proximity to the intense heat of the fusion plasma and the huge temperature swings that occur as the ITER cycles on and off.

The primary responsibilities of the U.S. contribution to ITER include providing the central solenoid magnets, which are the core of the ITER machine, and providing a sizable share of the plasma-facing components. "We are working with our partners at Savannah River National Laboratory on the tritium exhaust plant," Strawbridge says, "and with Princeton Plasma Physics Laboratory on developing diagnostics and providing steady-state electric power. ORNL's other major deliverable for ITER is the cooling water system for the tokamak—the part of the machine that contains the plasma."

Unlike a production reactor, ITER's initial objective is the generation of power in bursts that will enable researchers to understand how to control the energy-producing plasma. "There is a well-established mission for ITER," Milora says: "to generate 500MW of power for 500 seconds, wait 2000 seconds, then repeat continually the process of producing 500MW bursts for 500 seconds." The gaps between power bursts will be used to recharge the systems that produce and contain the plasma and to process data to prepare for the next pulse.

Strawbridge anticipates that ITER will be able to produce and control plasma for up to four or five minutes. If attainable, the result would represent essentially a steady-state operation and a breakthrough in scale from previous fusion demonstrations measured in seconds. Once that capability is demonstrated, the subsequent goal would be a full steady-state operation of fusion power.

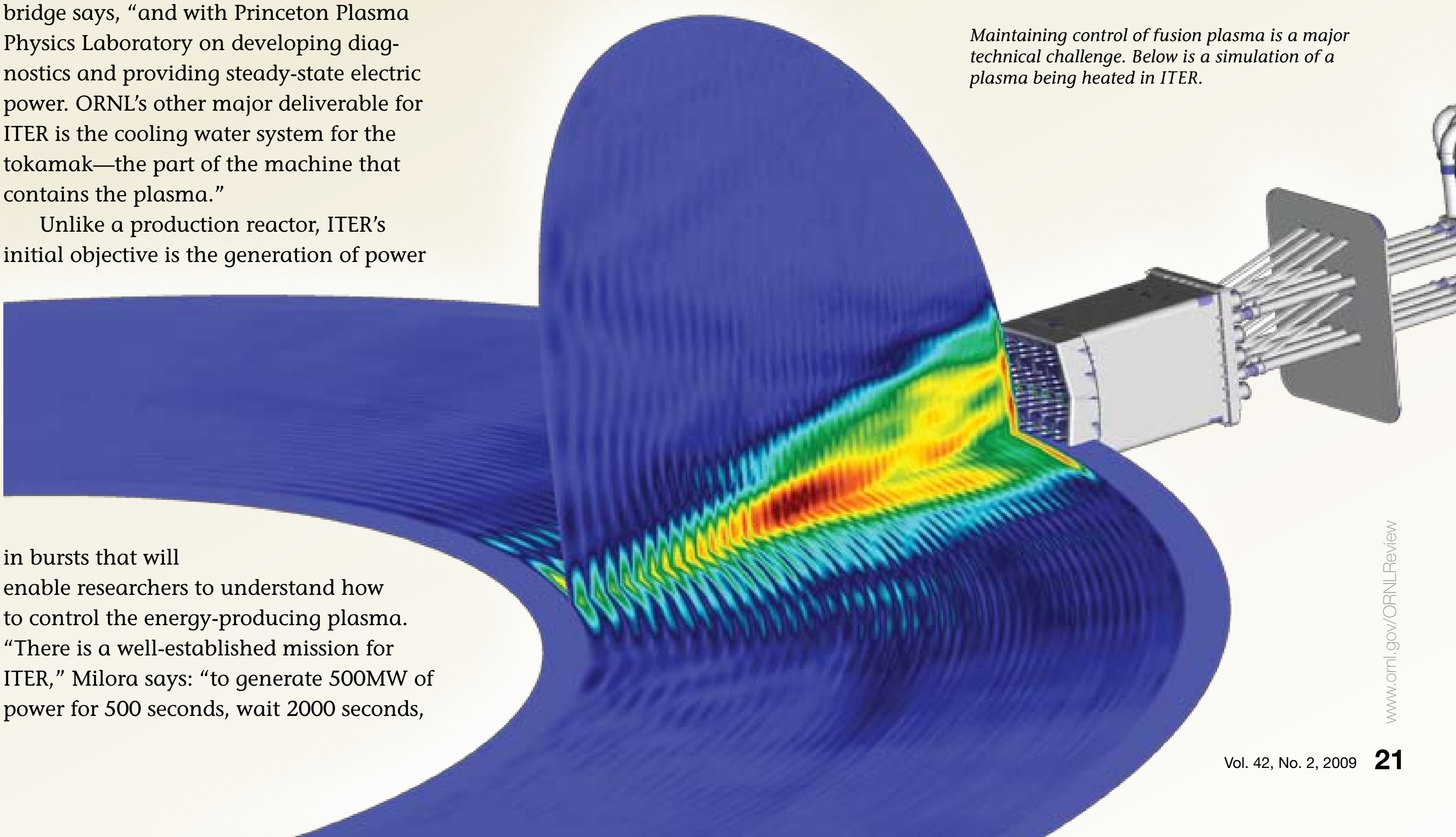
A key principle of the ITER project is the sharing, not only of cost but also of the information and data generated by the experimental reactor. Once ITER is in operation, plans call for an exhaustive experimental regimen. "After about five years of experimentation," says Strawbridge, "any ITER partner should have access to enough information to begin designing a commercial fusion reactor. In theory, any country that has participated in the collaboration will know enough to build their own machine. Countries with huge energy demands may choose to head down that path quickly."

