Oak Ridge National Laboratory

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

Nuclear 2.0

Fukushima response

Catalyzing reactor research

Mapping future power plants

Oak Ridge National Laboratory
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Reactor core simulation created on ORNL's Jaguar supercomputer

Ready to lead

Earlier this year the extent of ORNL's nuclear science and engineering capabilities was clearly demonstrated during the accident at Japan's Fukushima nuclear power plant. ORNL led the effort to bring researchers together from a number of Department of Energy national laboratories, to analyze and assess available data, and to provide the U.S. government with results and recommendations to support the Japanese recovery effort.

This issue of the *ORNL Review* focuses on the increasingly important role of nuclear science and engineering at the laboratory. ORNL has been at the heart of nuclear research and development since its origin in the Manhattan Project during World War II. Today, the breadth of the laboratory's nuclear expertise goes far beyond weapons development, extending from nuclear power to medical isotopes and from naval propulsion to nuclear nonproliferation.

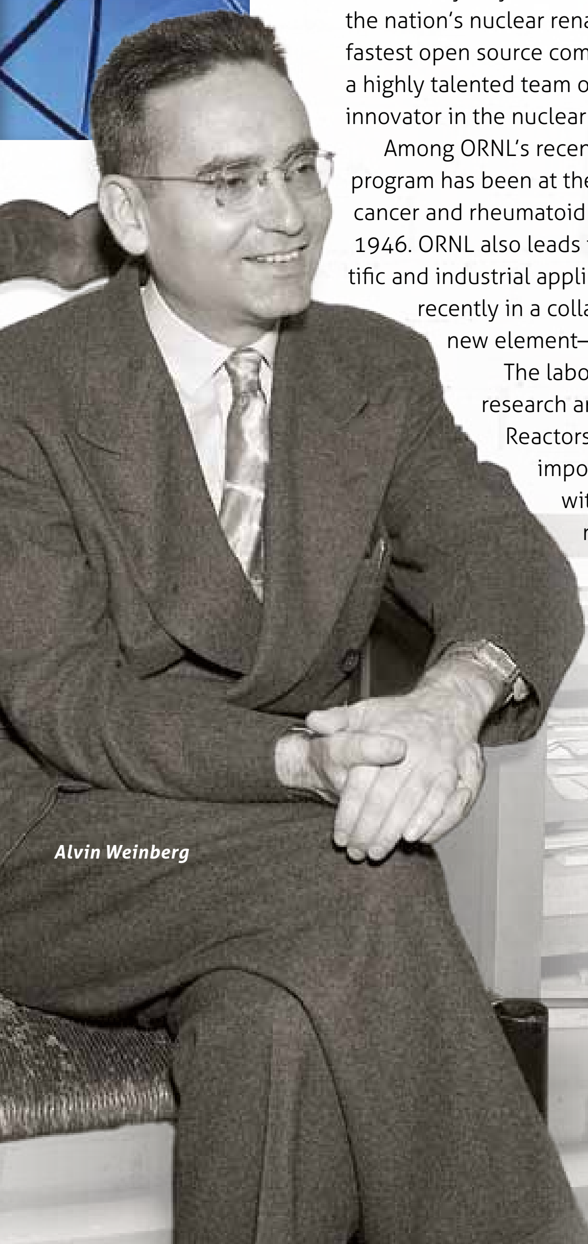
The driving force for ORNL's early nuclear program was Alvin Weinberg, who served as Laboratory Director from 1955 to 1973. Early in his career, Weinberg participated in Enrico Fermi's experiment that produced the world's first sustained nuclear reaction. Later, he came to Oak Ridge to help build a new laboratory and launch a 60-year odyssey of nuclear technological development that changed the world forever.

In many ways, ORNL is returning to its nuclear roots as it prepares to play a prominent role in the nation's nuclear renaissance. The laboratory combines the capabilities of one of the world's fastest open source computers, highest flux reactor, world-class materials science facilities, and a highly talented team of scientists and engineers to ensure that the U.S. remains a leader and innovator in the nuclear field.

Among ORNL's recent accomplishments, several are particularly noteworthy. ORNL's isotope program has been at the leading edge of research for diagnosing and treating diseases, such as cancer and rheumatoid arthritis, since the laboratory shipped the first medical radioisotopes in 1946. ORNL also leads the world in producing "heavy" elements, which have a variety of scientific and industrial applications. For example, a batch of ORNL-produced berkelium-249 was used recently in a collaboration with Russia's Joint Institute for Nuclear Research, to discover a new element—number 117 on the periodic table.

The laboratory's world-class computing capability is critical to advancing nuclear research and development. The Consortium for Advanced Simulation of Light Water Reactors is a fulfillment of Weinberg's vision for the laboratory—a place to tackle important scientific challenges by providing large, diverse teams of researchers with state-of-the-art scientific tools of discovery. CASL will enable researchers from universities, industry and the DOE's national laboratories to use high-resolution modeling and simulation tools to design safer and more efficient nuclear reactors.

These achievements, among many others, confirm that the nuclear laboratory Alvin Weinberg built remains in good hands, ready to lead the renewal of nuclear science and engineering.



Alvin Weinberg

Jeff Binder
Director
Fuel Cycle and Isotopes Division

RESPONDING TO THE

Fukushima nuclear accident

On March 11, 2011, a massive earthquake and tsunami struck Japan. The tsunami knocked out critical power and cooling systems at the Fukushima Daiichi and Daini nuclear power plants, leading to significant damage to three operating nuclear reactors and one that was shut down for maintenance. Damage included melted fuel, hydrogen explosions and leakage of highly contaminated water into support buildings and the surrounding environment.

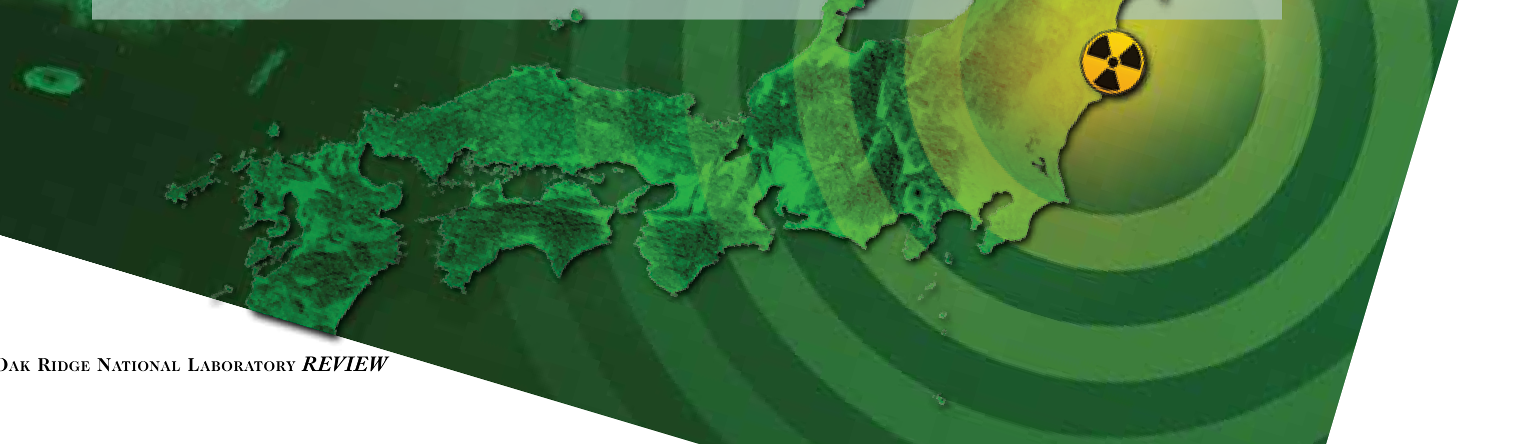
In the days after these events, the Department of Energy closely monitored the situation. DOE staff and experts from ORNL and other national laboratories helped collect, analyze and interpret the available data. These preliminary assessments were compared with similar analyses performed by the nuclear industry and the Nuclear Regulatory Commission for consistency. DOE provided this information to Japan through the U.S. embassy. More recently, DOE has provided additional assessments at the request of the Japanese government.

