Oak Ridge National Laboratory

REVIEW

Vol. 47 • No. 1 • 2014
www.ornl.gov/ornlreview

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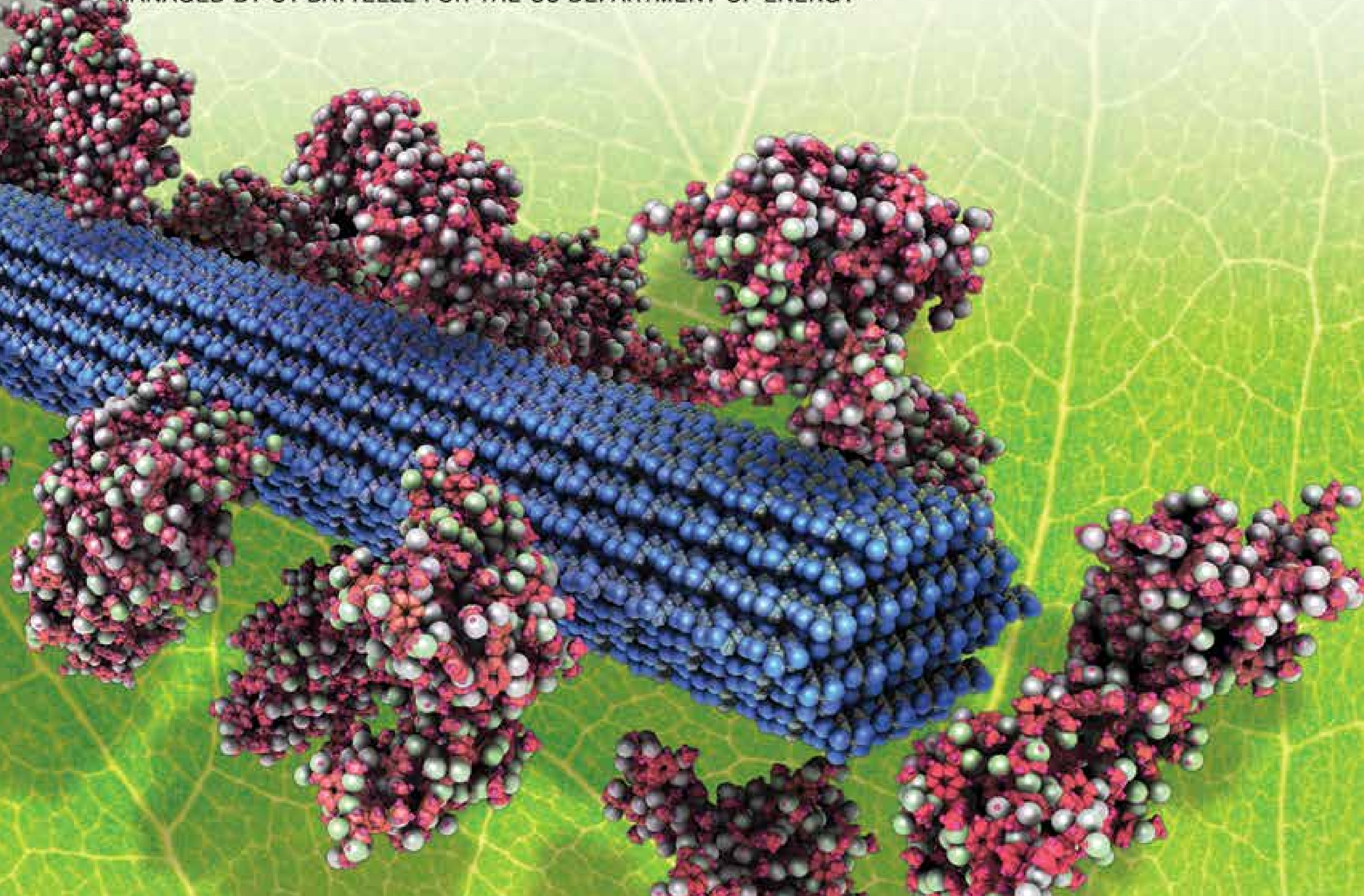

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Vol. 47, No. 1, 2014

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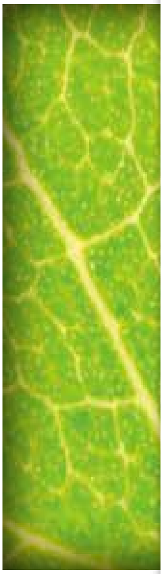
Neutron imaging and supercomputer simulation were used to develop this visualization of the interaction between a cellulose fibril (blue) and lignin (pink) molecules in biomass. Understanding this interaction helps researchers devise ways to convert biomass into energy more efficiently. *Visualization by Jamison Daniel*



Neutrons and bioscience

In the last 15 years, ORNL has revolutionized its neutron scattering capabilities by building the Spallation Neutron Source (SNS) and upgrading the High Flux Isotope Reactor (HFIR). These upgrades have provided world-class neutron sources that are having a transformational impact on science. The analytical capabilities of the SNS and HFIR, when combined with ORNL's supercomputing and materials science expertise, provide the laboratory with an enormous capacity to understand and explain fundamental phenomena across a broad range of materials—organic, inorganic and biological.

At the same time, there has been a revolution in our ability to understand biological systems. For example, over the last eight years, the BioEnergy Science Center has focused on the science of creating synthetic fuel from biomass—deconstructing plant materials all the way from cellulose and hemicellulose down to sugars and then to alcohols and other fuels.

We have seen that neutron science, computing and bioscience intersect intimately in the studies of the fundamental processes that lead to this deconstruction of biological systems. Discoveries that occur at this intersection are being applied to developing new bioenergy crops, biofuels and other bio-based products, as well as providing researchers with a greater understanding of our changing climate and its implications for society and the environment.

Finally, as we are thinking about the scientific opportunity that would be presented by building a second target station for the SNS, biological systems loom large—particularly when coupled with some of the new technologies in focusing and controlling both neutrons and protons.

Wigner Lectures

Over the last year, the laboratory has also promoted a dialogue among laboratory researchers and renowned leaders in science, industry, and government through the Eugene P. Wigner Distinguished Lecture Series in Science, Technology, and Policy. These lecturers have brought their unique perspectives to the lab's community of scientists and engineers, whose scientific discoveries and technological breakthroughs target some of the world's most pressing problems.

Albert Fert, recipient of the 2007 Nobel Prize in Physics, opened the series on November 4, 2013, 70 years to the day after ORNL's Graphite Reactor reached criticality. The milestone, achieved as part of the World War II Manhattan Project, helped to usher in the Nuclear Age.

Today, ORNL provides some of the world's leading research facilities and expertise in a range of fields that includes material science, high-performance computing, biological science, neutron science, and nuclear science and engineering.

Thomas Mason

Thomas Mason
Laboratory Director

Advancing the science of materials

Neutrons provide insights across a range of disciplines

Neutrons are uniquely suited to probing both the structure of materials and their interactions with one another across a range of scales and a variety of disciplines. The ability of neutrons to "see" features of materials that other technologies cannot see also makes neutron scattering analysis an indispensable complement to analytical techniques based on photons and electrons.

At the atomic scale, neutrons have long enabled researchers to study the basic structure of materials and to determine how a material's structure affects its physical properties. However, as scientists seek to understand even more advanced materials, the complexity of the relationships among the components both within and among materials increases dramatically.

"To give a sense as to how huge the materials problem is, imagine the size scale from a single atom up through real life objects," says Alan Tennant, chief scientist for Neutron Sciences at Oak Ridge National Laboratory. "That's the kind of size difference from a single dew drop on a blade of grass up to the global weather system. Think of all of the phenomena that happen from that size scale as you sweep through the scale of the clouds, to a hurricane system, to the global weather system. Similarly as you sweep through the diverse phenomena that happen within a single material, you can get an idea of the world there is to explore with neutrons."

Tennant explains that this analogy becomes even more powerful when you consider that there are billions of materials that researchers want to explore, and within each material is an amazing combination of possibilities.

For researchers like Tennant, neutron scattering is a prerequisite for helping move into informed design.

"We can explore materials more thoroughly with neutrons, and if we really understand what makes a material strong, we can optimize it much better," adds Tennant. "This discovery and informing process leads to advances in many different disciplines. Both the Spallation Neutron Source and the High Flux Isotope Reactor are particularly good at illuminating complex systems of materials to find out how all their parts work together."

Rich Environment to Tackle Big Problems

NScD is working to ensure that ORNL maintains neutron science capabilities that are unmatched anywhere else. Because the laboratory has both the world's highest flux research reactor and the world's most powerful pulsed accelerator, some people have high expectations for the quality and amount of science these facilities produce. Tennant notes that these facilities are also located next door to one of the first nanophase research centers, down the road from one of the world's fastest supercomputers, and at one of the world's premier materials science laboratories.

The only way to make this sort of leap forward is to think years ahead

He says, "SNS and HFIR support research to better understand, predict, and, ultimately control, matter and energy, but the true benefit of these two user facilities is their collocation with the Center for Nanophase Materials Sciences (CNMS) and the Oak Ridge Leadership Computing Facility (OLCF) at ORNL, making a campus full of materials scientists, technicians, and engineers eager to collaborate with the broad user community."

Being collocated at a national lab that's delivering new science and new solutions means the researchers are tackling big problems that affect America.

"It's a very fertile and stimulating environment, one that allows us to engage many

disciplines and expertise together like supercomputing and advanced materials synthesis to look at problems no other facility in the world could really work on—it makes an exciting combination," he says.

SNS and HFIR are being integrated more closely with the lab's supercomputing capabilities. What neutrons see is closely related to the things the models can compute, so computational modeling combined with neutron scattering is valuable for informed design.

Neutrons play an important role in being able to look inside materials and look at the stresses in materials themselves and allow researchers to make those component parts better, or lighter, or cheaper.

"For example, with a car, making it lighter means we use less fuel, which means there's a large impact on our economy directly," says Tennant. "One of the great attractions and strengths of ORNL is the opportunity to do really significant work."

Modeling and Simulation

Tennant notes that the technologies we take for granted now were developed without the benefit of the sophisticated experimental facilities available today.

"For thousands of years people have been solving difficult problems with math," says Tennant. "Humans landed on the moon using slide rules. But some seemingly simple problems that surround us—problems in biology, chemistry, and advanced materials and other complex systems—have proved far less tractable. Now when we combine observations and computation, we can simulate what is going on and develop a robust understanding of complex systems that were previously out of reach."

Computational modeling is the study of the behavior of a complex system using computer simulation. By combining computational modeling with measurements of materials, researchers can make connections between what the system is made of, how it is processed and then how it behaves. Theory allows researchers to understand the limits of a material—the fundamental structure. But it's only with computation that researchers can start to simulate possibilities of the material.

"With simulation, we can explore materials in a way we couldn't before," says Tennant.

He points to rapid advances in the understanding of magnetic materials that enable us to store and manage data on increasingly smaller devices. This kind of research has given rise to tablet computers, smartphones and other technologies that affect the daily lives of most of the people on the planet.

"Our neutron scientists are imagining new ways to transcend limitations of materials, for example by manipulating data through quantum mechanical phenomena," Tennant adds.

To continue having this sort of impact on the trajectory of neutron research, the laboratory's objective is to improve on existing capabilities while drawing out a roadmap for new capabilities that will enable researchers to explore the complex materials of the future.

"The behaviors of these complex materials are already challenging our ability to explain them using traditional techniques and models," Tennant says. "To keep up with these challenges, we work closely with researchers around the world to identify capability gaps in our facilities. We're closing these gaps by aligning our development priorities with those of the scientific community."

Understanding and ultimately controlling the interactions within complex materials will require a greater understanding of the physical rules that govern the behavior of matter. It will also require completely new kinds of scientific instruments to investigate this complexity.