Both Strawbridge and Milora are optimistic about the future of fusion energy, suggesting that if ITER proves successful, fusion might quickly become competitive with traditional energy sources. "We are convinced that when the demonstration reactors that follow ITER have completed the development cycle, the cost of building a production reactor will be competitive with that of other large fossil fuel or nuclear power plants," he says.

"If we are able to generate fusion power on a commercial scale," Strawbridge says, "the hope is that it will be every bit as cost competitive as other major power sources—especially if we consider the substantial costs associated with the supply chain of other fuels."

Perhaps even more important than cost and accessibility, ITER holds out the hope of abundant clean energy from a basically inexhaustible source—water. "The fusion process is entirely safe," Strawbridge says. "When the plasma's off, it's off." In effect, fusion power could be an energy option without dramatic accident scenarios and no long-lived waste products. Fusion is not a silver bullet for all of America's energy needs, but it could go a long way toward providing a part of an energy solution that is environmentally sustainable."

*Maintaining control of fusion plasma is a major technical challenge. Below is a simulation of a plasma being heated in ITER.*



# Protecting from the Unthinkable

## PROBLEM: *Can new technologies stem the proliferation of nuclear materials?*

ORNL's research and development portfolio, perhaps the most diverse of any U.S. national laboratory, has a distinguished tradition of nuclear research and innovation reaching back to the Manhattan project. Today a portion of that nuclear legacy is being applied to the international challenge of keeping nuclear materials secure and limiting their use for peaceful purposes.

Addressing what has become one of America's most critical national security challenges is ORNL's Global Security and Nonproliferation Programs group, headed by Larry Satkowiak. When it comes to non-proliferation issues, Satkowiak says the main concerns are always, "Materials, materials, materials—eliminating access to materials, moving materials from locations that are at risk, detecting the illegal movement of materials, and down-blending materials so they are no longer capable of being used as a weapon of mass destruction."

Most of the work Satkowiak's group is involved in is funded by the Office of Defense Nuclear Non-proliferation within the National Nuclear Security Administration. The ORNL group's activities run the gamut from basic research and development to field implementation of security systems.

Satkowiak notes that many of the non-proliferation issues we face today have been the same for the last 15 or 20 years, a period that coincides roughly with the collapse of the Soviet Union and the creation of former Soviet states that overnight became nuclear powers. Chief among these issues is the need to secure materials that could be used in an improvised nuclear device and securing and removing radiological materials that could be used in a dirty bomb. "The Department of Energy has made a lot of progress in this area," Satkowiak says, "particularly with the work that has been done with the states of the former Soviet Union, but we're not quite there yet."

Over the last three years, ORNL has been helping to fulfill the terms of the Bratislava Agreement, a nonproliferation pact negotiated between the United States and Russia in 2006. Under this agreement, the United States agreed to help provide safeguards and security assistance for weapons storage sites, missile sites, dismantlement locations, and other facilities within the Russian nuclear weapons complex. "There has been a genuine push by both parties during the last three years to complete the work outlined by this agreement," says Satkowiak.

ORNL's contribution to this assistance package included providing upgraded measurement equipment, technical experts for improving the security of the facilities, and training on the tracking of nuclear materials. "The critical first step is knowing what materials you have, how much you have, and where the materials are located," Satkowiak says. "Teams from ORNL and Sandia National Laboratories have made significant contributions to the security of these Russian facilities, with follow-on work to continue."

One of the keys to controlling the proliferation of nuclear materials is the ability to detect their movements—in and out of buildings, through ports, and across national boundaries. ORNL is working the detection issue on several technology fronts. "We are developing materials that can be used in the next generation of radiation detectors," Satkowiak says. "The researchers are trying to make them smaller, more sensitive, and more robust, so they can be deployed in the field both domestically and internationally."

Most of these down-sized detectors are hand-held devices, designed to be carried by inspectors. For larger-scale applications, Satkowiak's group is also working on improving the detection capabilities of so-called "portal" monitors—sensors that can detect nuclear materials being transported on roadways or through international ports. "Some are deployed overseas near government buildings to detect the presence of radioactive or nuclear materials within approaching vehicles," Satkowiak says. "Similar technologies are deployed at international and domestic ports to monitor goods going in and out of the United States."

The ORNL team is also working with a number of countries in the National Security Administration's Megaports Initiative, encouraging them to monitor U.S.-bound cargo shipments for nuclear materials. "It's another layer of protection," Satkowiak says. "We can monitor U.S. ports, but if we expand this monitoring by another layer and intercept dangerous materials before reaching our ports—even better."