ORNL continues to play a key role in developing these assessments. Hundreds of laboratory staff members from a variety of disciplines have applied their expertise and analytical skills to the task of supporting the international response to the events at Fukushima.

Key areas of support have included the following:

- Severe accident management assessment, simulations, and mitigation strategies, including insights from U.S. operating experience
- Assessment of support structures and other infrastructure concerns beyond the reactor buildings
- Data collection of key plant parameters, particularly tracking water injection and water levels
- Translation of key plans and documents from Japanese
- Causal analysis of the explosion in the spent-fuel pool in Fukushima Daiichi unit 4
- Extensive simulation of the conditions in spent-fuel pool in Fukushima Daiichi unit 4
- Expert advice on robotic tools used for remote surveillance and monitoring
- Chemistry expertise on seawater composition and effects
- Impacts of seawater on corrosion of key reactor components and systems
- Analysis of the reactor pressure vessel integrity
- Analysis of radioactive releases and input on atmospheric monitoring data
- Input and analysis of alternative cooling strategies for long-term stability at the Fukushima Daiichi units

As of early June, the situation at the Fukushima Daiichi nuclear plant had stabilized significantly. However, the Japanese government still faces challenges related to shutting down the reactors and cleaning up the site. DOE will continue to provide analyses and assessments of these events. ORNL's diverse expertise and professional approach to the situation have been critical to DOE's response to the Fukushima nuclear accident to date and will continue to play an important role in the department's future efforts.
—Jeremy Busby



Rifle sighting system scores a bull's-eye

Military and police marksmen could see their rifle sights move into the 21st century with a fiber-optic laser-based sensor system that automatically corrects for even tiny barrel disruptions.

The system, developed by a team led by Oak Ridge National Laboratory's Slobodan Rajic, precisely measures the deflection of the barrel relative to the sight and then electronically makes the necessary corrections. The lifesaving results are lethal.

"For military snipers, missing the target could allow high-profile terrorists to escape," said Rajic, a member of ORNL's Measurement Science and Systems Engineering Division. "For police marksmen, missing the kidnapper could endanger the lives of hostages and then pose subsequent danger to police officers and the public."

The Reticle Compensating Rifle Barrel Reference Sensor takes the guesswork out of shooting by shifting the burden of knowing the relative position between the barrel and the weapon sight axes from the shooter to an electronic sensor. The system precisely measures the deflection of the barrel relative to the sight and then electronically realigns the moving reticle, or crosshairs, with the true position of the barrel, or bore axis.

In the end, the resolution of ORNL's Reticle Compensating Rifle Barrel Reference Sensor is 250 times better than that of traditional reticles, which can normally be manually adjusted by one-fourth of a minute of angle. The ORNL sensor can sense angular displacement and shift the reticle by 1/1,000th of a minute of angle, Rajic said.

Rajic and colleagues are also developing a laser-based bullet tracking system to give the shooter even better odds of succeeding by providing specific information about the bullet flight path. —*Ron Walli*

Solar cells crank up efficiency

A team led by Oak Ridge National Laboratory's Jun Xu has fabricated a nanojunction photovoltaic cell in which conical zinc oxide nanostructures are partially surrounded by a layer of cadmium telluride. The light-to-power conversion efficiency of the ORNL nanocone PV cell is much greater than that of a cell fabricated from the same materials in the conventional planar configuration and is among the highest observed for a nanojunction PV cell.

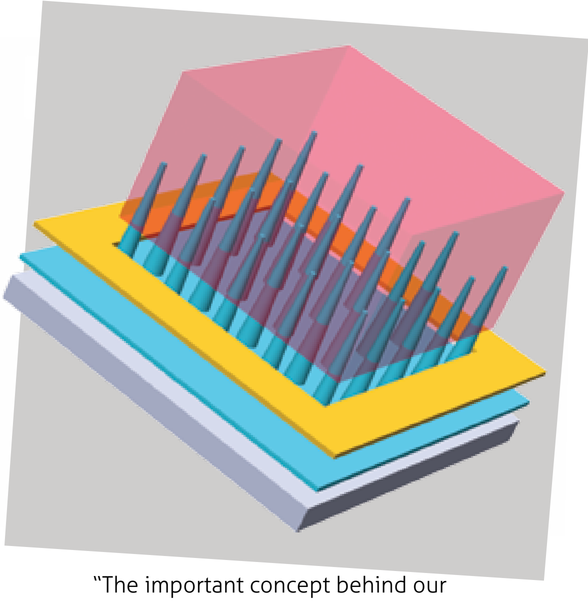
The technology substantially overcomes the problem of poor transport of charges generated by solar photons. These charges —negative electrons and positive holes— typically become trapped by defects in bulk materials and their interfaces and degrade performance.

"To solve the entrapment problems that reduce solar cell efficiency, we created a nanocone-based solar cell, invented methods to synthesize these cells and demonstrated improved charge collection efficiency," said Xu, a member of ORNL's Chemical Sciences Division.

With this approach at the laboratory scale, Xu and colleagues were able to obtain a light-to-power conversion efficiency of 3.2 percent compared to 1.8 percent efficiency of conventional planar structure of the same materials.

Key features of the solar material include its unique electric field distribution that achieves efficient charge transport; the synthesis of nanocones using inexpensive proprietary methods; and the minimization of defects and voids in semiconductors. The latter provides enhanced electric and optical properties for conversion of solar photons to electricity.

Because of efficient charge transport, the new solar cell can tolerate defective materials and reduce cost in fabricating next-generation solar cells.