Changing the way we think

The only way to make this sort of leap forward is to think years ahead.

"Addressing the most compelling future science questions will require high flux neutron sources and techniques that exploit broader bandwidth, and improved resolution in energy and momentum," says Tennant. "We're looking at new kinds of source configurations, new target systems that can give us transformational steps forward to address these problems. We have to envision what the scientific community will want to do a decade from now."

These new source configurations and target systems, specifically a second target station at SNS, will enable the team to create a whole new set of experimental infrastructure that's optimized for new classes of materials they can't study with current instrumentation.

"We're looking 10, 20, even 30 years out," Tennant adds. "Looking at the forward science challenges for the next 30 years, we're seeing that they're moving into new types of problems. Therefore, we're designing an experimental infrastructure to take us in that direction. We have to envision a future that doesn't just change the science we're doing, but changes the way we think about science." Ⓡ—*Katie Bethea*

A broad approach to green tech

Clean energy is becoming more than just "clean"

We expect a lot from clean energy these days. Besides being environmentally friendly, clean energy tech needs to be efficient and cost-competitive with traditional energy sources over the long term. Meeting these requirements takes many different kinds of scientists and advanced scientific facilities. ORNL brings those experts and resources together in one place.

The lab's clean energy research program reaches out to experts in biological and environmental sciences, advanced materials, neutron sciences, nuclear science and engineering, and high-performance computing to develop better ways to heat and cool our homes, charge our phones, fuel our vehicles, and power our factories.

"The overarching theme of our clean energy program has been figuring out the best way to integrate our research with the lab's broader research program—particularly its strengths in computing, neutron science and materials science," says Martin Keller, ORNL's Director of Energy and Environmental Sciences.

A good example of this is the laboratory's effort to develop and improve low-carbon energy technologies, including research into nuclear fission, nuclear fusion, and renewable sources including solar, wind, hydropower, geothermal and biomass. This work includes scientific and technical support for the US nuclear power industry, which supplies about 20 percent of the nation's electricity. By applying expertise in nuclear science and engineering with materials sciences and even supercomputing, ORNL is helping to improve the safety and reliability of next-generation nuclear power plants and is working with international partners to build the world's most advanced fusion reactor.

ORNL researchers are also discovering new materials and manufacturing techniques to improve the efficiency of energy technologies. Lighter materials, such as high-strength steel alloys and low-cost carbon fiber, are helping automakers meet higher fuel efficiency standards. ORNL also works with industry to develop super-efficient home appliances and combine them with advanced building materials and construction techniques to build houses that produce as much energy as they consume.

A new generation of vehicles

In the transportation sector, ORNL is laying the groundwork for new vehicles that are lighter, more efficient, and safer. Computer simulations of vehicle and component designs allow prototypes to be extensively tested before they're produced, reducing design time and lowering cost.

ORNL was also a partner in the US Department of Energy's SuperTruck effort, which improved the fuel economy of a Cummins-Peterbilt tractor-trailer rig by 75 percent, from 5.8 to 10.7 mpg. If similar trucks across the country could achieve that kind of mileage, fuel costs could be cut by almost $30 billion each year. In addition to Cummins and Peterbilt, the SuperTruck team included Modine, Purdue University, U.S. Xpress, Eaton, Bergstrom and Goodyear.

The laboratory's contribution to the effort was using a laser-based diagnostic probe to sample carbon dioxide levels inside the engine to ensure that the exhaust gas recirculated through the engine was thoroughly mixed. This process increases fuel efficiency and decreases emissions.

ORNL helped to improve the fuel economy of the Cummins-Peterbilt "SuperTruck" tractor-trailer rig by 75 percent.

ORNL's Carbon Fiber Technology Facility is accelerating the development and manufacturing of lower-cost carbon fiber for vehicles, wind energy and a range other applications.

Lab scientists are also working on a new way to charge electric vehicles that gets rid of the power cord in favor of a safer and more convenient wireless power transfer pad. A driver using this floor-mounted system can now simply park over a small charging pad, and the system will automatically charge the vehicle's onboard battery pack. Variations of this technology can be used to charge stationary vehicles in garages and parking lots, as well as vehicles driving down the road.

"We're even looking at linking transportation to buildings," Keller says. "For example, would it be possible to power your house using your car? This might require a new kind of engine that can efficiently convert engine heat into power, as well as materials with better heat transfer capabilities. It's a materials sciences problem, but it's more than that. Manufacturing methods, computation and neutron studies could come into play as well. Perhaps we can increase heat transfer through new designs that can be produced using 3D printing."

Bioenergy, biomaterials

ORNL's scientists are investigating new ways to address the nation's energy needs, such as producing liquid fuels from biomass and using a combination of experiment and simulation to provide a detailed look at the molecular intricacies involved in the production of next-generation biofuels.

Keller explains that the insights this research provides into how plant cell walls are assembled is then used to develop new ways to take them apart.

"The problem," he says, "is that plant cell walls are really hard to break down using heat and chemicals. ORNL studies have shown that some plants found in nature are easier to break down than others and that this quality is linked back to very specific genes. We're using this knowledge to produce biomass crops that are better suited to biofuel production.

"The next thing we want to ask ourselves is whether we can use the knowledge we get from studying the assembly of complex biological structures like plant cell walls for other products outside biofuels. This is where the field of biomaterials comes in. One of the primary byproducts of biofuel production is leftover plant polymer called lignin. Can we use lignin to produce carbon fiber? Can we use other plant materials to do the same thing? Can we genetically modify plant cell walls to improve the quality of lignin with an eye toward carbon fiber production? Can we produce new types of lignin that we can break down chemically to produce fuels or fuel additives? Can we use these technologies to get more out of biomass crops down the road? These are the kinds of questions we are trying to answer with clean energy technologies."

Sustainable alternatives

The lab's BioEnergy Science Center plays a key role in developing sustainable alternatives to fossil fuels by accelerating progress toward a viable biofuels market. BESC's goal is to enable breakthroughs in the use of biomass to produce transportation fuels.

"There's a lot of discussion about whether we have enough land for large-scale, sustainable biofuel production and about whether we can do this in a sustainable way, given the relationship between the landscape and competing needs for water, fuel, fiber and food," Keller says. "I'm convinced that we can manage our landscape, preserve diversity, and produce enough biomass to use for biofuel production without impacting the production of other crops."

ORNL has explored the impacts of energy production, distribution and use for decades, but this work has taken on a more multidisciplinary focus at the lab's Climate Change Science Institute. CCSI's climate research strengthens scientists' understanding of climate change through observation, experiments, and high-resolution climate models, as well as providing input to policy decisions on climate and the environment at the national and international levels.

A holistic perspective

ORNL's clean energy researchers are working to expand the nation's energy options. Experts in fields as diverse as biology, chemistry, computer science, and engineering are developing new bioenergy crops to help reduce our dependence on imported oil. Other scientists are exploring how batteries work on the atomic level and are combining the knowledge they gain with manufacturing R&D to produce cheaper, longer-lasting energy storage systems that can provide US industry with a competitive advantage in the global marketplace.

"This is how we approach all of our clean energy challenges—from a holistic perspective," Keller says. "We're moving from fundamental science to solutions using input from across the laboratory's scientific disciplines." ®—*Jim Pearce*

Building better biofuels

Gaining insights through neutron science

In theory, making biofuels is easy; in practice, not so much. Biofuels are made from biomass, the cell walls of plants. It turns out that, although biomass has only three main ingredients, pulling those ingredients apart—the first step in making biofuel—is devilishly difficult.

"The cell walls of plants are very complex," says Paul Langan, Director of ORNL's Biology and Soft Matter Division. "They're mostly made of cellulose, hemicellulose and lignin. Cellulose acts like the rebar in a concrete wall—it gives the cell walls structural strength. The cellulose is encrusted with a tangled matrix of hemicellulose and lignin. If cellulose is the rebar, then the matrix is the concrete."

Separating the rebar from the concrete is important because cellulose is rich in sugar, and sugar is what gets fermented to create ethanol and other biofuels. Finding an efficient way to separate these ingredients is one of the biggest challenges facing the biofuel industry. Solving the problem will enable biofuel companies to produce fuel from "waste" plant material, like corn stalks, or from crops that don't compete with food sources.

"Our focus is on biofuels that are produced from plant waste or energy crops like poplar and switchgrass," Langan says. "There are other biofuels and fuel additives that are produced from corn starch, but we're concentrating on using waste products and crops that don't compete with food sources. It's relatively easy to take corn starch and convert it to ethanol. We're not interested in doing that."

Probing pretreatment

To get access to the sugar stored in biomass, the plant material is put through a process called pretreatment. This involves breaking biomass into its component parts by putting it into a pretreatment vessel—basically a big pressure cooker full of water and acid or alkaline—and turning up the heat until the cell walls come apart. After the biomass has been pretreated, enzymes are used to separate the sugar from the cellulose. Then microbes and yeast are used to ferment the sugar into ethanol or higher-grade biofuels.

This seems simple enough, but the details of the chemistry that occurs in the pretreatment process are a bit of a mystery—that's where the neutrons come in.

"We don't actually know, scientifically, exactly what happens during pretreatment," Langan explains. "If we did, we could improve the process and reduce its cost. Pretreatment is one of the main costs of producing biofuels.

"Neutrons are ideal for probing the details of this process—all the way down to individual atoms—because they are one of the only techniques we can use to 'see' hydrogen atoms. Half of the atoms in biomass are hydrogen, so if we can see the hydrogen atoms, then we can figure out what they're doing in the cell wall during the pretreatment process."

Langan notes that neutrons can see through otherwise impenetrable materials, so scientists can actually take a steel pretreatment vessel and put it on a neutron beam line, allowing them to basically make videos of minute changes in the structure of cell walls throughout pretreatment.

"That can't be done with any other technique," he says.

Innovative, integrated tool

Data gathered by these studies become much more useful when researchers use the laboratory's computing power to translate this information into molecular dynamics simulations—complex computer models that show the interactions among molecules.

"We have uniquely powerful neutron sources and uniquely powerful computing resources," Langan explains. "It's a no-brainer to see that if we combine these two that we will end up with an innovative, integrated tool we can apply to various scientific fields to get high-impact information.

"Carrying out simulations allows us to understand which forces are driving the various changes we see in the pretreatment process. Neutron analysis provides us with highly detailed information about the basic physical forces that drive these changes, and interpreting that data with the help of computer models allows us to make predictions about how we could change pretreatment to make it work more efficiently."

Langan and his team have used computer modeling to ferret out important details about the structure of cellulose. For example, they found that its interior is rigid and crystalline, but its surface is dynamic and includes hydrogen bonds that are continually forming and breaking.

The ability of a neutron facility to produce insights like these is of particular interest to scientists working in the biological sciences

"That kind of information is important for understanding both how enzymes interact with cellulose and how cellulose interacts with the hemicellulose and lignin matrix," Langan says.

"Our simulations have also shown us that, before pretreatment, the lignin and hemicellulose are actually mixed together in a gel. After pretreatment the hemicellulose and lignin separate and the lignin collapses into globules that clump together and stick on to the cellulose. This is a bad thing because it prevents enzymes from degrading the cellulose."

The door is open

The ability of a neutron facility to produce insights like these is of particular interest to scientists working in the biological sciences. Langan notes that the trend in biological research is toward understanding complex systems, such as biomass.

"This is a field that's growing rapidly," he says, "and we're making a special effort to open our doors to the biology community."

This open door policy has manifested itself in a couple of key ways. First, Langan's team has spent a lot of time talking to biological researchers at workshops and in other venues—trying to understand exactly what they need in a neutron research facility. They are building instruments that are specifically tailored to those needs.