Some countries initially were less than enthusiastic about the Megaports Initiative. Satkowiak says their perspective changed when the monitors revealed radioactive materials coming into their own countries.

ORNL's new generation of detectors is designed to be sensitive to smaller amounts of radioactive material, as well as to accommodate the need to detect materials in fast-moving vehicles. "One of the limitations of our current detection systems is that vehicles need to be moving at a steady rate of about 8-9 miles per hour," Satkowiak says. "By making detectors more sensitive, researchers can increase the transit speed of the vehicles and still maintain the detection capability." Keeping transit speed high is a key element of deploying portal detectors in high-traffic areas.

In addition to enhancing detector technology, Satkowiak's group has also responded to concerns over the need for more effective controls on the shipment of nuclear components. In the last several years, networks dedicated to the smuggling of nuclear

technology and related components have been responsible for the some of the most highly publicized examples of nuclear proliferation, including those involving Libya, North Korea, and Iran. When authorities looked at how these networks operated, they found that the material was often shipped through several countries, often with limited or ineffective export controls.

This realization has resulted in a concentrated effort to raise awareness about the importance of export licensing. “If someone tries to ship equipment that potentially has anything to do with uranium or nuclear technology in the United States,” Satkowiak says, “the Commerce department sends the issue to DOE, and DOE sends it to ORNL. We have several staff who are experts in uranium technologies and can provide technical expertise in these license reviews. The other part of the equation requires that our group spend a lot of time working with other countries to help them become more aware of what to look for in terms of equipment that has the potential to be used for nuclear technology.” In the last two years, Satkowiak’s group has conducted export license review training in 40 countries.

Another key aspect of the non-proliferation effort is securing highly enriched uranium (HEU) from dismantled weapons, research reactors, and other sources. Once secured, chemical processes are used to convert the materials to commercial nuclear reactor fuel, or low-enriched uranium (LEU). The nonproliferation group is in the fifteenth year of a 20-year program to take HEU from dismantled Russian weapons and blend it down, in Russia, to commercial reactor-grade fuel that is then sold to the United States. “We have teams that go to Russia and monitor this process,” Satkowiak says, “but we also have a blend-down monitoring system, developed by Los Alamos National Laboratory and ORNL, to monitor this process literally every day of the year. When ORNL staff go to Russian installations, they can immediately download the data and verify how much weapons-grade material went into the process and how much LEU came out.”

The agreement with Russia committed them to blending down about 500 metric tons of nuclear material out of the Russian nuclear stockpile. To date they have blended down about 320 metric tons—about 13,000 nuclear weapons worth of material. This material provides about half of the fuel for our nuclear power plants.

A corollary component of the blend-down program is an effort to reprocess highly enriched research reactor fuel. “In the Eisenhower-era,” says Satkowiak, “the United States and Russia were in a race to build multiple research reactors—a lot of them powered by HEU. Our group has been working with the Russian Research Reactor Fuel Return Program to retrieve fuel from a number of international locations. Once returned, the fuel is blended down to LEU, thus dramatically reducing the risk of proliferation. We have ORNL staff involved in the removal of the fuel and throughout the blend-down process, effectively eliminating any risk of bomb-grade material being diverted,” Satkowiak says.

Nuclear nonproliferation is increasingly viewed as a problem to be addressed globally, rather than just by the “nuclear powers.” Nonetheless, the remaining issues are daunting in both their scope and potential consequences. The magnitude of the challenge is starkly illustrated by Satkowiak’s description of the physical size of the threat. “The plutonium required for a nuclear weapon would fit inside a soft drink can,” he says. “The highly enriched uranium needed for a terrorist to build a nuclear weapon would fit inside a grapefruit.” Despite the challenge, he remains optimistic. “Even though, on a day-to-day basis, the progress may be incremental, over the last ten years we have made significant progress in securing these materials. There’s still much to do, but it’s a good area to be in. We are making a difference.”

*ORNL's non-proliferation work includes upgrading safeguards and security, materials accounting, and packaging practices at foreign nuclear materials storage facilities.*

When Thomas Zacharia was named Oak Ridge National Laboratory's Deputy for Science and Technology in March of this year, he traded responsibility for the world's leading computing program for the challenge of managing ORNL's $1.4 billion research and development portfolio.

We asked Zacharia about his new role and the challenges of leading the lab's technology agenda in changing times.

# Thomas Zacharia

**You come from a computing background. What role do you see computing playing in the development of the laboratory's agenda?**

I actually began my career at the laboratory as a postdoctoral fellow in the Metals and Ceramics Division, so I have both physical and computational sciences in my background.

Computing, alongside theory and experiment, has an important role to play in scientific discovery. From climate change to energy production to energy storage and distribution, computing offers the opportunity to address problems that could not otherwise be solved and to guide the next generation of experiments. As we pursue new energy technologies and new opportunities, computing has the potential to accelerate our progress. Also, because it brings multiple disciplines together, it has the ability to integrate the laboratory around a common purpose. I believe that computing and computational sciences will allow us to address important challenges more effectively as multidisciplinary teams.