"The important concept behind our invention is that the nanocone shape generates a high electric field in the vicinity of the tip junction, effectively separating, injecting and collecting minority carriers, resulting in a higher efficiency than that of a conventional planar cell made with the same materials," Xu said. —*Ron Walli*

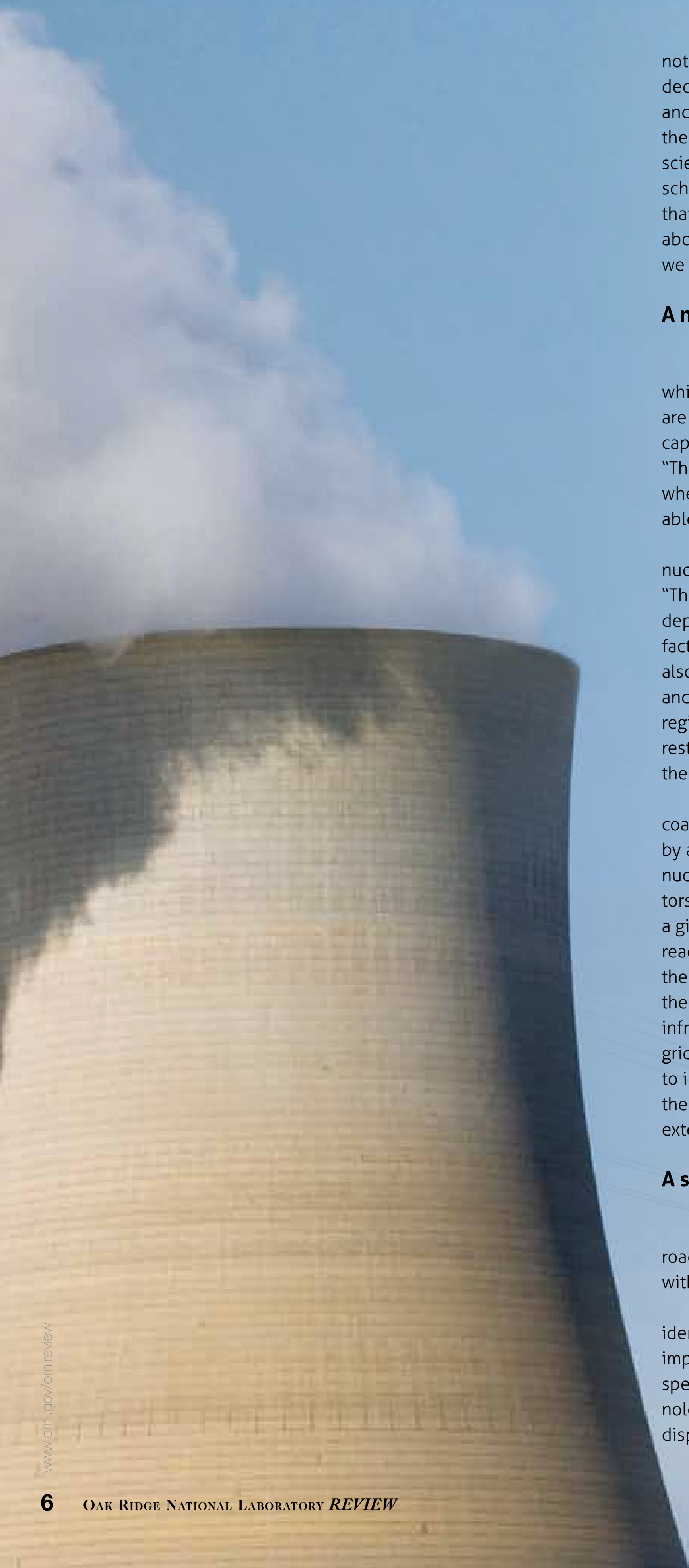
NUCLEAR 2.0

Oak Ridge National Laboratory boasts an unusually broad array of research capabilities—from computing to biology to advanced materials. Surprisingly, many of these programs trace their roots to the laboratory's nuclear origins in the World War II Manhattan Project and the Cold War. Established out of a need to master the nascent field of nuclear science, ORNL designed, built and operated 13 research reactors in its first two decades of operation, establishing itself as one of the nation's premiere research institutions and making significant contributions to the scientific community's evolving understanding of nuclear science and technology.

Today, with renewed worldwide interest in nuclear power in general—and in a new generation of smaller, safer, more efficient reactors in particular—ORNL is poised to play a key role in a rebirth of innovation in the field of nuclear technology. "At its heart, ORNL is a nuclear laboratory," says Kelly Beierschmitt, head of the laboratory's Nuclear Science and Engineering Directorate. "We specialize in fields from fundamental nuclear physics to the disposal of used fuel and environmental cleanup." Between those endpoints, Beierschmitt's organization develops cleaner, more efficient nuclear fuels; creates computer simulations of safer, more efficient reactor systems; and produces isotopes for medical and research purposes.

An aficionado of nuclear history, Beierschmitt underscores the relative youth of nuclear science as a scientific discipline,

The High Flux Isotope Reactor's research capabilities are unique in the world.



noting that the neutron wasn't even discovered until 1932. Just three decades later, ORNL's High Flux Isotope Reactor was in operation, and to this day, some of HFIR's research capabilities are unique in the world. "HFIR and other early nuclear facilities were designed by scientists using slide rules in a little more than a generation," Beierschmitt says. "We should be humbled by the progress they made in that short period of time. If they could do that with slide rules, think about what we should be able to do with the computing resources we have today."

A new generation of technology

There are currently 104 nuclear power plants in the U.S., many of which are nearing the end of their useful lives, and utility companies are faced with making a huge investment to replace their generating capacity. "The 'do nothing' option does not exist," Beierschmitt says. "The decision to spend this money will have to be made, regardless of whether these plants are replaced with nuclear, coal, gas or renewable energy sources."

Beierschmitt is among a growing number of scientists who see nuclear power as a necessary part of the nation's energy portfolio. "Thirty or 40 years from now, I don't think industry will be able to depend exclusively on fossil fuel, because of both environmental factors and the volatility of energy markets," he says. Beierschmitt also contends that, while renewable energy sources, such as wind and solar can play a key role in meeting energy demands in some regions of the country, the relatively low output of renewables and restrictions related to weather, sunlight and energy storage will limit their contribution to the 21st century power grid.

Utilities are also faced with the retirement of thousands of aging coal-fired power plants. The void left by these plants could be filled by a range of clean energy options, including a new generation of nuclear power plants that employ one or more small modular reactors. Unlike traditional large-scale nuclear plants that generate up to a gigawatt of electricity, SMR-based facilities will use several small reactors to produce 300 to 500 megawatts of power—comparable to the coal plants they replace. These smaller reactors also don't require the huge capital investment of traditional nuclear plants, and their infrastructure needs, in terms of water and connections to the power grid, are similar to those of coal plants. Additionally, SMRs promise to improve reactor safety by incorporating passive systems that shut them down in the event of an emergency—without the need for external power or water.

A spectrum of expertise

As the U.S. and other nations approach this technological crossroads, ORNL is finding more opportunities to apply its experience with nuclear technologies in several key areas.