"The biological community is interested in complex systems for three main reasons," Langan says. "They want to understand them so they can manipulate them using biotechnology—for example, changing microbes to enable them to make better biofuels. They also want to fix them—that's health, and they want to copy them—that's material science and bio-inspired materials.

"We're opening our doors now because we can offer these users new instruments with capabilities that they've never seen before. This is an unprecedented opportunity."

The path forward

Langan observes that although his team's biomass studies have removed some of the mystery surrounding the pretreatment process, they still have plenty of work to do.

"By combining neutrons with high-performance computing, we're gaining fundamental insights into how we can use cellulose and hemicellulose to produce biofuel more efficiently," he says. "But there's a third component of biomass called lignin."

At the moment, lignin is a waste product. However, through their neutron studies Langan's team has gained a lot of information about lignin's physical properties and how it behaves under different circumstances.

"We'll produce lignin that has been genetically modified in response to these findings, and this feedback loop of genetic modification and experimentation will allow us to tailor its properties so that it can be useful in biofuel production as well.

"ORNL is a unique place," he says. "Nowhere else in the world are there neutron sources located alongside this caliber of high-performance computing facilities. This kind of integration is extremely useful for the development of biomass and biofuels." Ⓡ—*Jim Pearce*

Postdoctoral chemist Daisuke Sawada uses neutron analysis to better understand the structure of cellulose.

All eyes on the Arctic

Multilab project focuses on vulnerable high-latitude ecosystems

Permafrost core samples help scientists gauge climate conditions thousands of years ago.
Photo: Stan Wullschleger

When your laboratory is an open field on the northernmost coast of Alaska, experimental design includes atypical variables—polar bears, mosquito swarms, and sub zero temperatures. But for Stan Wullschleger and his colleagues, extraordinary conditions are all in a day's work.

"I didn't start out thinking that you could work outdoors doing science at 30 degrees below zero," he says. "But I've learned that even in those conditions, you can dress appropriately, do science in the field and still have feeling in your fingers and toes at the end of the day."

Wullschleger is leading a team of 125 scientists from four national labs and five universities on a decade-long endeavor to determine what is happening to high-latitude ecosystems through experiments and observations. The researchers plan to use their findings to improve models projecting the fate of the Arctic in the face of climate change.

The US Department of Energy–funded project, called the Next Generation Ecosystem Experiment, or NGEE Arctic, is focused on a unique feature of the Arctic landscape known as permafrost, a layer of soil that stays permanently frozen throughout the year. Permafrost is of special interest to climate scientists and modelers because it serves as a long-term storage unit for huge amounts of carbon—an estimated 1,700 billion tons, or roughly twice that contained within the current atmosphere—in the form of plant and other organic matter.

"We can take core samples that go down 6 or 7 feet, take cross-sections, thaw them out and find plant leaves that have been there for thousands of years," Wullschleger says. "But they look like they were just sitting on the surface. It's amazing that when something gets moved into that very cold subsurface environment, it stays there in that form."

Computer simulations suggest that by 2100, temperatures in Arctic regions could increase by 5 to 13 degrees Fahrenheit. Exactly how this warming will affect permafrost regions is unclear because the dynamics of permafrost-shaped landscapes are still poorly understood.

"The concern is that with global warming, the permafrost will start to thaw and the organic matter will became available for microbial decomposition, and it will release carbon dioxide, methane and other greenhouse gases to the atmosphere," Wullschleger says. "There is a big question mark as to the amount, the timing and the rate at which those greenhouse gases may be emitted."

Biology at the extreme

The NGEE Arctic project, now two years under way, brings together a multidisciplinary team of researchers including geophysicists, plant biologists, ecologists and climate modelers to figure out what is happening in the Arctic as permafrost thaws. The diverse group is focusing its efforts on a multi-year set of field experiments on the North Slope of Alaska near the town of Barrow. By combining field experiments with subsequent laboratory analysis and computer modeling, the researchers hope to develop a broader understanding of the complex Arctic ecosystem.

"A lot of people have a misconception of what field research is," Wullschleger says. "They think we're just out there harvesting plants and digging in the dirt. And we are doing those things—but we're also taking the sophistication of the national lab capabilities to the field. That means we're taking capabilities from DOE's Joint Genome Institute to the Arctic to study microbial dynamics, taking capabilities from the SLAC National Accelerator Laboratory to investigate organic matter chemistry, and then bringing all that information together with high-performance computers at ORNL. Who else can do that?

"When we take a permafrost core sample in Alaska, we're shipping it to all of these places and to our partners so that we can understand what's going on. These tools and approaches that have not been used before are helping us tackle critical uncertainties in our understanding of these sensitive ecosystems."

A large part of the NGEE Arctic team's battle, explains Wullschleger, is that biology in Arctic regions seems to fly in the face of scientific assumptions.

"A lot of things do not translate from tropical or temperate ecosystems to the Arctic," he says. "It's such a unique environment that the biology takes place in ways it doesn't elsewhere in the world."

The Arctic growing season takes place in a short window during which the top layers of soil thaw out briefly, allowing plants and microbes a brief flurry of biological activity. Even though air temperatures can reach 60 degrees Fahrenheit, the soil in this active layer warms up only slightly, forcing roots and microbes to live in an extremely cold environment.

"We're only talking about one or two degrees above zero, and all the biology throughout the year takes place in these harsh conditions," Wullschleger says. "I'm continually amazed that biology can do what it does or needs to do given all these constraints of this unique system."

While some NGEE Arctic researchers are gathering experimental data in the field and laboratory, others are integrating those findings into climate models to improve the accuracy of regional and global projections of climate change. Climate models that describe the contributions of oceans, atmosphere, land and ice are coupled and set into motion through simulations that run on supercomputers to reveal the dynamics of Arctic ecosystems.

"Not only are we trying to understand what's going on now, we also want to predict what's going to happen next—and not just at a process level, but at a landscape level by looking at the system as a whole," Wullschleger says. "We ultimately want to be able to provide that information for climate models, not just how temperature affects the biology, but how it affects biology on this landscape that's changing so dramatically."

In the Arctic, you can see what people think climate change means for their ability to live as they have done for 500 years

A six- or seven-foot core sample may contain plant leaves that are thousands of years old.
Photo: Stan Wullschleger

Cascading effects

To illustrate the fragile nature of high-latitude ecosystems, Wullschleger points to a photo of a healthy Arctic landscape made up of polygonal shaped islands of vegetation surrounded by water. Midway through the image, the lush greenery changes into dry, brown uneven ground. The exact reasons behind the degradation are unclear, but Wullschleger notes that this example demonstrates how altering one element of the ecosystem can have broad impacts.

"The minute you begin to transform the landscape, the redistribution of water changes and it starts to flow off those environments, causing this dryness which contributes to plant mortality," he says. "I've been surprised how subtle the changes can be to bring about dramatic impacts in other components of the system. It's like dominos or a cascade. A small change seems to ripple through the system to bring about dramatic consequences."

Changes to the landscape and wildlife populations have not gone unnoticed by people who have inhabited the Arctic environment for centuries. During their trips to Alaska, Wullschleger and his colleagues have met with local community leaders and listened to their observations about what has changed in their lifetimes.

"These are people who rely on their environment to provide them food, resources, and shelter, and they're out on the land every day," Wullschleger says. "They're out fishing, hunting, looking for caribou, picking berries—a lot of things that rely on what you see out on the landscape, which can be affected by even subtle changes in temperature."

Among the changes they have noticed are decreases in fish populations because of sediment run-off, shifts in whale migration patterns due to changing patterns in sea ice, and terrain that has become dry and uneven. These conversations with local people are a powerful reminder of the need to conduct scientific research in the Arctic, Wullschleger says.

"Intellectually we might feel like climate change is taking place, but you can't walk around East Tennessee and really grasp the warming that might be taking place. But in the Arctic, you do. You can see their faces, their concern. You can see what they think this means for their ability in the future to live a lifestyle that's consistent with how they've lived for 500 years.

"Now that I'm in the Arctic, there's a face that goes with climate change, and that makes it more important. For me it ratchets up the urgency for understanding what's going on." ®—*Morgan McCorkle*

Biological boundaries

Membrane research requires extremely pure water, like that produced by this still. Ordinary tap water contains minerals, sediment, chlorine and other contaminants that could skew experimental results.

Neutrons have a unique ability to "see" cell membranes

Boundaries—between the layers of a computer chip, between liquids and solids, between the earth and the sky—are of particular interest to scientists because things happen in these places that don't happen anywhere else. Researchers at ORNL are combining neutron scattering, biochemistry and supercomputing to study cell membranes, the boundaries between cells and their environment, to get a better idea of how they carry out their life-supporting work. While scientists have a good understanding of the chemistry that goes on inside and outside of cells, they understand less about the cell membrane's structure and how it performs its role as gatekeeper for the myriad molecules and messages entering and leaving the cell.

Defining the cell

"Membranes are essential to everything in biology," says ORNL neutron scientist John Katsaras. "They define the cell and how it communicates, how it metabolizes, what it lets in and what it lets out."

Neutrons are ideal for probing the structure of cell membranes—or any other biological membranes for that matter – because they can "see" hydrogen and one of its isotope, deuterium, better than other analytical techniques, like X-ray scattering. Hydrogen plays a key role in the structure of organic compounds such as proteins, lipids (fats), and other components of cell membranes, so being able to see where the hydrogen atoms are gives researchers insights into how these components are arranged and how they interact with one another.

Traditionally, this kind of research might have been done with X-rays. However, because X-rays see atoms by detecting their electrons, hydrogen and its single electron are a little hard to find. For similar reasons, X-rays can't tell the difference between hydrogen and deuterium because they both have just one electron. Neutrons, on the other hand, don't have any problem seeing hydrogen atoms because they are sensitive to the atom's nucleus—hydrogen nuclei have one proton, while deuterium nuclei have both a proton and a neutron. This difference between the hydrogen and deuterium nuclei enables neutrons to tell them apart.

"We use this difference between hydrogen and deuterium to enhance the visibility of the various structures that make up the cell membrane," explains ORNL biological scientist Bob Standaert. "By selectively replacing hydrogen with deuterium, we can highlight certain components of biological samples and cause others to blend into the background. This technique is called "contrast variation." We have established a chemical labeling program that enables us to make lipids, cholesterol and other membrane ingredients that are enriched in deuterium. This capability allows us to make our own custom-labeled molecules for analysis."

Model membranes

Once they were convinced that neutrons were capable of seeing the structure of cell membrane components, Standaert and Katsaras decided that, if they were going to take advantage of ORNL's analytical capabilities, they would have to develop model membranes that could be studied with both computation and neutrons.

"Right now, we are using simple model systems," Standaert says. "We're trying to add function to them, so they're more like true biological membranes. We use both vesicles (small, bubble-like structures) and flat, planar structures."

Until recently, the main feature that had been missing from these models was asymmetry—having distinct internal and external surfaces. In natural biological membranes, the lipids that make up a large part of both surfaces are in constant motion. One of the main questions researchers are interested in is how these internal and external layers communicate with one another. Do they cooperate, for example, to enable molecules to pass in and out of the cell? Do they operate independently? If not, how do they work together?

To shed some light on this question, the research team implemented a new way to make vesicles, which like their natural counterparts have inner and outer surfaces with a different chemical and isotopic composition.

"Now we want to add deuterium-labeled cholesterol, another component of natural cell membranes," Standaert says. "Cholesterol stiffens the membranes and enables them to remain fluid, and it may be involved in the formation of lipid patches called 'rafts.' Rafts provide organized lateral structure to the fluid sea of lipids and proteins in the membranes. Some researchers think that understanding the formation and function of these rafts is a key to understanding cell membranes."