**What has been the greatest difference in your new role as Deputy for Science and Technology?**

The principal difference is that I now have a broader exposure to and deeper appreciation for the laboratory, and I now represent the entire laboratory, rather than primarily computing.

I have the opportunity to facilitate laboratory-wide engagement across a broader spectrum of issues and programs. As I look toward the future and the role that the laboratory will play in the areas of scientific discovery and innovation, energy security, environmental sustainability, and national security, I'm impressed by the talent that we have and how well positioned we are to support the Department of Energy's missions and goals. We have the opportunity to positively impact not only the nation but also the planet.

**Are there specific areas in which you may want to reshape this job?**

I don't believe there is any job at this level that is very prescriptive. Everyone brings to the job a unique experience base, as well as goals, dreams, and aspirations for the organization. Will I do this job differently than my predecessors? Probably, yes—because we are different individuals with different life experiences. Am I coming into this job thinking I have to reshape it? Absolutely not. I think my predecessors have done a terrific job in helping this laboratory grow—doubling its budget over a period of about seven or eight years. During that period, we have hired almost 1900 new staff.

During my career, I have been able to pull together different capabilities and talent from across the laboratory to pursue major initiatives and objectives. The challenge that faces all of us in terms of energy security and environmental sustainability requires all of the capabilities we have, from neutron sciences, to computing, to materials, to energy technology, to our strength in translating basic science to applied technologies. I'm hopeful that I can be effective in developing a strategic path forward by engaging the leadership from across the laboratory.

**What areas do you view as ORNL's greatest opportunity in the years ahead?**

We have been given a tremendous opportunity to shape the course of history. I think the research that we perform at the lab—if we are successful—is going to dramatically change how the planet evolves, how we produce and consume energy, how we improve our standard of living, and how we drive the economy.

There is a Chinese proverb that says if we don't make any changes, we are likely to end up where we are headed. We have an opportunity to make some fundamental changes in energy generation and consumption, that will directly affect the global economy. Both are very important because they drive our quality of life. The challenges we face in these areas are immense. I believe Oak Ridge National Laboratory—the people who are the organization—is going to have a huge impact.

We also have the opportunity to create a strategic vision for the future of the laboratory and execute. As Wayne Gretzky said, "Skate where the puck's going, not where it's been." That means we have to be very strategic in our recruiting. We have to hire the people who will create a laboratory that is impactful—not just today or tomorrow, but 10, 20, or 30 years from now. Decisions we make in recruiting are going to have a long-term impact on our ability to perform research and continue to bring about improvements for humankind.

We must also be a good neighbor. A recent article by Chairman Bart Gordon of the House Science and Technology Committee stated that scientists who benefit from the funding provided by the American Recovery and Reinvestment Act (ARRA) program should focus not only on solving scientific challenges but also on creating jobs—not only in the community, but in the region and in the nation. This must be a priority for the laboratory.

**Will the ARRA alter ORNL's mission in a major way?**

Let me use a sports analogy. When you go into a game with a game plan or a strategy, you don't change it based on instantaneous scores, because that causes you to second-guess yourself. You might tweak the game plan a little, but you don't dramatically change the strategy.

The laboratory has some central themes: excel in science and technology, excel in operations, and excel in community service. We have scientific priorities in neutron science, computing, energy technologies, and materials. We're not going to change any of these. We are going to build on our unique ability to translate basic science into applied technologies to tackle the energy challenge.

ARRA along with base S&T budget growth will enable us to accelerate our progress and to sharpen our focus on delivering value and results, while creating jobs. It also gives us tools for growing our S&T base budget.

**What will be the greatest obstacles to meeting the enormous expectations of ARRA?**

The obstacles are clearly the ability to strategically recruit in a timely way and to execute in a purposeful way. We have to execute quickly, and we have to execute wisely. We must have the talent to accomplish those two goals.

I believe that laboratory management and leadership throughout the organization are aware of the importance that this administration and this nation have placed on the scientific community delivering on the goals of ARRA. The President recently announced that he would like to spend three percent of our gross domestic product on science and technology. As a result, I expect substantial growth in science and technology investments—particularly those that are energy related.

This is the time for us to make wise decisions. History will judge us all based on the decisions that we make. If we make wise and thoughtful decisions, history will be kind to us.

**Is there anything you would like to add?**

I knew I would enjoy the new responsibility based simply on the opportunity to positively influence a storied institution with a historic impact in advancing science discovery and innovation. I am thankful for the opportunity to learn more about the laboratory. I look forward to getting to better know the talented people and the capabilities that we have. I am making it a priority to visit different areas of the laboratory at least once a week, to be exposed to the interesting science—but more importantly, to the capable people we have all across the laboratory.