Reactor siting – ORNL has made considerable progress toward identifying potential SMR sites across the U.S. and defining variables important to siting decisions. Laboratory researchers combine site-specific data with geographical information system mapping technology to produce highly detailed, computer-generated maps that display plant locations, infrastructure availability, population centers and much more. "The point of pulling all this data together is to build a resource that policy makers can use to test various scenarios," Beierschmitt says. "For example, if someone wants to replace 20 percent of the power generated by coal plants with nuclear power, how would that change the nation's energy mix? Where would these plants be located? How would this impact the use of water? On the other hand, what if they want to replace the existing, big nuclear plants with coal and gas plants, and how does that change the carbon footprint for the region? This technology allows us to play 'what if' games and simulate or even optimize how we might deploy nuclear power across the U.S."

Nuclear nonproliferation – The laboratory's Global Nuclear Security Technology Division has established a training center for the International Atomic Energy Agency and various governments to teach them how to operate and monitor nuclear power reactors in ways that are transparent to other nations and help to ensure that nuclear materials cannot be diverted for use in weapons. In addition to operating the training center, ORNL staff members provide expertise and advice on all phases of handling and processing uranium to countries and organizations all over the world.

Nuclear isotopes – ORNL produces nuclear isotopes for uses ranging from basic research to nuclear medicine to industrial applications. For example, the laboratory's ability to produce berkelium was critical to last year's discovery of element 117 by an international research team. ORNL also produces most of the world's supply of californium, an isotope used in cancer treatments as well as in industry for ensuring the quality of welds in bridges and buildings.

Reactor modeling and simulation – The laboratory recently began applying its high-performance computing capabilities to the nuclear sciences. Beierschmitt notes that ORNL is home to the Department of Energy's Consortium for Advanced Simulation of Light Water Reactors, an initiative to build detailed computer models of complex nuclear systems. "CASL will enable us to simulate how both existing and proposed systems behave on a very fine scale," he says. "Then we can validate the data produced by these models through experiments."

ORNL's nuclear fusion research program is another beneficiary of supercomputer-based simulation and modeling. Beierschmitt notes that much of the next phase of fusion research will focus on applying high-performance simulation to the challenge of developing new materials that can contain the fusion reaction and translate its heat into electricity.

Storage and advanced fuel cycles – Until policy makers decide whether and how nuclear facilities should reprocess used nuclear fuel, it will continue to be stored at nuclear sites around the country. ORNL applies its simulation and modeling capabilities to address some of the questions surrounding long-term fuel storage. Existing models are based on several years' worth of real-world data. By combining this knowledge with detailed simulations of fuel stored under a range of conditions, researchers develop a better understanding of how used fuel ages and how to improve the safety of fuel storage facilities.

If nuclear fuel reprocessing is mandated, ORNL will provide its industrial partners with support for the technologies needed to handle and process used fuel. The laboratory will also provide computer models of fuel-handling processes to the Nuclear Regulatory Commission for use in licensing reprocessing facilities.

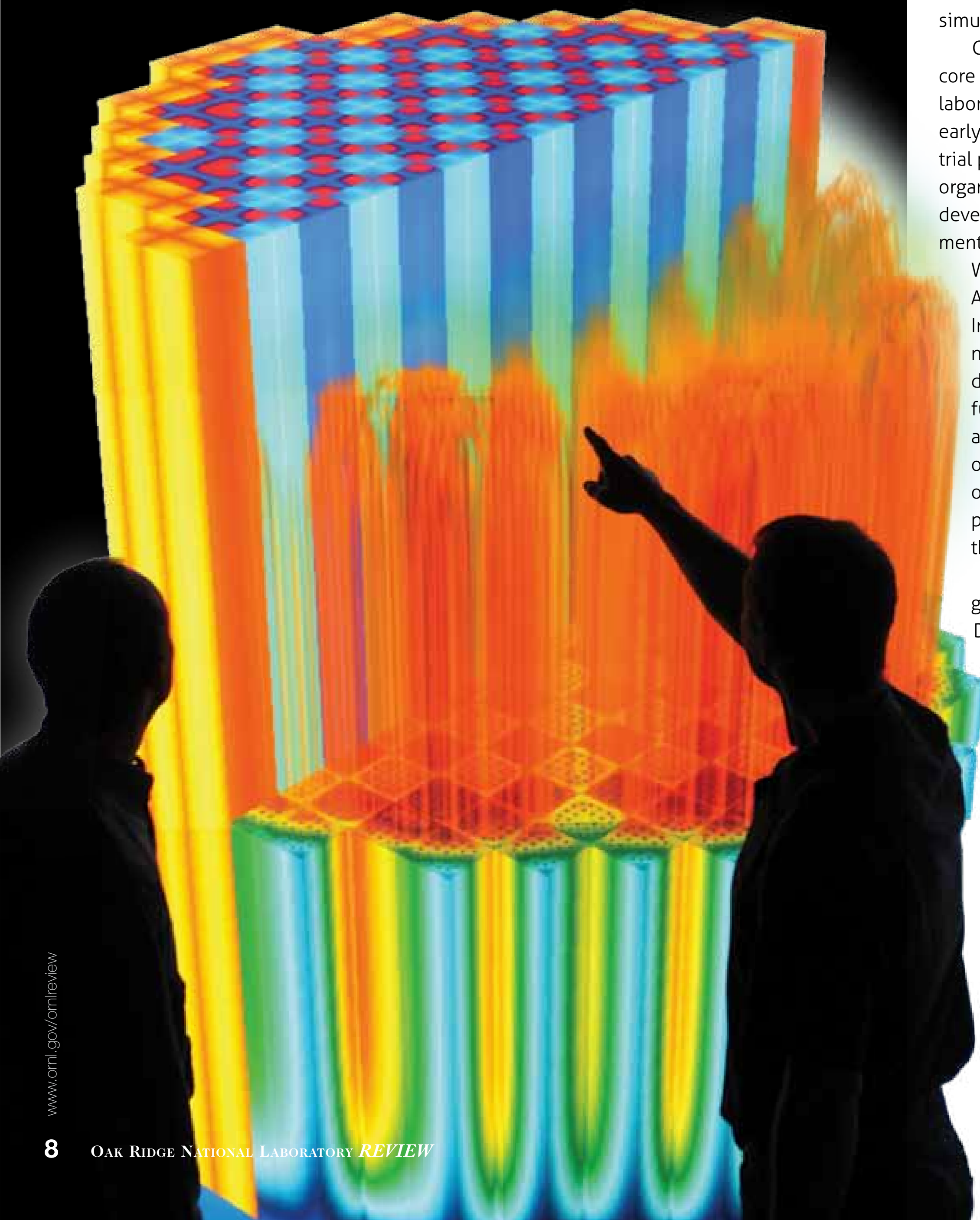
Materials science – ORNL applies its long-standing expertise in materials science to developing structural materials and accident-resistant fuels needed for use in advanced nuclear energy systems. The laboratory's advanced materials researchers test safe performance limits of materials in existing nuclear reactors, develop improved replacement materials, and conduct exploratory research on potential fuels and materials for use in the next generation of nuclear power plants.