Neutrons can look at the entire sample at once—so they won't miss anything; and they can highlight specific structures, making them more visible, compared to other commonly used techniques

Standaert is quick to point out that the existence of lipid rafts in cell membranes is not fully proven at this point, explaining that there is indirect evidence that lipids and proteins form rafts in biological membranes. However, there is no direct proof.

"We think that rafts are transient, always coming and going," he says. "They're also extremely small, so it is very hard for optical techniques, like microscopy, to capture them. This question should be one that neutrons are good at answering. Neutrons can see very small objects; they can look at the entire sample at once—so they won't miss anything; and they can highlight specific structures, making them more visible, compared to other commonly used techniques."

Crystals of sucrose in which hydrogen molecules have been replaced by deuterium for use in neutron scattering experiments.

Simulation insights

Katsaras notes that neutron analysis is only the first step in the team's comprehensive approach to analyzing and understanding what's going on in the cell membrane.

"Cell membranes are disordered, they are changing all the time," he says. "As a result, they yield low-resolution structural information. Because membranes are fluid, to understand what's happening with every single lipid, you really need to use computer simulation. We have one of the world's biggest supercomputers and excellent computational chemists here at ORNL. As a result, probably for the first time, we can think about modeling entire vesicles, and small structures within cells, which are also surrounded by lipid-based membranes. If we use our neutron data to develop a detailed model on the supercomputer, we can better trust the simulation to give us an accurate picture of what's happening in the cell membrane. These models allow us to get all kinds of insights that we couldn't get using experimental techniques alone."

"By the same token, the simulations need neutron data to fine-tune their results," Standaert says. "This reality check allows the simulations to get the molecules' associations correct—how sticky they are, how flexible, how long, how they move. This is why

Bob Standaert loads samples onto an instrument that analyzes lipids for composition, purity and hydrogen/deuterium content.

having neutron and computational capabilities co-located is important. Experimental data is used to refine the model, and what we learn from the model is used to refine the next experiment. The process is iterative."

Sometimes, multiple ways of looking at biological samples are used to create better simulations. One of the projects Katsaras and Standaert have been working on involves combining data from both neutron scattering and X-ray scattering experiments and using it to refine simulations.

"Structural data based on X-rays alone is not always particularly reliable," Katsaras says. "But when you combine it with neutron data, then you end up with very robust and reliable structural data that simulations can use. This is an area in which neutrons are used to refine and produce robust structural models of cell membranes."

Simulations are critical to understanding how the internal and external layers of the cell membrane function on an atom-by-atom and molecule-by-molecule basis. For example, in vesicles there may be 20 percent more lipids on the outside than there are inside because they are spread out on the outside and pressed together on the inside. Factors like this can't be taken into account by experiments using flat membranes. A detailed model is needed to reproduce the whole vesicle and to capture its curvature.

This is why having neutron and computational capabilities co-located is important. Experimental data is used to refine the model, and what we learn from the model is used to refine the next experiment.

"That's where supercomputers come in," Standaert says. "Using ORNL's computing power, we can finally start modeling entire vesicles. This feat would have been unthinkable just a few years ago. There are other neutron facilities in the world that do this kind of research, but they can't do the things we're trying to do because they don't have the expertise and the different capabilities all in one place."

Reaching out and moving forward

"The cell membrane is a molecular machine," Standaert says. "We're looking at how that machine is assembled and how it operates. Our next steps will be to make more realistic systems in the laboratory, to work more closely with ORNL's Center for Nanophase Materials Sciences and to reach out to our biology collaborators for help in understanding complex biological systems and problems of biological relevance, like interactions between cells and how molecules move through cell membranes.

"From a purely practical standpoint, we would also like to develop ways of making biological membranes that are more resistant to the toxic effects of biofuels in order to boost productivity. A way to accomplish this may be to find organisms with membranes that are naturally more tolerant of fuel molecules and to use our structural, computational and biological tools to understand why."

"Because we are taking a comprehensive approach and combining biochemistry, computation and experiment all under one roof, our approach to studying the structure and function of cell membranes is unique in the world," Katsaras says. "We have brought in some extremely intelligent and hard-working people, and we are capitalizing on ORNL strengths in neutrons, bioscience and computing. We have a flagship program here at the laboratory, and our goal is to deliver the best program in the world." —*Jim Pearce*

Tailoring the poplar genome to biofuel production

A big speed bump on the road to cost-competitive biofuels has been the amount of processing needed to extract the sugar contained in plant fiber. Chemistry-wise, it's a pretty straight shot from sugar to ethanol, but getting to the sugar in the first place has proven to be a tough nut to crack. You might expect the solution would be to come up with better chemistry, but ORNL biologist Gerald Tuskan is taking a different approach: He's inventing better plants.

To develop plants that are more easily converted to sugar, Tuskan and his team are looking at the differences in plant fiber that result from differences in genetics, environment, and growing conditions.

Plant fiber is made up of a tough matrix of cell walls that allows the plant to stand upright. The cell walls, in turn, are made up mostly of lignin, cellulose and hemicellulose. Cellulose and hemicellulose contain the sugar needed to make biofuels, but it's all tied up in a hard-to-process lignin wrapper.

Tuskan notes that while scientists know a lot about the biological process plants use to produce lignin, they have a lot to learn about the genes that control lignin formation. To understand more about how these genes function, his team is studying the genome of a variety of poplar tree that is widely used as a raw material for biofuel production.

Teasing apart differences

"One of the ways we find the genes that control cell wall formation is by looking for differences in how individual plants control the production of lignin, cellulose and hemicellulose," Tuskan says.

To begin these "association studies," the team sequenced the genomes of 1,000 unrelated poplar plants, so they would have a way to determine exactly how each plant differed from the others. Then they took cuttings from each of the 1,000 genetic varieties and planted them in multiple locations.

"Now that we have plants with the same genotype growing in multiple environments," Tuskan explains, "we can use statistics to determine whether various physical characteristics of the plants are controlled locally by the environment, geographically by planting site, by the plant's genes or by a combination of these factors."

Because this approach involves comparing whole genomes of a thousand different plants, Tuskan and his team apply high-powered computational biology to look for tiny differences among the billions of bits of DNA that make up each genome. Sheer computing power allows them to crunch enough data to go beyond identifying a particular chromosome or section of a chromosome that contains a gene of interest and to isolate the specific gene or genes that control a given physical characteristic.

"In most cases we can not only identify the gene but the allelic form of the gene," Tuskan says, "meaning that we can pinpoint whether it was the male or female parent that passed along the favorable characteristic. Using this method we can find plants that have both that particular gene and the desired physical characteristic and do further studies to verify that the gene actually does what we thought it would do."

Tuskan's team has used this approach to discover a number of genes that control the production of lignin, cellulose and hemicellulose.

Ultimately, once you can relate genes to functions, then you can intentionally move the chemistry in one direction or the other

"These are genes that no one had associated with any of those cell wall components," Tuskan says. "The last 30 or so biochemical steps that lead to the production of lignin are well-documented, but what happens prior to that is a black box in some ways. There may be hundreds of prior steps in the process."

Transformation

Another method of gene discovery Tuskan's team uses is called transformation. Unlike genomic techniques, which are

based on DNA, transformation relies on the information contained in a plant's RNA. RNA molecules take the instructions encoded in the plant's DNA and deliver them to the protein-making machinery of the cell. The types and amounts of protein the cell makes determine how it develops and how the plant grows.

Naturally, Tuskan's team is interested in how this process affects the development of plant fiber. He notes that, in the case of woody plants such as poplar, plant fiber is created through cell division in the outer layer, or "cambium" of the plant.

"As a poplar tree grows," he says, "cells are added to the inside of the cambium and it moves outward. If we take this tissue and run it through RNA sequencing, we can see which genes are 'up,' or activated to produce a particular protein. Fifty percent of the genes that are 'up' in any organism, whether it's a mouse, a human or a poplar tree, have no known function.

"Of course, the plant already knows how to translate the information contained in the RNA. We're trying to understand these instructions by looking at the entire dictionary rather than at a single letter. One of our scientists, Udaya Kalluri, used RNA sequence information for a variety of poplar, looked at what genes were 'up,' and targeted those genes in a series of transformation experiments."

Transformation experiments involve causing cells to amplify the RNA messages so that the corresponding genes are always "on," or to suppress them, so the genes are always "off." Kalluri studied the genes she had identified in the RNA sequence data this way and discovered that one of them, which had no known function, was involved in tethering the biochemical machinery that produces cellulose to microtubules—structural components of the cell.

"Ultimately, once you can relate genes to functions, then you can intentionally move the chemistry in one direction or the other," Tuskan says. "You can produce more cellulose by enhancing the availability of this tethering protein, or you can produce less cellulose or shorter polymers of cellulose by down-regulating the protein. The same is true with lignin. If you have a favorable gene—and in our case the favorable gene yields less lignin—you overexpress that gene or select for it in a population, so that the parents in the population only have that gene. If you reduce lignin, you have greater access to sugar. Similarly, if you increase the amount of cellulose, you have higher amounts of sugar. These developments give us options for modifying either lignin or cellulose independently of the rest of the plant's genome."

Biofuel and beyond

"These discoveries are important to science—and not just science in the context of the BioEnergy Science Center or ORNL or the Department of Energy," Tuskan says. "They could also influence the way we make cotton for clothing or lignin for carbon fiber.

"In the near-term we may be able to tailor poplar trees that have above-ground portions that yield high amounts of sugar by modifying the way they produce lignin and cellulose. Having high amounts of sugar translates into higher amounts of transportation fuel, which translates into economic feasibility, which translates into sustainability.

"We can also push the below-ground portion of these trees to produce more lignin, less cellulose and roots that decompose faster, so the carbon that is absorbed by the roots ultimately becomes part of the soil and stays there for longer periods.

"If we do that, we can have both short-term economically available fibers for biofuels and carbon fiber and long-term carbon sequestration in the same tree." —*Jim Pearce*

Postdoctoral researcher Anthony Bryan examines a tray of Arabidopsis.

Seeking sustainability

Can environmental impacts be as easy to understand as a weather report?

Humans have been using bioenergy since they first discovered fire and began burning wood to cook food and keep warm. Yet, today, bioenergy is often thought of as something novel, with unclear environmental impacts.

As we seek to limit the use of fossil fuels and move toward environmental and energy sustainability, however, bioenergy is one of the tools that can help.

Sustainable practices are designed to improve social, economic and environmental benefits for future generations. Virginia Dale and her team of environmental scientists at ORNL are determining how to quantify bioenergy's effect on sustainability.

"From a science perspective, our team is identifying science-based measures to determine what we actually mean by sustainability," Dale says. "One challenge with sustainability is that some parties focus on only one aspect—such as greenhouse gases or biodiversity—while other parties want to consider 100 different aspects. We are trying to establish an approach in the middle. We're working to develop a process to assess sustainability that is useful to decision makers and captures the complexities of bioenergy systems."

Right now, this process includes a checklist that specifies environmental and socioeconomic indicators of bioenergy sustainability. The environmental indicators of sustainability measure soil quality, water quality and quantity, greenhouse gases, biodiversity, air quality, and productivity. The socioeconomic indicators are in the categories of social well-being, energy security, trade, profitability, resource conservation, and social acceptability. Dale's team communicates with groups around the world who collect environmental, social and economic data to assess the utility of the checklist and discover what could be improved. Sometimes, the checklist offers examples that can help these groups consider how their projects can focus on more measurable and meaningful information—and that's progress toward quantifying sustainability's multiple aspects.

A big challenge, though, is making this information understandable. Aggregating such information mathematically and comprehensively can be extremely difficult. How can the information be presented sensibly?

Dale's answer: Build on the example of your local weather report.