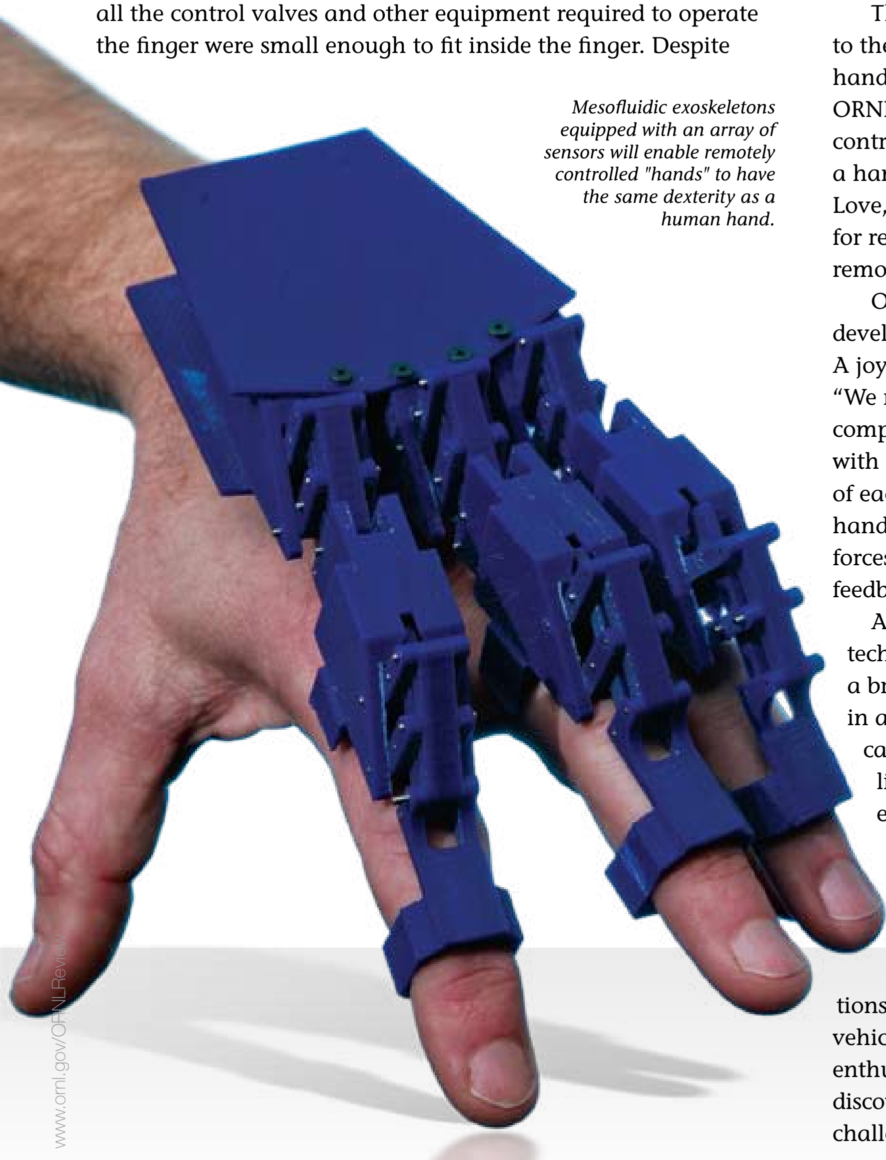
I would also like to mention that the national laboratories, in general, have experienced relatively modest growth for more than a decade. As a result, sometimes people and programs have been narrowly focused. Just as I would like to help facilitate collaboration within Oak Ridge National Laboratory, I am making it a priority to visit our sister laboratories with the goal of being a catalyst for collaboration across the laboratory system.

# Bionic Science

## PROBLEM: *Can prosthetic devices be engineered to feel natural?*

Lonnie Love's robotics group traditionally has worked on robotic applications for big things—really big things, like industrial-scale manipulators and mobile robots. In predictable scientific fashion, one of his colleagues posed the question, "What if we reversed our thinking, scaled the process down and, instead of designing huge robots, started making very small robotic devices?" Some two years later, the answer has materialized in the form of a surge of research in the relatively new field of mesofluidics.

Mesofluidics is the application of millimeter- to centimeter-sized hydraulics to problems that require substantial amounts of power to be generated and applied in a limited space. "One of the first things we demonstrated in this relatively new area of research was an artificial finger powered by mesofluidics," says Love. The unique thing about this accomplishment was that all the control valves and other equipment required to operate the finger were small enough to fit inside the finger. Despite their miniature size, the hydraulics in the finger provide about 20 pounds of pinch force—about twice the force generated by a human finger.



*Mesofluidic exoskeletons equipped with an array of sensors will enable remotely controlled "hands" to have the same dexterity as a human hand.*

Packing that level of performance into such a small space required some innovation on the part of the mesofluidics team. Love credits the group's development of two "enabling" technologies for much of the progress they have made. The first is a small but powerful pump. About a cubic inch in volume, the pump operates at 200 psi and generates about 30 watts of hydraulic power. The other new technology is the specialized valves that control motion in the system. "We cannot buy control valves off the shelf that provide this level of performance at this small scale," says Love. "Because no one makes the kind of high-pressure, low-flow valves needed for mesofluidic applications, we were forced to make them ourselves."

The design of a hydraulic finger led, perhaps predictably, to the group's current effort to design and control a mesofluidic hand. In addition to the obvious prosthetic applications, the ORNL team believes the hand also could serve as a remotely controlled device used for disposing of explosives. "If we can make a hand that has the same dexterity as the human hand," says Love, "we could use the device not only for prosthetics but also for remotely disarming weapons, handling IEDs, and thereby removing humans from the risk zone."