The tools and the talent

As more attention is focused on nuclear power, more groups are looking to ORNL as a source of nuclear experience and expertise. Beierschmitt recalls that, on a recent day, representatives from the Australian Nuclear Science and Technology Organisation, the United Kingdom's National Nuclear Laboratory, the U.S. Navy's nuclear reactor program, and the Saudi Arabian government all passed through his office on their way to tour the laboratory's nuclear facilities and meet its scientists.

"People around the world are rediscovering Oak Ridge National Laboratory as a 'go-to' place for nuclear science and technology," Beierschmitt declares. "We are already playing a role in the renewal of nuclear science. We have superior tools and talented staff; we just need the opportunity to innovate. If we can have a fraction of the impact of the generation that came before us, that will be significant."—*Jim Pearce*

Catalyzing REACTOR RESEARCH



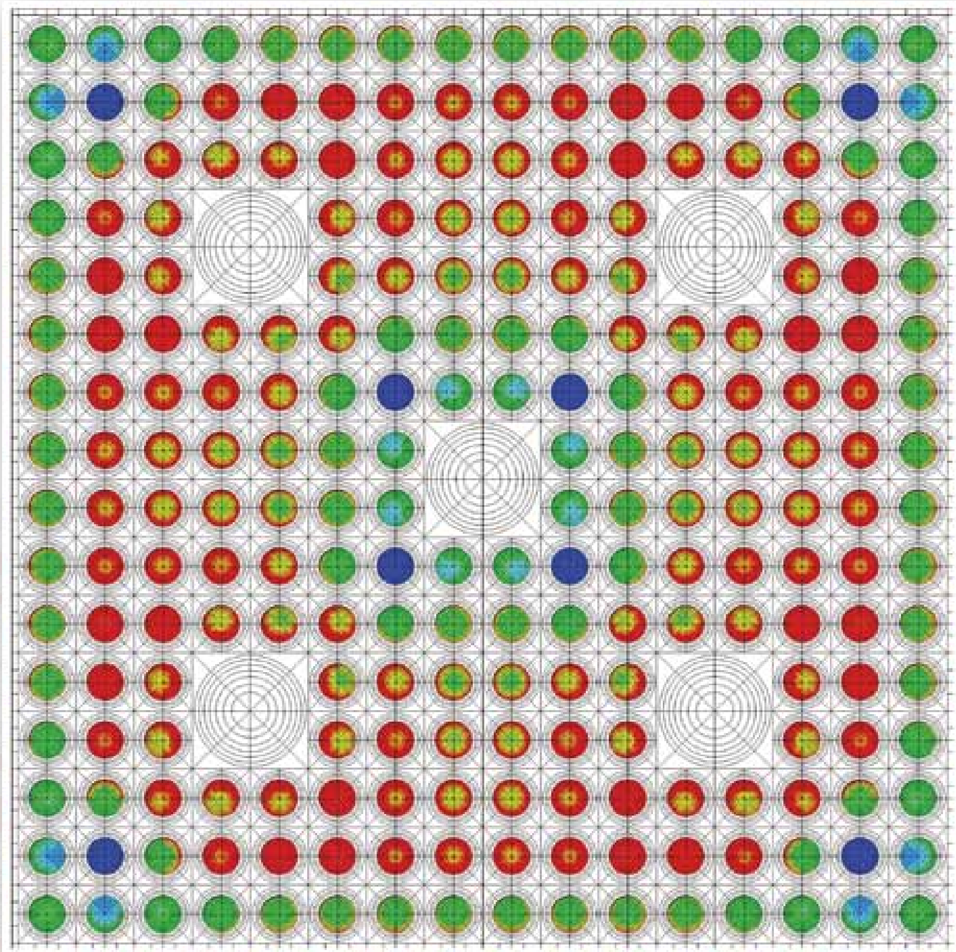
ORNL's recently dedicated Consortium for Advanced Simulations of Light Water Reactors is the Department of Energy's first energy innovation hub. The facility is designed to catalyze nuclear research and development with its unprecedented simulation and modeling capabilities.

CASL is supported by a consortium of 10 core partners—three from industry, four DOE laboratories and three universities. In the early days of the partnership, CASL's industrial partners are the key players, setting the organization on a heading that will ensure developments can be sucessfully implemented in the nuclear industry. The partners, Westinghouse, the Tennessee Valley Authority and the Electric Power Research Institute, represent a cross section of the nuclear energy industry. Westinghouse designs and sells reactors and reactor fuel, TVA operates nuclear power plants, and EPRI acts as the research and development arm of the nuclear industry. These organizations provide CASL with a broad perspective on issues and requirements that affect the entire nuclear sector.

"Overall, nuclear energy performance goals drive our activities," says CASL Director Doug Kothe. The CASL research team focuses on improving the performance of pressurized water reactors, which account for 60 percent of the hundred or so reactors currently on line in the U.S. This includes devising safe, innovative ways to run these reactors more efficiently, driving operating costs down, and burning reactor fuel longer to minimize waste products.

To accomplish these goals, the CASL team is currently concentrating on developing a new suite of simulation tools called the Virtual Environ-

ORNL's computing resources enable scientists to visualize reactors in unprecedented detail.



CASL will investigate fuel performance to help nuclear plants produce more power with less waste.

ment for Reactor Analysis. Researchers will use VERA to model what happens inside a working reactor vessel—specifically the kind of pressurized water reactors that TVA operates. (Three of the six reactors TVA currently operates are PWRs.) In the longer term, CASL will broaden VERA's scope to encompass modeling operational and safety scenarios for other types of reactors, including proposed next-generation designs.

Kothe notes that in the wake of the recent events at Japan's Fukushima nuclear site, a lot of people want to know if CASL's simulations might help scientists understand what went wrong with the Fukushima reactors and how to prevent similar problems in the future. He explains that while CASL's goal isn't to model severe accident scenarios, one aspect of CASL's scope of work is Fukushima related: understanding how reactor fuel behaves when coolant is lost or when it is suddenly exposed to steam or air. "What we learn will be relevant to a range of safety analyses," Kothe says, "including studies of the problems that occurred at the Fukushima site—but we're not modeling any site-specific accident scenarios."

Virtual reactor

The first issue CASL will address is the efficiency of the current generation of nuclear reactors. This has been a concern of the nuclear industry for several years. In fact, utilities have put an additional 6 GW of power on the grid without building a new reactor through improvements in operational efficiency. "This means running the plants more efficiently and at higher power," Kothe says, "which usually involves using more fuel, fresher fuel and increasing the flow of coolant through the reactor core." One of the main challenges CASL researchers will face is understanding how fuels perform under these conditions and determining how to generate more power while producing less waste.