In the early 1900s, the government funded research on weather because there was interest in supporting military activities. Much of the research determined how to assess information and established weather-monitoring programs. As a result, weather became something people talked about with up-to-date information.

Bioenergy markets can create incentives to contribute to improved management of land, soils and water

Today, weather data is communicated around the clock in detailed, spatially explicit formats that most people can interpret and understand.

"People understand complex phenomena like humidity and storm systems, and they appreciate how temperature patterns relate to their daily lives," Dale says. "We're trying to take this same approach to make the complexities of sustainability understandable through quantitative information that can be effectively communicated to the public."

People notice weather patterns and talk about them. They check the weather reports in the morning, making sense of the many types of radar and other displays to determine how their drive to and from work could be impacted. Some may even check the advanced humidity statistics to choose the day's hairstyle. As many know, the weather has even become the go-to conversation kicker for those days when there just isn't much to say.

Could the sustainability of your energy consumption become popularly understood and discussed in similar ways?

Even though bioenergy is getting much of the focus now, Dale plans to eventually apply this same approach to all energy activities. "This process of sustainability assessment should affect all parts of our lives," Dale says.

Making bioenergy sustainability understandable to the public doesn't stop with identifying and acquiring data, so Dale's team is collaborating with municipal, state and national groups as well as scientists with US Department of Energy, US Department of Agriculture and the Environmental Protection Agency to develop a complete approach to compile, assess and communicate the information.

Although challenging, the researchers are working to help DOE and the bioenergy industry move forward while devising and deploying more sustainable bioenergy pathways.

Even so, there are difficult science questions to solve. And, like understanding the weather, Dale must look at naturally occurring patterns and the processes that allow them to discover trends and effects.

"Bioenergy can be derived from agricultural, forest or urban wastes or purpose-grown crops. But before deciding how to manage these feedstocks, it is important to identify appropriate best places to grow and produce them and how best to transport them to refineries," Dale says.

Dale, however, also thinks about the ecological, economic, and social implications of each step—from feedstock production, collection and transportation to refinement for use in energy products such as biofuel and pellets.

"There are many difficult questions involved in this analysis—and they need to be solved yesterday," Dale says.

Like weather, the effects of bioenergy vary by location. Bioenergy makes more sense in some situations than in others. Bioenergy projects need to be designed, deployed and managed in different ways depending on site-specific conditions. Generally, bioenergy makes sense because it replaces the need to rely completely on limited fossil fuels that produce greenhouse gas emissions, and using renewable energy sources is often the best option from an economic, environmental and social perspective.

That being says, sustainability requires minimizing fossil fuel usage. More sustainable energy pathways involve energy conservation and efficiency, as well as a host of renewable options. Bioenergy is just one piece of the puzzle.

"Depending on available resources and the economic, political, social and environmental situation, hydro, geothermal, tidal, wind, solar, nuclear or other energy options and combinations may be the preferable approach to address energy needs," Dale says.

Today bioenergy provides 28 percent of renewable energy in the United States. And for some mobile applications such as long-haul shipping and air transport, a liquid fuel is necessary. Some people see biomass as a bridge to other renewable energy options that may take longer to develop. However, the living plants and organisms that create biomass are integral parts of our ecosystem, providing many services ranging from clean air to aesthetic beauty. Incentives need to be in place to manage natural resources wisely. Bioenergy markets can create incentives to contribute to improved management of land, soils and water for sustainable biomass production.

"Fossilized carbon has many unusual chemical attributes, and it makes sense to reserve its use for unique purposes such as specialized synthetics and plastics," Dale says.

Dale's colleague Keith Kline points out that "fossilized hydrocarbons were created under unique circumstances over millions of years. Unlike many other materials, fossil fuels cannot be recycled." So it makes sense to conserve them for future emergencies—when they are needed most and can be used with least harm.

For a plan of sustainable action that focuses on preserving the environment for the future, perhaps the greatest challenge is broader understanding of how emerging energy systems interact and their effects on the environment and society. With a group in Australia, Dale is exploring how simulation games can be used as a research tool to help people understand, and better manage, ecosystem services such as improving water quality and quantity.

Taking ideas right out of a science fiction novel and combining them with the story-telling prowess of Dr. Seuss, Dale wants to create a serious simulation game that immerses the players in a real-world environment where their choices affect their quality of life.

"It's like a 'Sim City' game that focuses on energy use and people employing natural resources to produce food, building materials and biofuels. If players don't grow food, fiber and fuel correctly, the environment will become contaminated, and the characters in the game get sick or die," Dale says. "But if resources are managed appropriately, players can build successful lives."

A game like this provides opportunity

"We want people to learn from this game, but the game can also be used as a research tool where the user's choices inform our understanding of the player's perspectives about tradeoffs," Dale says.

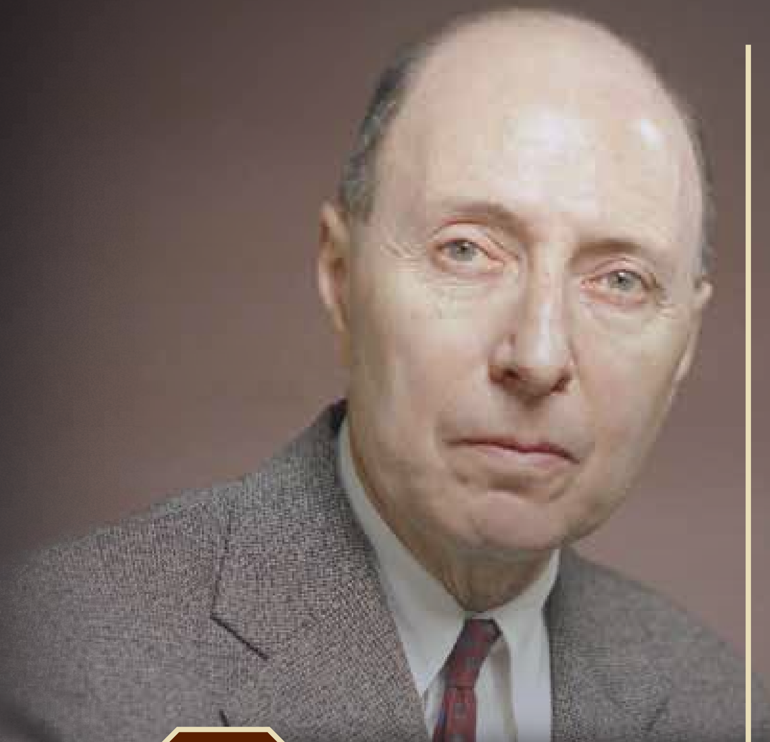
By opening up the game to teaching and research, Dale's group of scientists will also be able to witness, first hand, other people's solutions to difficult sustainability problems—especially children, who are known to pick up on details adults overlook. Science doesn't stop with answers; observed responses generate new ideas.

"Scientific publications are one product of the work, but at ORNL, we don't want to produce 'shelf art'—we produce tools and insights that people actually use," Dale says.

It is important to get the public, and especially youth, involved in sustainable action plans. It's impossible to continue building on ideas without someone waiting in the wings to keep it going. And in the game of sustainability, continued practice is the backbone.

"I was told that Oak Ridge needs to be 'out in front of the cutting edge of science,'" Dale says. "We're working to stay there." —*Dylan Platz*

Earth scientist Esther Parish examines a sample of switchgrass in one of ORNL's greenhouses.



Eugene P. Wigner Distinguished Lecture Series in Science, Technology, and Policy

ORNL's Eugene P. Wigner Distinguished Lecture Series in Science, Technology, and Policy promotes dialogue among Oak Ridge researchers and renowned leaders in science, industry, and government. The invited lecturers bring distinct perspectives to the lab's community of scientists and engineers, whose scientific discoveries and technological breakthroughs target some of the world's most pressing problems.

Albert Fert, recipient of the 2007 Nobel Prize in Physics, opened the Wigner Lectures on November 4, 2013, 70 years to the day after ORNL's Graphite Reactor reached criticality. The milestone, achieved as part of the World War II Manhattan Project, helped to usher in the Nuclear Age. Today, to fulfill its missions in clean energy and global security, ORNL provides some of the world's foremost facilities and expertise in an array of fields including materials science, high-performance computing, biological science, neutron science and nuclear science and engineering.

The Wigner Lectures are named in recognition of ORNL's first research director, Eugene Wigner, recipient of the 1963 Nobel Prize in Physics. Wigner was both a towering figure in theoretical physics and a key contributor to the development of nuclear reactors. He established an enduring vision for the laboratory and laid the foundations for programs that continue to this day.

Questions and answers

We had the opportunity to sit down with our first four Wigner lecturers—Albert Fert, Arun Majumdar, Steven Chu and John Holdren—to discuss what they do and why they do it.

Albert Fert

Nobel Laureate Albert Fert gave the inaugural Eugene Wigner Distinguished Lecture at the Spallation Neutron Source's Iran Thomas Auditorium. His lecture was titled "Novel Directions for Spintronics: Spin-orbitronics and Magnetic Skyrmions." Fert shared the 2007 Nobel Prize in Physics for the discovery of giant magnetoresistance (GMR), a phenomenon that launched the field of spintronics and revolutionized the electronics industry.

We asked him about his half-century in science and how the research and development process is changing.

Your research career spans over 50 years. What in the nature of scientific inquiry has kept you interested for that long?

When I was in my first year at university I didn't really have the patience for science. I saw it as an accumulation of knowledge that had been well-established by prestigious scientists, but I did not think that I could add anything else to this beautiful landscape. Then when I began to do research during my PhD, I found that there were a lot of things to discover. It is very gratifying to see what you have in mind result in concrete applications. I have been amazed by the power of science.

Scientific research is becoming increasingly interdisciplinary. How has this trend impacted studies of magnetoresistance effects and their applications?

Science is expanding. So in my field, condensed matter physics—the observation of the natural materials—we are using a number of new tools like nanotechnology and taking advantage of links with other fields, like biology.

For example we are working on what is called neuromorphic computing. That means trying to use what we know about the operation of the human brain to conceive of a new type of computing. Because of advances like this, there are now many links between the various scientific disciplines. It is fascinating how my discipline, physics, is taking advantage of advances in other fields.

We often hear about the increasing importance of modeling and simulation in scientific research. How have these techniques helped to advance the field of spintronics?

Our job is helped by new tools and advances in nanotechnology that allow us to prepare and characterize nanostructure. Advances in supercomputing enable us to predict relatively accurately the best way to get to a result.

Where might people encounter results of studies of GMR, spintronics, and magnetic skyrmions in their daily lives today—or 20 years from now?

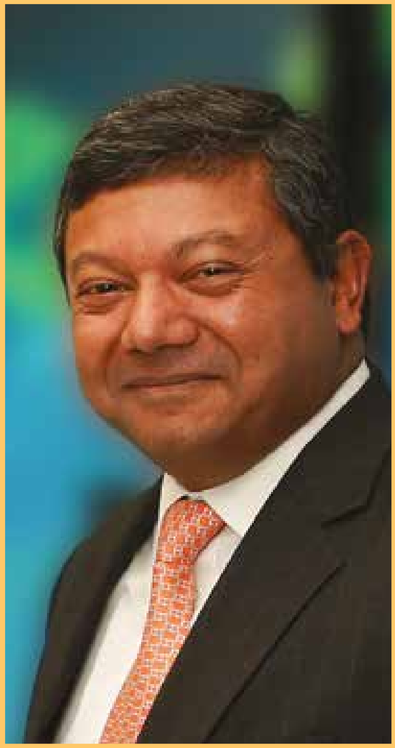
For example, magnetic skyrmions open some possibilities for very dense information storage. That will improve on the storage capabilities of today's hard disks. Hard disks are very high capacity, but they have some disadvantages. For example, the mechanical system of the hard disk is not robust and it consumes energy. The skyrmion opens a new way to achieve a purely solid-state information storage device that will be even more dense than the hard disk. We are also working on graphene. Graphene is promising for many applications. This new material with its single layer of carbon atoms is promising for many devices, including display screens and high-speed electronics. We are also working with graphene to conceive of a new type of logic circuit for computers—for what can occur after silicon-based electronics.