One of the first challenges that confronted the project was developing the ability to control a device of such complexity. " A joystick for every joint in the hand is not practical," says Love. "We needed something more natural." To find the balance of complexity and natural function, Love's team is designing a glove with a mesofluidic exoskeleton. They hope to enable the position of each finger joint to be measured and transmitted to the remote hand. Similarly, the exoskeleton would be able to measure the forces occurring remotely and use mesofluidics to provide force feedback, so the user can 'feel' what the remote hand is doing.

As is often the case with scientific exploration, the enabling technologies developed by Love and his colleagues are leading to a broader understanding that wearable robotics can be applied in a number of areas. The team is currently working with Orthocare, one of the leading American manufacturers of prosthetic limbs, on a system to strengthen weakened joints such as elbows or knees. 'If you have a weak knee," Love says, " it would be nice if you could wear a device that would give that joint a little extra power—not to make you a superman, but to restore the strength that you've lost."

Several companies have expressed an interest in applying mesofluidic technology to other prosthetic applications, as well as the production of small-scale, unmanned aerial vehicles with almost bird-like agility. Not surprisingly, Love is enthusiastic about the future of this line of research. "Our initial discoveries have opened a variety of opportunities," he says. "Our challenge now is to find even more unique applications."

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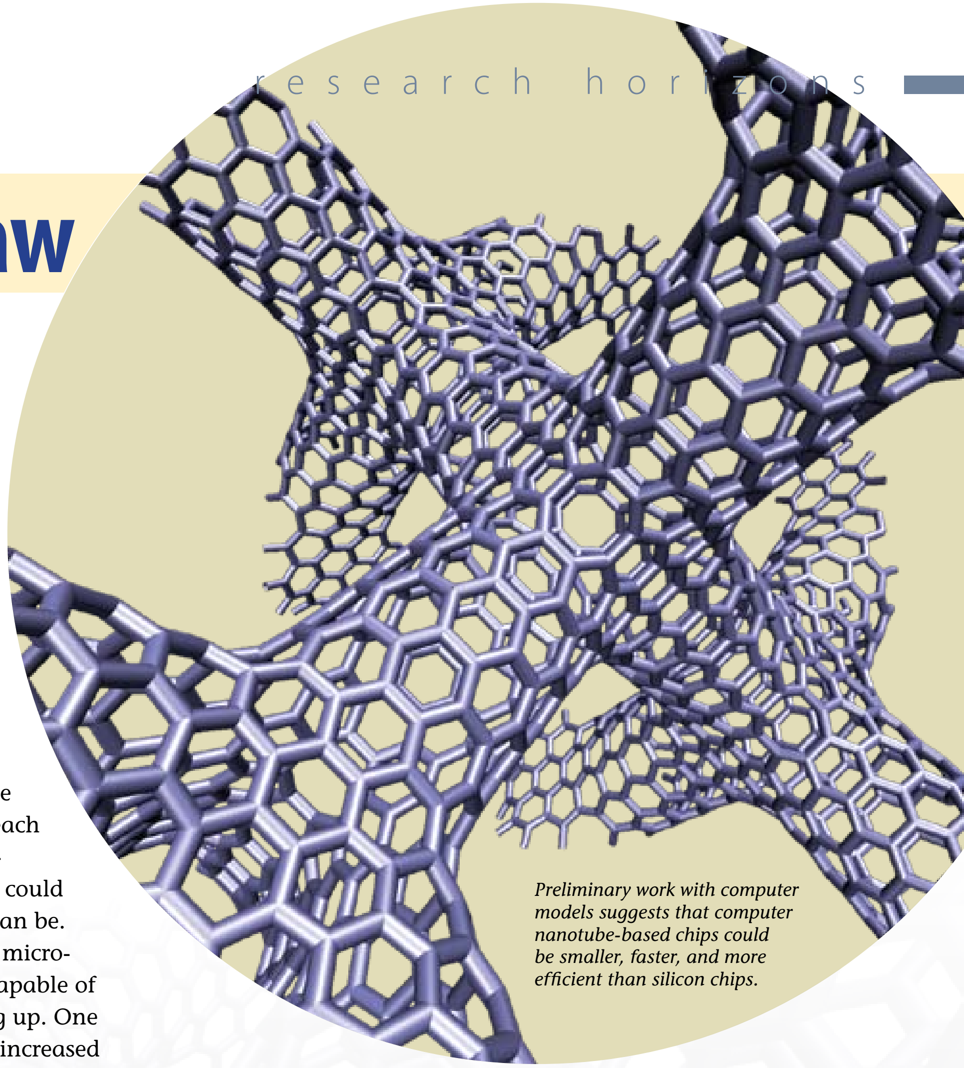
# Breaking the Law

## PROBLEM: *Is the continued growth of supercomputers challenged by laws of physics?*



*Preliminary work with computer models suggests that computer nanotube-based chips could be smaller, faster, and more efficient than silicon chips.*

The ability of Oak Ridge National Laboratory over the last five years to build more powerful supercomputers at an extraordinary pace has been fueled, in large part, by semiconductor manufacturers devising ways to pack more electronic circuits into smaller spaces on silicon microchips. Despite this success, some in the computer industry predict that the drive toward scaled-down silicon microcircuitry will reach its zenith within the next decade as silicon-based electronics collides with fundamental laws of physics that could impose limits on how small silicon-based electronics can be.