In the longer term, CASL will also investigate what Kothe calls "localized issues," those involving a specific fuel rod or fuel pellet in a scenario where the reactor has suffered a loss of coolant. "We're trying to determine with a high level of confidence what the behavior of the rod or pellet would be under those conditions," he says. "How hot does the fuel get? Does it melt? Does it release gases?" To accomplish this, researchers will build computer models of fuel behavior and then benchmark them against known behaviors. For example, if researchers know from experience how hot the cladding on a fuel rod gets when a reactor loses coolant for a given period of time, they want to ensure that models accurately reproduce this.

The computational power available on ORNL's Jaguar supercomputer will enable researchers to build models in unprecedented detail. CASL scientists will be looking at fuel behavior at the pellet level in reactors that have 51,000 fuel rods, each filled with 300 to 400 pellets. "It might look like we're losing the big picture by zeroing in on one pellet," Kothe explains, "but it's important to understand what's happening on that level before we can understand the overall performance of the reactor." CASL researchers expect VERA to start with a full-core simulation and then find vulnerable or weak points of the design—down to individual fuel pellets.

Of course, CASL's main goal is to give researchers a better understanding of the overall performance of a working reactor core. For example, VERA's simulation abilities allow nuclear fuel designers to experimentally enhance the performance of a real-world reactor by changing the arrangement or composition of the fuel in its virtual twin. Kothe notes that VERA's simulations will be limited to the reactor core. "CASL is not going to model entire nuclear plants," he says. "Other groups have already developed simulations that model the systems outside the reactor. The CASL virtual reactor is initially going to be a core simulator, not a plant simulator."

However, in anticipation of pairing VERA's modeling capabilities with those of other simulation tools, CASL researchers are coordinating their work with an Idaho National Laboratory research team that has developed software to simulate safety-related situations at a nuclear plant. This partnership ensures that the INL system simulator can be plugged directly into VERA. "We're making sure that VERA can be integrated into efforts to model core and system failures," Kothe says. "We can envision a real-time nuclear power plant simulation in which VERA is simulating the reactor and additional software is simulating the behavior of other systems."

Measures of success

Kothe says that CASL researchers want to deliver three things as measures of success. First is an accurate, detailed simulation technology that helps nuclear professionals anticipate what happens in an operating reactor core in a more predictable way. This will be the VERA virtual reactor. They also want to provide simulation-guided solutions to industry problems related to reactor power upgrades, reducing waste and enhancing safety. Finally, Kothe's team would like to help bridge the gap between fundamental research and commercialization by accelerating the deployment of basic science advances into industry.

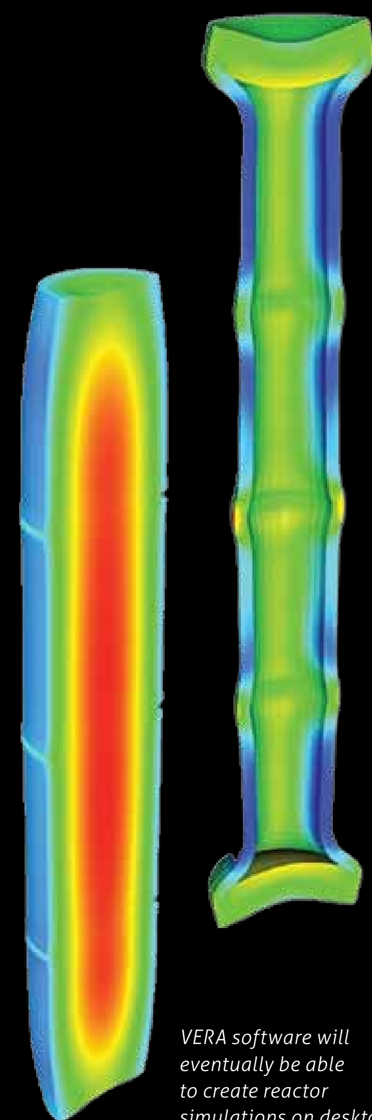
One step toward bridging this gap will be making VERA accessible to a number of different users. Even though VERA will be optimized to run on Jaguar, the software must be portable enough to run in less exotic environments, including desktop and laptop computers. "Although the models generated on laptops will be less complex than those generated by Jaguar," Kothe explains, "developing software that will produce high-quality simulations across a range of computing platforms is a priority."

A new state of the art

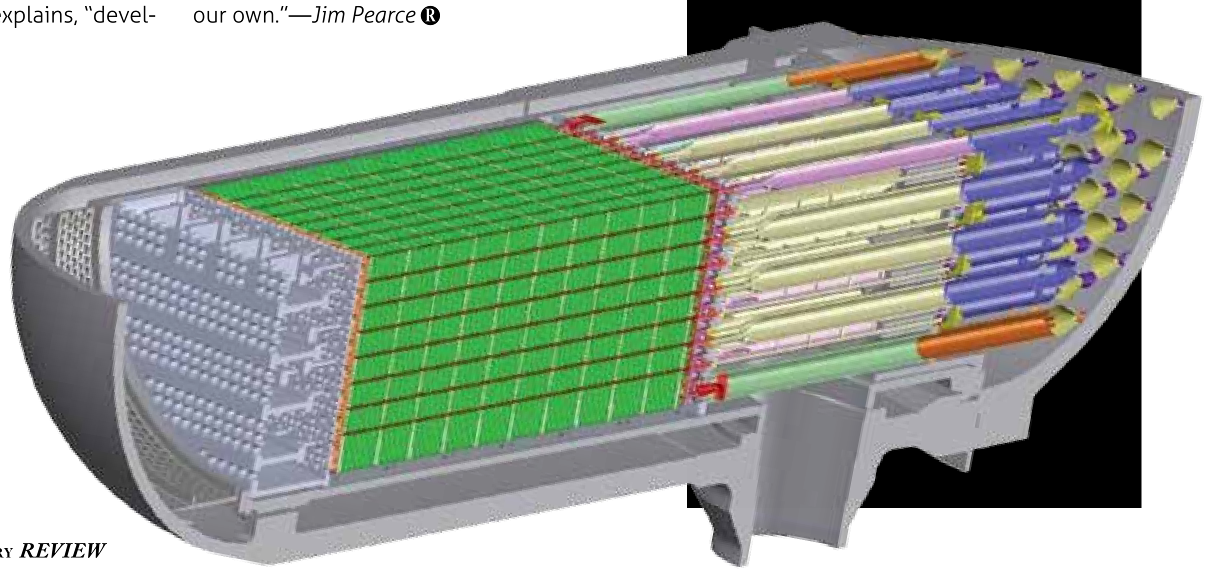
Over the next three years, CASL expects to release several versions of VERA. The big advantage VERA will have over the current state of the art in reactor modeling is its ability to model all the significant aspects of reactor core operation and their simultaneous interactions. "In order to do a really good job of predictability and simulation you have to do these things simultaneously," Kothe says.

By the end of the consortium's first five years of operation, the expectation is that nuclear vendors and operators will use VERA in engineering their designs and increasing the output and efficiency of their nuclear plants. Kothe also expects that, through research, discussions with industry and published papers, CASL will help utilities with their goals of burning fuel more thoroughly, decreasing the time it takes to power-up a reactor and extending the lives of their facilities.