When you're not doing research, what do you like to do?

Many things. Actually it depends on the age of my life. When I was young I had time to do many things. I used to play rugby. When I was preparing my PhD, I made a film. Now I am more and more busy. I like reading. I like movies. I am a fan of jazz music.

What is your impression of Oak Ridge National Laboratory?

I am very impressed to see the combination of fundamental and applied research—the way of thinking that you must go improve your understanding of the fundamental aspect of the research as you work toward the application. I've been very impressed by this way of working.



Arun Majumdar

Arun Majumdar is Google's vice president of energy. That, combined with his time as head of the US Department of Energy's ARPA-E program—an effort to promote high-risk, high-payoff energy technologies—provides him with a unique perspective on the nation's changing energy needs. His talk "Energy and the Industrial Revolution: Past, Present, Future" addressed a range of energy issues, including how Google handles the energy demands of its physical data operation.

We talked to him about his work at Google and energy R&D in general.

When Google says it's "going green," what does that mean?

It means a lot of things. Google is a 100-percent carbon-neutral company. It achieves that by paying a lot of attention to how it uses electricity. In fact it's probably the leading company in terms of how effectively power is utilized. It's creating benchmarks for efficiency. When we pay for electricity, we work with utilities like Duke Energy and (the state of) North Carolina where we have data centers and where we have introduced a different kind of tariff structure for renewable electricity, for clean electricity. We are willing to pay more if it is clean.

Then we have invested slightly more than $1 billion in clean energy projects—wind, solar, high-voltage direct current transmission lines and infrastructure in order to introduce clean electricity into the mix, and to the grid. Most of this has been invested in the United States, but we just started investing overseas. We invested in a large solar plant in South Africa, and we will keep doing that. This is not for charity; this is for returns on investments. Finally, we buy carbon offsets. That's why when Google says it's going green it really means it. It is trying to reduce carbon emissions as much as possible and be carbon-neutral.

What technologies is Google using to make its data centers more efficient?

It's not just one; it's many. It has a lot to do with how a data center uses its computing resources—how it balances the load, how it does its cooling. There is a metric called PUE, which is power utilization effectiveness. Our PUE used to be 2.0 several years back, which means you need as much energy for cooling as for computing. Right now that number is about 1.05 or 1.06, sometimes 1.01. That means it only takes about 5 to 10 percent extra energy for cooling, which is a really good number because 90 percent of the electricity is used for computing. This efficiency is a combination of many things: how you design, how you compute, how you network, and how you distribute your electrical power.

How can moving apps and data to the cloud reduce energy consumption?

There was a study from Lawrence Berkeley lab which did a full quantitative analysis and found that moving to the cloud saves on the order of 50 to 100 billion kWh. That's a combination of many things. If you use your desktop or laptop computer as opposed to the cloud, most of the energy use is when it's in idle state—and no one turns off the computer. On the other hand, when you're pushing things to the cloud, a lot of energy is saved by providing computing resources for a group of people, not just one. So, the effectiveness of using the computing resources is much higher because you can distribute the resources so that they are most effectively used.

Is there an overarching strategy behind Google's renewable energy investments?

Google wants to play a role in addressing energy and climate. It's a global company. It's also a technology company. It's run by engineers, and we develop technology internally for our own work, for computing resources. This is not just computing technology, but cooling technology and power-handling technologies. We do a lot of that internally. So Google is as much of a hardware company as it is a software company. At times we will use our technologies internally beyond just computing and we will try to address the energy climate issue, which is a very complex problem. There is no silver bullet. Google will address this issue in as many ways as possible—whether it's financing, whether it's technology development, whether it is business models. It's a combination of all those. It wants to been an industry leader in this area.

You used to head the Department of Energy's Advanced Research Projects Agency—Energy. How do federal agencies like ARPA-E accelerate tech development in the energy sector?

There are multiple ways. In ARPA-E we've recruited some really top-notch active scientists and engineers who knew what was going on in the research community. We then had them provide some thought leadership as to what the new areas of research ought to be; convened the various communities that are relevant for particular topics, whether it is biofuels or power electronics or next-generation batteries; and then we really set the bar very high for the scientific community to innovate, to do the research in science and engineering, to come up with new technologies which are too risky for the private sector to initiate. We asked the question: If it's successful, will it be game changing? If you set the bar high, and provide some possibilities which are in uncharted territory but which are worth looking into and you provide the funding and the direction, the scientific community in this country will innovate and they will deliver. That's what we found. It is very important for the people inside ARPA-E to be part of this community and thereby understand what it takes to really innovate.

What part do DOE's national laboratories play in moving new energy technologies from the lab to the market?

The network of national labs as a whole is really sort of a crown jewel in the scientific infrastructure of this country. It is something that a lot of people around the world look at and say, "This is something to emulate." I would say it's not just the national lab network but the network of really top-notch research universities combined with the national labs. That infrastructure is the best in the world. If you look at, over the long term, what has led to US economic growth in the 20th century—whether it is nuclear energy, whether it is the transistor, the Internet, space technology—it is really the combination of universities providing the human capital and education and the research environment to try out new things as well as the national labs combined that has really developed the technologies. The 20th century really has been the era of technology innovation that has gone from discoveries and inventions to innovations and to business. And that has really come from the research infrastructure of science and engineering that we have in the United States, including the national labs.

That is where the new ideas and the new innovations—the new Industrial Revolution which we need for a sustainable future—are going to come from. It has played a very significant role in the 20th century, but I think it will play an even bigger role in the 21st century, and the problems are probably going to be even more difficult than those we had in the 20th century.

Steven Chu

Former Energy Secretary Steven Chu's Wigner Distinguished Lecture included both an overview of his current research at Stanford University—where he is collaborating with other scientists on biomedical imaging techniques that are focused on treating cancers and bacterial diseases—and his thoughts on energy policy and climate change.

We asked the Nobel Prize winner to talk a little about America's energy challenges.

What is America's greatest energy challenge?

Coordinating our rich renewable energy resources with the infrastructure we need to take advantage of it as the prices become competitive with other kinds of energy—which they will.

What role do the national laboratories play in meeting this challenge?

They play a role in the area of systems engineering by developing an integrated grid that is able to respond to renewables. They can play a role in developing technologies for short-term weather forecasting—of the 10-15 minute variety. The new gas generators can spin up very fast. And of course they play a role in inventing improved battery technologies and things of that nature. And they also do a lot of weather prediction, climate prediction, things like that. Weather prediction and global climate prediction are very important.

People have different ideas about what constitutes sustainable energy. What energy sources do you consider to be sustainable?

I would say energy sources that have a very, very low carbon footprint are sustainable—those where you don't see an end to the supply. For certain energy sources like nuclear, if you have a fraction of fast reactors, you can have fuel for hundreds of years. Renewable energy—wind and solar and things like that—are sustainable because the amount of energy we would need to capture from the fraction that reaches the areas on land is about one one-hundredth of 1 percent. Renewable energy of that kind is very sustainable. If we can get fusion to work economically, that becomes sustainable. Nuclear—we don't know if we're going to need it going into the next century, but both fusion and fission have very high capital costs.

To what extent should the sustainable energy technologies we adopt be market-driven?

They all have to be market-driven in the end. I don't believe we should encourage a sustainable technology that can't deal with an off-ramp. Meaning that, if you don't see a path to deployment without subsidy, I would put the technology in the category of research. You don't want to be using tax dollars to be doing that. Research and development is different than saying let's use tens or hundreds of billions of dollars to do something. I think it's better spent finding better solutions.

Given a limited budget, is there a trade-off between trying to mitigate climate change and adapting to its impacts?

Well, we have to adapt anyway. There are minor adaptations that I wish we would think of. Like when you are rebuilding in the flooded areas in New Orleans, you put your home on stilts. A surprising number of people do not do that. Also, when you rebuild, you should really be thinking twice about rebuilding on a beachfront.

We are adapting in New York City in terms of weatherizing the electrical cables in the subways and things like that. So we do adapt. This century's floodlines will probably be different than last century's floodlines, so you will have to make changes there when you retrofit. Here's a trivial thing: Circuit breaker boxes where the electricity feeds into homes are generally put on the ground floor or in the basement—generally for meter readers. You don't need meter readers anymore—it can be done electronically. Put the box on the second floor, so the circuit box doesn't blow. That's adaptation.

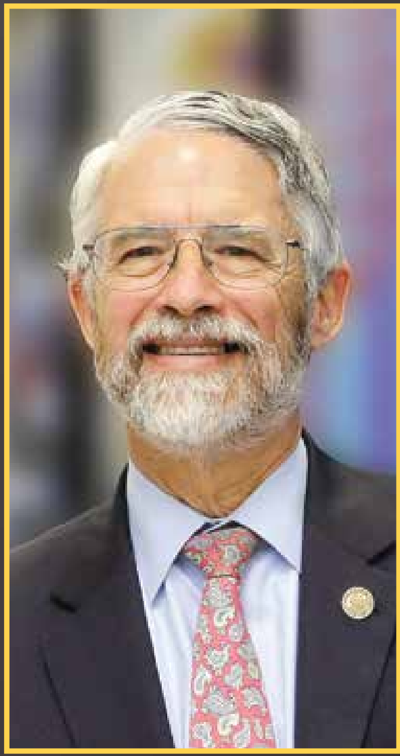
What advances in sustainable energy might we hope to see in the next 5 to 10 years?

The cost of solar and wind will continue to drop. The projections are for the cost of solar to drop by 50 percent. Projections for wind are 30 percent. I see the cost of batteries dropping by at least one-half, maybe to one-quarter or one-fifth in the next 15 years.

Now that you're back at Stanford, what do you miss most about life inside the Beltway?

The museums are nice.

John Holdren



John Holdren serves as assistant to the president for science and technology, director of the White House Office of Science and Technology, and co-chair of the President's Council of Advisors on Science and Technology. During a distinguished career spent in government and academia (serving, for example, in faculty positions at Harvard and Berkeley), Holdren has developed insights into both science and science policy. In his lecture, he discussed science and technology in the Obama administration.

We asked him about the role of government and the national laboratories in promoting scientific advances.

What is the role of the president's science/technology adviser?

There are two roles. The first is to keep the president informed about the scientific and technological aspects of all the policy decisions on his plate. Practically everything he's thinking about—whether it be the economy, the health of the American people, the energy challenge, the climate change challenge, or national and homeland security—has scientific and technological dimensions.

The other job is to oversee the science and technology enterprise that the federal government pays for and stimulates. That means the research and development budgets of all of the science-and-technology-rich agencies. It means the federal government's programs in science, technology, engineering, and math education. It means workforce training issues, intellectual property rights issues, export restriction issues, and immigration policy as it affects high-skills immigration. It means anything that the government does that's going to influence science, technology or innovation space.

What is our top scientific challenge?

There are so many scientific challenges that are both fascinating and important. But if I had to vote for one, I would say developing a better understanding of how the human brain works. We're trying to do that through a variety of neuroscience initiatives and through the relatively new brain initiative that the president announced a little more than a year ago. By better understanding how the brain works, we can make advances in treating neurodegenerative diseases like Alzheimer's and Parkinson's, in treating traumatic brain injury and post-traumatic stress syndrome, and in learning and cognition.

What is our top technology challenge?