In anticipation of silicon's projected demise as the microchip substrate of choice, the search for a technology capable of supporting far greater circuit density has been heating up. One contender, carbon nanotubes, has been the subject of increased scrutiny by Vincent Meunier and his colleagues in ORNL's Computer Science and Mathematics Division and the laboratory's Center for Nanophase Materials Sciences.

"The biggest advantage of carbon nanotubes is that electrons flow through them easily with little resistance," Meunier says. His preliminary work with computer models suggests that computer nanotube-based chips could be smaller, faster, and more efficient than silicon chips. However, when his team attempted to design nanocircuits by stringing nanotubes together, they discovered that electrons treat the intersections between nanotubes as dead-ends.

"Think of ping-pong balls traveling in a small tube," Meunier says. Now imagine that the tube has two branches, like the letter 'Y'. Sometimes the ball may go down one of these branches, but most of the time it will hit the wall between them and bounce back up the tube. Electrons moving through nanotubes behave the same way; when they come to a junction with another tube they are usually reflected back."

To overcome this problem, Meunier's team found that, if the interior surface of the carbon nanotubes is made "rougher" by adding structural defects or impurities, electrons move through the circuit without being affected by transitions between tubes. "We showed that with artificial defects in the nanotubes, we can actually provide more functionality," he says.

Sulfur atoms help to accomplish this trick by adding variety to the normally six-sided ring structure of the tube's carbon molecules. When the sulfur is added to the mix, five- and seven-sided rings appear. These structures not only enable electrons to traverse the molecular network, but they also cause the nanotubes to curve and branch.

One of the ORNL team's goals is to develop a means of seeding impurities selectively throughout the network to create various types of circuits and to guide electrons through the network on a specific path. "Our experimental collaborators grow these networks using a chemical process called self-assembly," Meunier says. "If we tried to assemble them manually, one tube at a time, it would take forever. We are working on techniques, like chemical vapor deposition, to place the tubes where we want them in what would be, essentially, a process of self-assembly."

In addition to developing methods of producing viable nanocircuits, Meunier's team is also seeking ways to establish functionality between nanocircuits and normal-scale electronic devices. One approach has been to use cobalt nanoparticles to make connections between the nanotubes and copper wire. "The ability to connect nanocircuits and even nanodevices to the real world is a big hurdle," he says. When researchers in the past have tried to do this , the connections have been unsuccessful. Any device on the nano side of the connection would be completely overwhelmed by the effect of the interface."

Despite these challenges, Meunier is optimistic about the potential of using carbon nanotubes for a new generation of computer chips. "Circuitry on silicon chips is created on the micrometer scale. But nanotubes are a thousand times smaller and allow us to pack many more circuits in the same space. If we can use nanocircuits and simultaneously use less energy, we will have found a new pathway to even more powerful computers."

# ...and the WINNERS are...

## Accomplishments of Distinction at Oak Ridge National Laboratory

**B.R. Appleton** (former ORNL Associate Director), **Lynn Boatner**, and **C.W. White** (retired) have been elected **fellows** of the **Materials Research Society**.

**Dana Christensen** has been appointed a member of the **University of Tennessee's College of Engineering Board of Advisors.**

**Thomas Wilbanks** has received the **President's Award for 2009** from the **Association of American Geographers.**

**Patrick Mullholland** has been elected a **fellow** of the **American Geophysical Union.**

**ORNL** received the **Secretary's Achievement Honor Award** from the **U.S. Department of Energy,** for significant technical contributions to support nonproliferation goals of the Department and the U.S. Government. **Stan Moses, Norm Turk, Emily Jones** and **their team** have received the **Secretary's Achievement Honor Award** from the **U.S. Department of Energy,** for their major contributions to U.S. nonproliferation policy that significantly strengthened national and global security.

**Claudia Rawn** has been appointed a member of the **U.S. National Committee for Crystallography** by the **National Academies.**

**Mark Reeves** has received the **Laboratory Representative of the Year, 2008,** award from the **Federal Laboratory Consortium, Southeast Region.**

**ORNL** has received the **Federal Champion Award** from **Morehouse College. ORNL** has also been cited as the **Top Supporter of Historically Black Colleges and Universities and Minority-Serving Institutions, 2009**, by ***U.S. Black Engineer and Information Technology Magazine.***