Kothe emphasizes that CASL's success will depend, to a great extent, on meeting the needs of nuclear utilities and reactor vendors who have already invested a lot of time and money in their own modeling capabilities. "We're making sure we incorporate these capabilities into VERA as well," he says. "It's important for us to understand our partners' requirements—otherwise we can't help them improve their operations. Working with the nuclear power industry is not an 'if you build it they will come' thing. It's a cultural thing. We're starting from their baseline, rather than our own."—*Jim Pearce*



VERA software will eventually be able to create reactor simulations on desktop and laptop computers.



DESIGNER FUELS

Enthusiasm for nuclear power has waxed and waned for decades as people have tried to balance its real and perceived risks and benefits. Despite shifting support for this technology, nuclear reactors continue to provide 20 percent of the electricity used in the U.S. and 14 percent of the electricity used worldwide—without generating carbon emissions. In the last decade, however, as both energy costs and concern over greenhouse gases have increased, nuclear research and development has enjoyed a resurgence in the U.S.

One sign of this change is a renewed interest in advanced nuclear fuel formulations. Scientists working with power companies have found that fine tuning a reactor's fuel mix has several advantages. The most obvious benefit is increased efficiency. By 2015, advanced fuels will help to increase the output of existing nuclear plants by 9.2 gigawatts—the equivalent of nine new power plants. Advanced fuels also help power plants operate more safely, reduce the production of long-lived radioactive waste products, and make it harder to divert used fuel for use in nuclear weapons.

Advancing the art

"The 'advanced' part of advanced fuels means we help make the nuclear fuel cycle safer and more efficient," says Jeff Binder, head of ORNL's Fuel Cycle and Isotopes Division. "We do this by developing fuels that are more tolerant to accidents, devising less costly ways to process used fuel and designing fuels that incorporate recycled waste products."

One priority for Binder's staff is developing fuels that are more tolerant to accident conditions like those experienced recently at Japan's Fukushima Daiichi Nuclear Power Plant. "Devising fuels and cladding materials that are less likely to degrade when a reactor core loses coolant for a period of time is of the utmost importance," Binder says. For example, current light water reactor fuel is encased in a zirconium-based alloy metal cladding. When a reactor loses coolant, this cladding reacts with the steam and high temperatures that are present in a severe accident and produces hydrogen, creating the potential for an explosion. "If a completely ceramic-composition fuel could be devised," Binder explains, "this would eliminate hydrogen production during nuclear accidents that involve a loss of coolant to the reactor core. The production of significant amounts of hydrogen in several of the reactors at Fukushima contributed significantly to the severity and consequences of the accident."

The other top priority for the Fuel Cycle and Isotopes Division is developing fuel cycle technologies that enable nuclear utilities to wring more power out of the same amount of fuel. "We only use about three or four percent of the energy potential of the fuel," he says, "so part of the economic motive for advanced fuel cycle work is to use this resource more efficiently. Also, because enriched uranium is fairly inexpensive, there hasn't been a lot of incentive from a cost perspective to recycle spent fuel. But there is growing interest to do so for both nonproliferation and waste management reasons."

Another incentive for reprocessing used fuel is that it can be a source of isotopes used in medical and industrial applications. Binder notes that there are a number of potential synergies between fuel cycle research and the production of nuclear isotopes. Both technologies depend on the ability of researchers to design complex materials, anticipate how they will change when placed in a reactor and devise ways of chemically separating the resulting materials. ORNL is one of the few places in the nation that has both the range of expertise and the facilities to accomplish this.

Managing the actinides

Another pressing problem Binder's group is addressing is separating long-lived waste products known as actinides (including plutonium, americium, curium and neptunium) from used fuel more efficiently. Although these materials account for only about one percent of nuclear waste, they are extremely difficult to handle and dispose of. Separating actinides from the rest of the waste and from each other makes them much easier to process and allows researchers to consider how they can be routed back into the fuel cycle. Binder explains that part of his team's job is to develop fuels that incorporate these by-products, so they can be sent back into the reactor to be burned or transformed into more easily handled waste.

Considerable research goes into changing the composition of reactor fuel. Scientists must consider how the redesigned fuel will affect reactor operation and how characteristics of the reactor, such as coolant flow, need to change to ensure safe, economical reactor operation. ORNL's recently dedicated Consortium for Advanced Simulation of Light Water Reactors will accelerate researchers' ability to consider these factors by applying the power of the laboratory's supercomputers to the study of advanced fuel performance and a range of related issues.

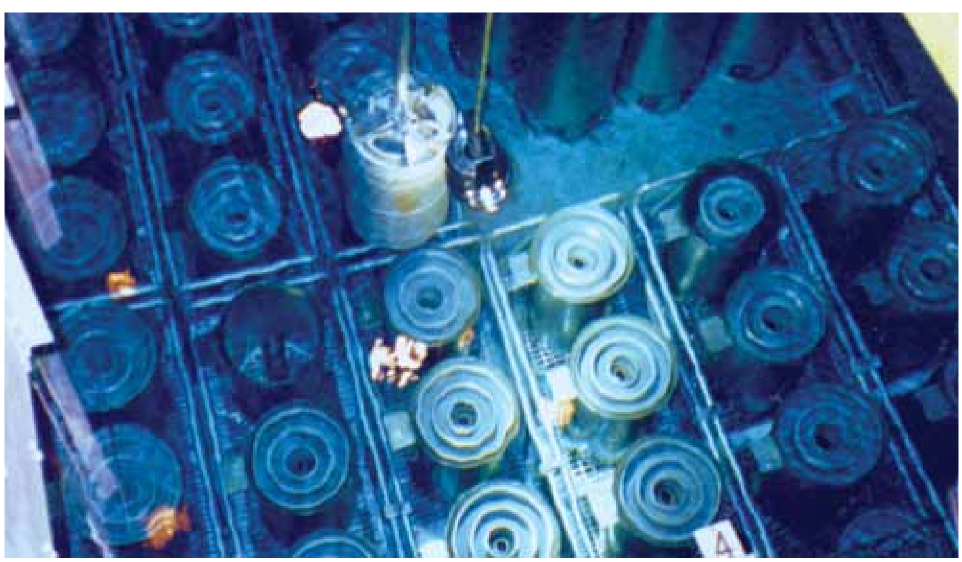
Chemical fingerprints

Binder's group also applies its expertise to supporting the laboratory's national security and nuclear nonproliferation efforts. Working with ORNL's Global Security Directorate, fuel cycle researchers investigate increasingly sensitive ways of detecting chemical evidence of small-scale nuclear fuel reprocessing. This involves extremely precise analyses of isotopes—in concentrations down to the parts per billion level—to generate distinctive chemical "fingerprints" of materials. These forensic clues can provide indications of attempts to divert both new and used nuclear fuel to the production of nuclear weapons.