I think the biggest technology challenge is to make the transition from the energy system we have today to an energy system that is more secure, more reliable, at least equally affordable, and also incredibly cleaner in terms of impacts on the environment and above all impacts on the global climate.

What role do the national laboratories play in facing these challenges?

The national laboratories are enormously valuable resources in bringing science and technology to bear on the challenges we face. Oak Ridge National Lab has important capabilities and programs in materials science, and if you look at a very wide range of technologies, you find that the properties of materials are often the limiting ingredient. High-performance computing is also enormously important. And again, it happens that this national lab and others are leaders in high-performance computing. When you think about the energy and climate change challenge, our national labs again are in the forefront.

You've gone back and forth between government and academia. What are the relative merits of each?

I spent about 36 years as a professor at a variety of institutions. And the most satisfying thing about that was dealing with incredibly bright and energetic students who are going to go on, and who have gone on, to do enormously important things.

In the federal government, and particularly in the White House, the enormous advantage is the opportunity to advise the top decision-maker in the country on the possibilities, opportunities, and challenges we face in science, technology, and innovation.

Why was it important to visit ORNL, meet with researchers here, and participate in the Wigner Lecture Series?

It's a great honor to be invited to come and give the Eugene P. Wigner Distinguished Lecture. I had the pleasure of knowing personally a number of his contemporaries.

But one of the things I do as the president's science adviser is to visit our leading institutions of research and innovation to understand what's going on there so that I can bring insights that I get back to the process of helping the president formulate policy.

Daniel CLOSE

Wigner Fellow Daniel Close says he was working as a research assistant at Northwestern University's Feinberg School of Medicine studying the response of brain cells to alcoholism when he "got the bug" for scientific research. His work at Northwestern also convinced him that if he wanted to go much further in the field, he needed more education.

"I ended up coming to the University of Tennessee to get my PhD. That's when I started getting into the kind of biomedical imaging, synthetic biology and biotechnology that I'm doing today," Close says. After finishing his degree at UT, Close did another year of postdoctoral research at the university before being invited to work at ORNL as a Wigner Fellow.

We asked Close about what drew him into the field of biotechnology and how he's applying it at the lab.

What got you interested in a career in biotechnology?

Biotech is really fascinating to me. As far back as I can remember, I have wanted to look at how life functions and to be able to understand the little things that are going on within people and within cells. I really love both the mysteries and figuring out how to use them for the benefit of other people. It's amazing to me that, no matter what we want to do in the field of biochemistry, there is probably some bacterium or some animal or some cellular process that's already doing it. The idea that we can figure out how to move that DNA or those proteins or that system and tweak it into something that can benefit all of us is just mind-blowing for me.

ORNL is a US Department of Energy lab. How does the lab use biotech to advance energy research?

Biotechnology is a very broad word. There's so much that we have to learn from organisms and biological processes that can be applied to areas as diverse as fuel production, creating new materials for solar panels, or developing heat sinks for electronic components. There's really no aspect of technology today that doesn't have a partner technology that is already developed within a living organism. The breadth of research disciplines at ORNL gives us an opportunity to bring together people with backgrounds in different subjects and look at the various aspects of biotechnology. This is a great way to share ideas, improve existing technologies and develop new ones.

Has the Wigner Fellowship enabled you to do anything that you wouldn't have done otherwise?

Absolutely. The focus of my postdoctoral work was synthetic biology-based development of new biomedical imaging technologies. We were taking human and animal cells and trying to turn them into tiny little light bulbs. We wanted the cells to produce light so we could use that light to detect them within an organism. We also wanted the cells to vary their brightness depending on how healthy they were. If this trait were present in cancer cells, for example, we could look at the light they were producing and be able to tell, in real time, how the cells were responding to anticancer treatments.

It turns out that the light-making DNA we were using at UT can potentially also be used to advance biofuel production. This is a great example of how biotechnology can be adopted to a variety of different purposes. The Wigner program has given me an opportunity to take the biotech we developed and redesign it for a completely different purpose—to take the things that I've done before and completely reroute them.

You've said that your research focuses on making cells "talk." What are they telling you?

Light-producing cells act like sensors that can tell us how each cell's metabolism is responding under various circumstances. Traditional imaging technologies required us to provide an external input to get a response from the cell. Every time we wanted to look, we had to expose the cell to a chemical or hit it with UV radiation and then read back an answer. So we ended up getting snapshots of what was going on in the cell. This new technology allows us to monitor the brightness of the cell in real time, so we have switched from taking snapshots to what amounts to watching live video. We can see what's going on as the cells respond to different conditions. Things like that have never been done before, and we're getting information from these cells that we have never been able to get before.

Beyond physiological processes, what other kinds of information do you think cells might be able to provide?

We're limited mostly by our own creativity. Can we use bacteria or yeast or some other living organisms to make a chemical that's vitally important to the way we live our lives? We have often discovered that it's not only possible, but it's already being done in nature. There are biological pathways out there that we have never paid attention to. Some of these are making materials that we need, but they're doing it on a tiny scale. The magic of technology is that once we discover the blueprint for making a material, we can determine how to scale up the process or piece of a process to get it to do exactly what we want, at the scale we want, at the time we want, and in the organisms we want. That's construction in the new age—we're beginning to build with living tools.

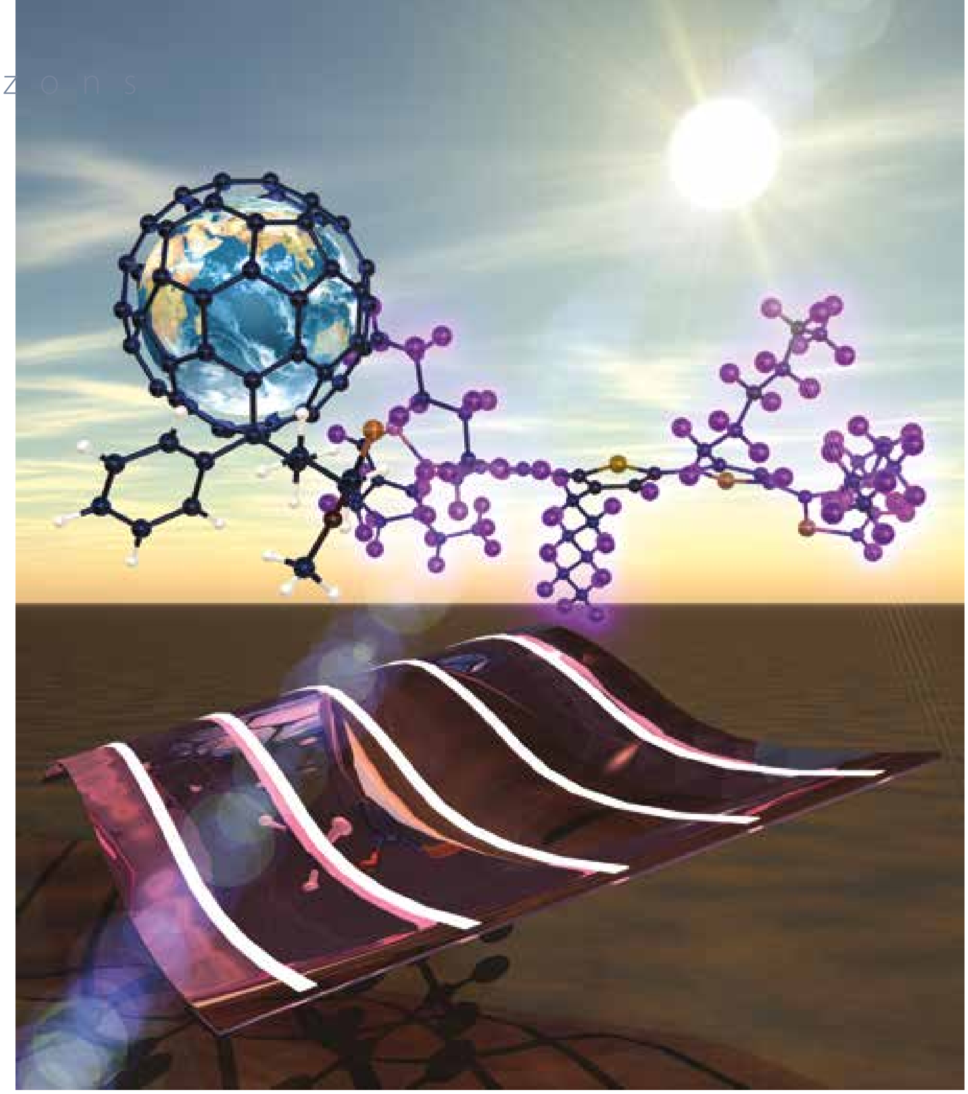
How are advances in biotech translated into advances that improve people's lives?

It's all around you. Most people don't realize how much of the technology that surrounds them has relied on biotechnology at some point. Many new materials have been developed with the help of biotechnology. It's being used to improve battery technology, solar power technology, and medical technology. The general public only sees the end product. They only know that they're getting things like medical diagnoses that are better, faster and cheaper.

It's absolutely fascinating what we can do with the technology we have available today. And this technology is just the low-tech of tomorrow. We're building the basic tools that future generations are going to build upon to create biotechnology that we can't even imagine. ®

Solar surprise

Multidisciplinary ORNL team discovers unexpected effect of heavy hydrogen in organic solar cells



Conceptual drawing shows a flexible organic photovoltaic. The polymer blend in the device (bottom) will harvest the sunlight to generate electrical power (carbon: blue; sulfur: yellow; hydrogen: white; deuterium: purple). Image: Christopher Rouleau, ORNL

Photovoltaic spray paint could coat the windows and walls of the future if scientists are successful in developing low-cost, flexible solar cells based on organic polymers. Scientists at ORNL recently discovered an unanticipated factor in the performance of polymer-based solar devices that gives new insight on how these materials form and function.

"One of the dreams is to bring home some polymer paint from the hardware store, spray it on a window and make your own solar cell because it self-orders into a structure that can generate electricity," ORNL's David Geohegan says. "But right now there are many unknown things that happen when you spray it down and it dries. Changing the electrical property of a polymer also changes its structure when it dries, so understanding this process is one of our big science mysteries."

When ORNL scientists Kai Xiao and Kunlun Hong analyzed neutron scattering data obtained at the lab's Spallation Neutron Source to measure the structure of seemingly identical polymer-based solar devices, they stumbled upon a new piece to the scientific solar puzzle.

The key to their finding was deuterium, also known as "heavy hydrogen," which is commonly used in neutron scattering analysis. Scientists use the isotope as a labeling tool, replacing hydrogen with deuterium in organic samples because deuterium's extra neutron helps reveal soft materials' structure.

"Normally scientists assume that the deuteration doesn't change the electronic structure at all," says Xiao, a materials scientist at ORNL's Center for Nanophase Materials Sciences. "But when we used it to study conducting polymers in solar cells, the devices' electronic performance changed significantly."

To understand the mechanisms behind deuterium's effects, the team turned to ORNL's Bobby Sumpter and another lab strength—supercomputer simulation. Modeling the system through quantum calculations helped the researchers determine that heavy hydrogen changes the molecules' vibrations, which indirectly but significantly affects the material's electronic properties.

In the case of the team's organic solar cells, deuteration turns out to have a negative impact, decreasing the devices' electrical efficiency. But the ORNL researchers note that other organic electronics such as organic spintronics or light-emitting diodes could benefit from deuterium's effects.

"Overall, deuterating polymers helps us understand how energy flows in organic electronics so we can improve and optimize them in the future," Xiao says. "It's opening our eyes to the fact there is an impact."

The researchers' unexpected results could also inform future neutron studies in the organic electronics field. Xiao notes, for instance, that the precise position of deuterium in the polymer chain determines whether the overall electrical properties will be altered.