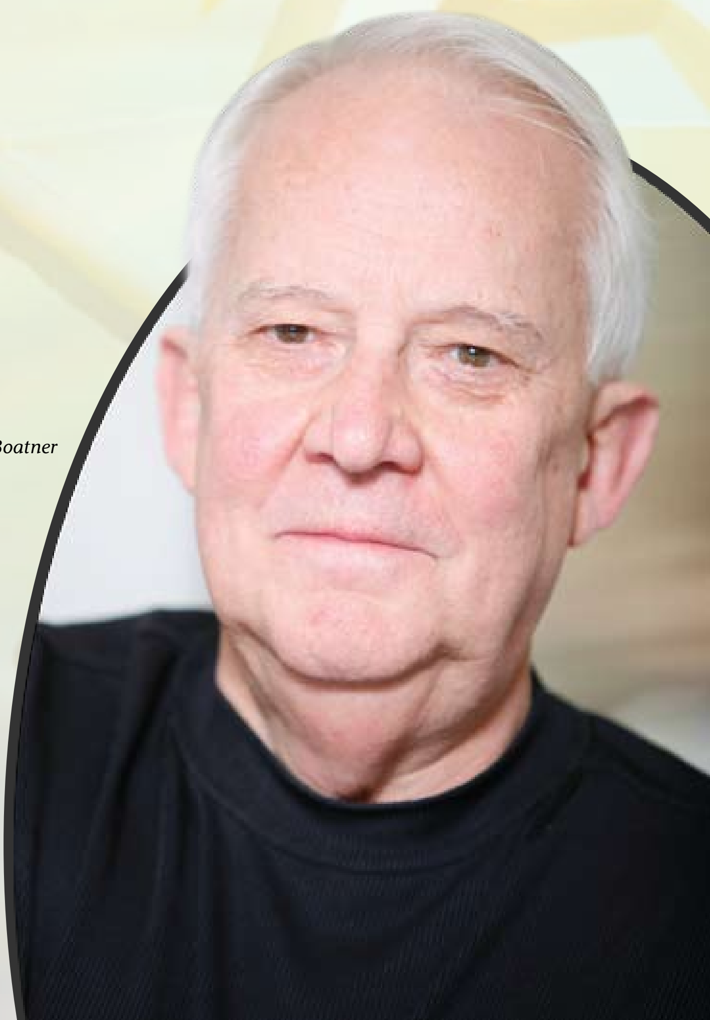
**Pat Hu** has been appointed a **member** of the **National Cooperative Highway Research Program Project** by the **National Research Council/Transportation Research Board.**

**John Groff** has received both the **Bronze Star,** for his exceptional meritorious service and contribution to Operation Iraqi Freedom, and a **Meritorious Service Medal,** for his exceptional leadership, knowledge and dedication to duty, from the **U.S. Army.**

**Edgar Lara-Curzio** has received the **Arthur Frederick Greaves-Walker Award** from the **American Ceramic Society** and the **National Institute of Ceramic Engineers.**

**Stephen Burnette** has been elected to the **Distinguished Alumnus Academy** by the **Tennessee Technological University's Department of Industrial and Systems Engineering.**

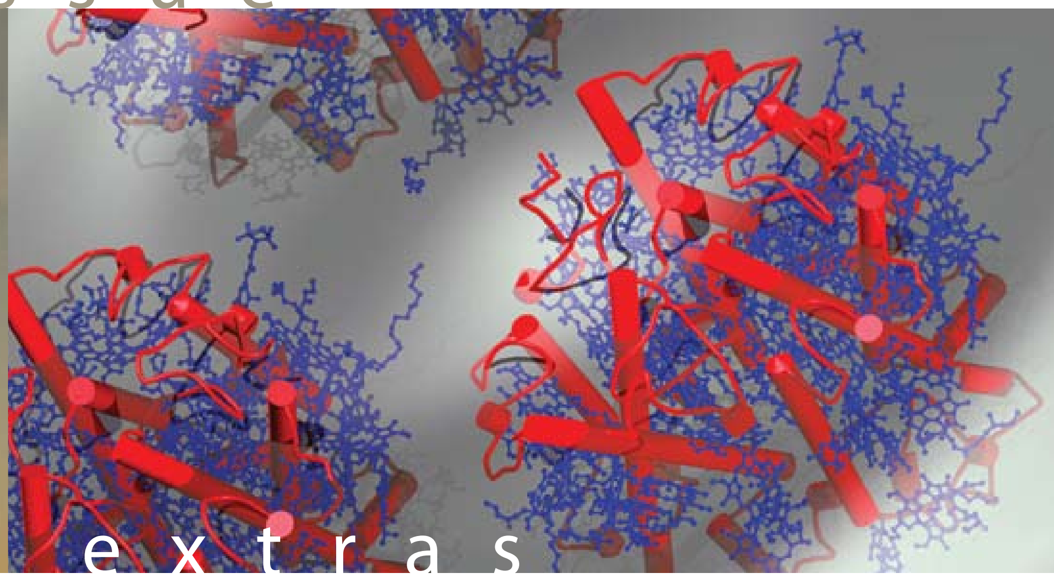
**Fue Xiong** received the **Outstanding Graduate Award in Mechanical Engineering Technology** from **Pellissippi State Technical Community College's Engineering and Media Technology Department.**



*Lynn Boatner*

## next issue

# The Spallation Neutron Source Comes of Age



## online extras

www.ornl.gov/ORNLReview

**on the web**

### Reference desk:

- Read journal papers on research described in this issue.

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