"We need to carefully control the deuteration of polymers for neutron experiments," Xiao says. "Adding deuterium to the polymer's side chain doesn't affect the neutron results, but deuterating the main backbone of the polymer chain does change the structure of the films." ®—*Morgan McCorkle*

3D printing yields advantages for US ITER engineers

Desktop additive printers are changing the engineering design process

ITER, the international fusion research facility now under construction in St. Paul-lez-Durance, France, has been called a puzzle of a million pieces. US ITER staff at ORNL are using an affordable tool—desktop three-dimensional printing, also known as additive manufacturing—to help them design and configure components more efficiently and affordably.

"Now for pennies instead of tens of thousands of dollars, we can have impact right away with 3D printing. It lets us see what the part actually looks like," says Kevin Freudenberg, an engineer who supports the US ITER magnets team and has led the project's use of 3D printing. "On 3D CAD (computer-aided design) displays, you can't feel the shape of an object. You just see it. Many people have trouble seeing 3D projections or find them tiresome to view over time. With the 3D printed objects, you can run your finger over the surface and notice different things about the scale and interfaces of the component."

The fusion engineering design process has long relied on mock-ups and prototypes. Full-scale models cast or machined from metal and other materials continue to have value and will still be a part of the US ITER development process, as will 3D computer modeling, but the affordability and accessibility of desktop 3D printing offers a number of advantages.

Freudenberg says that 3D printing helps mitigate risk: "The models show complexity and help us catch issues earlier in the process."

A normal part of the engineering process is the identification of interferences or design problems before a component is finalized. Mark Lyttle, an engineer working on the pellet injection and plasma disruption mitigation systems for US ITER, observes, "It's a lot more time consuming and expensive when you find that mistake in a metal prototype than it is in a 3D printed component. 3D printing is very low cost. With metal, you may have to start over if you can't re-machine it."

Gary Lovett, a designer with US ITER, added, "If you can correct one design and make one revision, you've basically paid for the printer. It's so much more informative, especially if you have assemblies to put together."

The printed components are also shifting how manufacturers interact with the ITER designs. Freudenberg recalls, "We went to a vendor meeting recently. We looked at line drawings for a minute, and then the vendors spent hours looking at and discussing the 3D parts. Most of the meeting was spent talking about the parts. Having something in your hand that is tactile can show what machine processes and best practices to use in manufacturing."

Some components, such as the 60-foot-tall central solenoid, must be printed at "toy" scale; others can be printed at actual size. Even handling objects at toy scale is useful, as it brings massive components into the hands of engineers and manufacturers and provokes useful analysis.

Lyttle explains, "3D printing helps you look at the design and see specific parts, like an O ring that needs more space around it to sit properly. On the computer screen, you could miss that.

"On the screen, some components don't look especially bulky," Lyttle adds. "But when you make it in metal, it will be a hunk of material that is too heavy and hard to handle. When you have a physical model, it is easier to spot opportunities to save material and make the design more efficient and the manufacturing less expensive."

Printing the component also helps engineers check the interfaces for possible collisions. "You can put it together, move it a bit and visualize how it's going to be built. You can see problems like a weld you can't get to or a screw head that is inaccessible," Lyttle says.

Lyttle also points out how engineering has changed over time: "When I was in school, 3D modeling on computers was starting to really catch on, although two-

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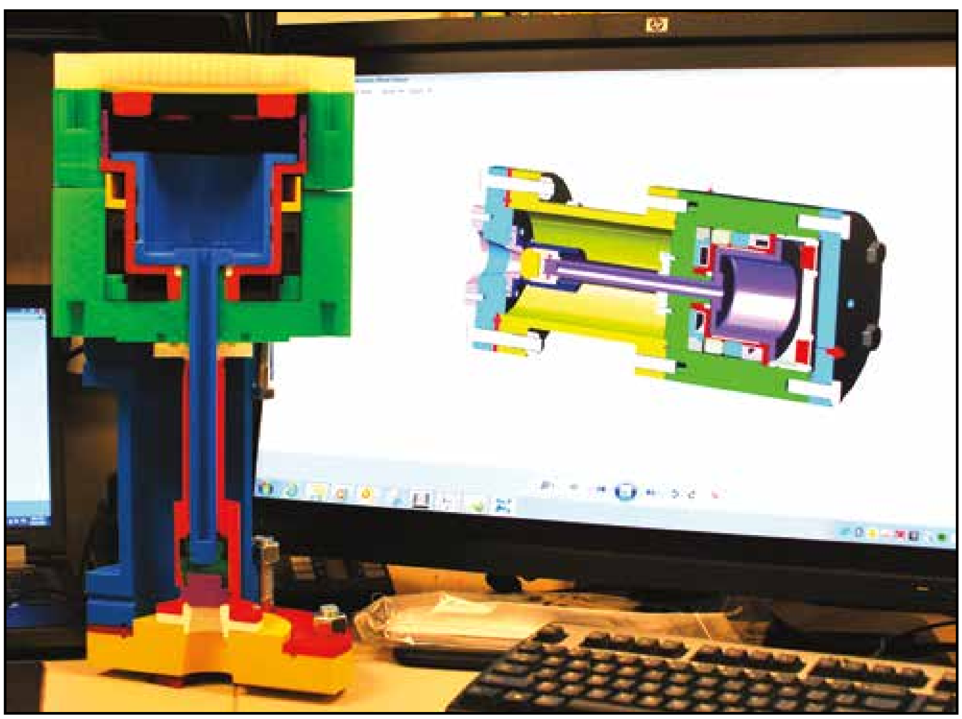

A 3D printed version of a fast gas valve for the disruption mitigation system. The 3D design is shown on the computer screen in the background. Photo: US ITER

Novel ORNL technique enables air-stable water droplet networks

ORNL researchers have developed a method to create air-stable water droplet networks that are valuable for applications in biological sensing and membrane research. Photo: Kyle Kuykendall

A simple new technique to form interlocking beads of water in ambient conditions could prove valuable for applications in biological sensing, membrane research and harvesting water from fog.

ORNL researchers have developed a method to create air-stable water droplet networks known as droplet interface bilayers. These interconnected water droplets have many roles in biological research because their interfaces simulate cell membranes. Cumbersome fabrication methods, however, have limited their use.

"The way they've been made since their inception is that two water droplets are formed in an oil bath, then brought together while they're submerged in oil," says ORNL's Pat Collier, who led the team's study published in the Proceedings of the National Academy of Sciences. "Otherwise they would just pop like soap bubbles."

Instead of injecting water droplets into an oil bath, the ORNL research team experimented with placing the droplets on a superhydrophobic surface infused with a coating of oil. The droplets aligned side by side without merging.

To the researchers' surprise, they were also able to form non-coalescing water droplet networks without including lipids in the water solution. Scientists typically incorporate phospholipids into the water mixture, which leads to the formation of an interlocking lipid bilayer between the water droplets.

"When you have those lipids at the interfaces of the water drops, it's well known that they won't coalesce because the interfaces join together and form a stable bilayer," ORNL coauthor Jonathan Boreyko says. "So our surprise was that even without lipids in the system, the pure water droplets on an oil-infused surface in air still don't coalesce together."

The team's research revealed how the unexpected effect is caused by a thin oil film that is squeezed between the pure water droplets as they come together, preventing the droplets from merging into one.

With or without the addition of lipids, the team's technique offers new insight for a host of applications. Controlling the behavior of pure water droplets on oil-infused surfaces is key to developing dew- or fog-harvesting technology as well as more efficient condensers, for instance.

"Our finding of this non-coalescence phenomenon will shed light on these droplet-droplet interactions that can occur on oil-infused systems," Boreyko says.

The ability to create membrane-like water droplet networks by adding lipids leads to a different set of functional applications, Collier noted.

"These bilayers can be used in anything from synthetic biology to creating circuits to bio-sensing applications," he says. "For example, we could make a bio-battery or a signaling network by stringing some of these droplets together. Or, we could use it to sense the presence of airborne molecules."

The team's study also demonstrated ways to control the performance and lifetime of the water droplets by manipulating oil viscosity and temperature and humidity levels. Ⓡ

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dimensional design still dominated most industries. The generation after me saw the 3D tools get better and cheaper, and now the field has really embraced 3D CAD on the computer. I expect to see the same trend with additive manufacturing tools like our 3D printer. An engineer or designer can now plot physical parts almost as easily as plotting a drawing. Each step up in engineering design technologies is pretty significant."

Freudenberg observes, "We've used 3D printers before but have outsourced the printing. Now that we have it in-house, we can produce high-resolution parts in a couple of hours."

High-end 3D printing using titanium powders and other alloys is an area under development at the Manufacturing Demonstration Facility at ORNL. Eventually, rapid prototyping that employs a broad range of materials is expected to be routine.

"I think we will see this method of producing metal parts compete in the engineering market in 5 to 10 years," Freudenberg says. These developments could have a significant impact on fusion engineering and future progress in fusion technology. Ⓡ—*Lynn Degitz*

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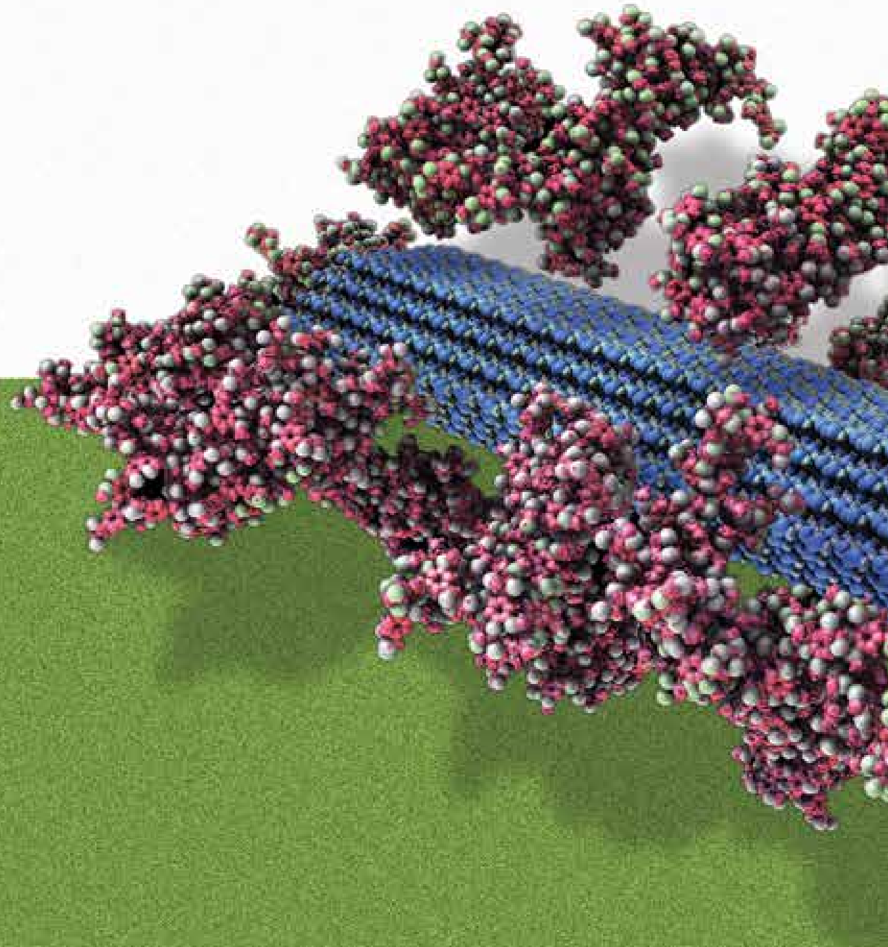

ORNL *Review*

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Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the US Department of Energy under contract DE-AC05-00OR22725

ISSN 0048-1262

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