Techniques like these can be used from a distance to analyze the chemistry of smokestack emissions, or by nuclear inspectors to determine whether a plant normally dedicated to legitimate activities has been diverted to producing materials for use in nuclear weapons. Scientists can apply similar analyses to tracing the origin of a nuclear material or to deducing the origin of a nuclear device or dirty bomb–either before or after detonation.

Bridging the gap

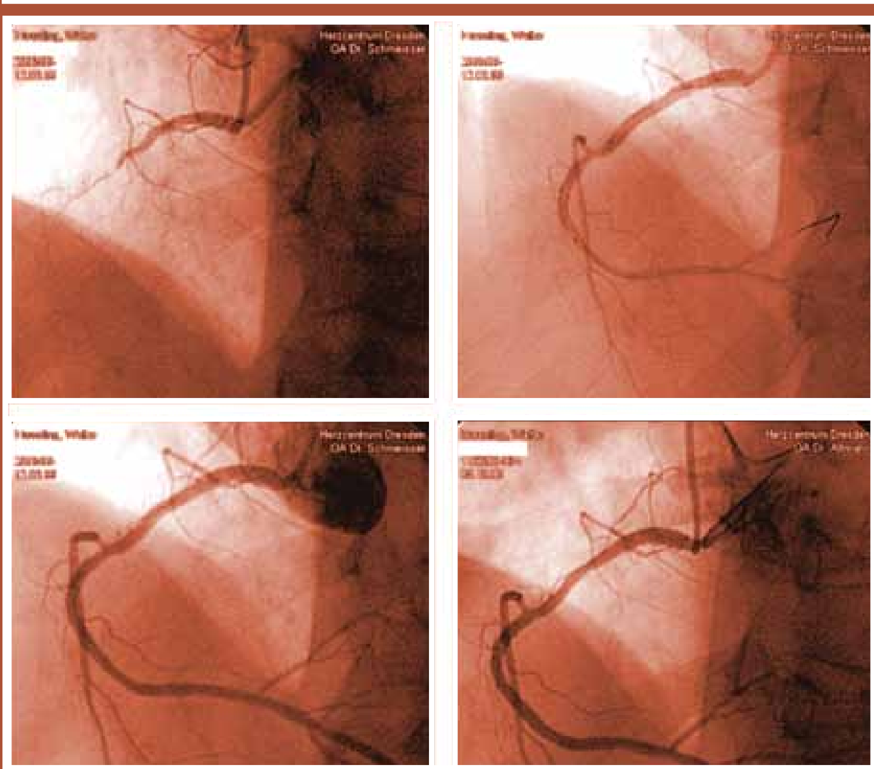
The advantages of applying fuel cycle and isotope technologies effectively will become increasingly important as the nation's power companies bridge the gap between current nuclear plants and the generation of reactors that will take their place. In addition to maximizing the efficiency of our current power plants, this area of research and development has the potential to make the next-generation nuclear fuels cleaner, safer, more durable and less susceptible to proliferation. These advanced fuels also hold the promise of a waste stream that is safer to store, simpler to process and easier to recycle. —*Jim Pearce* Ⓡ



ADVANCED MEDICAL ISOTOPES

Medical isotopes are used in a variety of medical procedures, including cancer treatments.

Like fuel-cycle researchers, scientists in ORNL's isotopes program have a vested interest in exploring the production and processing of radioisotopes—in this case for medical applications. Dating back to 1946, the laboratory's radioisotope program relies heavily on the production capabilities of the High Flux Isotope Reactor. Since its construction in the mid-1960s, researchers have used HFIR to produce a wide range of medical radioisotopes and have greatly advanced the design and testing of new radiopharmaceuticals.

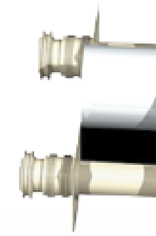


The production of different isotopes requires neutrons with various energy levels. HFIR is one of two facilities in the world that provides enough neutrons in a specific energy range to enable the production of several critical isotopes. These radioisotopes are used in a variety of therapeutic applications in nuclear medicine, cancer research and other specialties, including therapies for liver and skin cancer. Other applications of ORNL-produced radioisotopes include treating rheumatoid arthritis and relieving bone pain associated with the spread of prostate, breast and lung cancers. These pain-relieving treatments don't kill cancer cells, but they greatly increase the quality of life for terminally ill patients.

ORNL's Nuclear Medicine Program develops technologies for both the production and use of radioisotopes and has participated in several clinical trials involving isotope-based treatments. The program also collaborates with the International Atomic Energy Agency and other institutions around the world on research into radioisotopes as well as their medical applications.

Some of this research entails investigating new techniques for purifying isotopes for use in imaging and treating tumors. These efforts involve developing and testing processes for attaching radioisotopes to molecules, antibodies and nanoparticles that zero in on specific biological features of tumors. Among the radioisotopes being applied in this way are HFIR-produced therapeutic agents, such as rhenium-188, used in the treatment of bone, liver and skin cancers; bismuth-213, used to treat acute myeloid leukemia; and radon-223, expected to be useful in the treatment of bone pain.

Another prospect on the program's horizon is harvesting isotopes from used nuclear fuel, or even proactively tweaking the composition of new fuel to yield specific isotopes in its waste stream. The thought among some isotope researchers is that if waste products are treated as the source of valuable medical isotopes, rather than strictly as a liability, recycling used fuel could become a more attractive option.—*Jim Pearce* Ⓡ



INVENTING *the future*

Fusion energy—clean, plentiful power from readily available resources—has long seemed just out of reach. Now, increased interest in several fusion-related research projects is bringing the reality of fusion power closer than ever before.

The most prominent of these efforts is the ITER project, an international collaboration of scientists and engineers assembled to build an experimental fusion reactor. ORNL's experience in shepherding the mammoth Spallation Neutron Source project to completion, combined with its decades of experience in fusion research, uniquely qualify ORNL for a leading role in the ITER partnership. The laboratory is playing a key role in ITER's construction and in meeting the ever-evolving research and development needs of this project that defines the leading edge of twenty-first-century technology.

Stan Milora, head of ORNL's Fusion Energy Division, notes that much of the work his organization has performed over the last few years involved anticipating technologies and materials needed to build and operate not only ITER, but also its near-term successors. Scheduled to be completed in the fall of 2019, ITER will produce a superheated fusion plasma, as well as 500 MW of thermal power. However, ITER's heat will not be used to demonstrate power production. The task of proving the viability of fusion power for commercial use will be left to one of ITER's successors, known as DEMO, a demonstration fusion power reactor that is expected to churn out several hundred megawatts of electricity.

Extreme materials challenge

Many of the challenges faced by ORNL's fusion researchers involve developing exceptionally durable materials for use in ITER and in other proposed fusion research facilities. Milora says these materials must be able to withstand the unforgiving environment inside a fusion reactor (constant neutron bombardment and contact with 150 million degree plasma); convert heat of the fusion reaction into electricity; and use neutrons created by the fusion reaction to breed more tritium, which, along with deuterium, fuels the ongoing reaction.

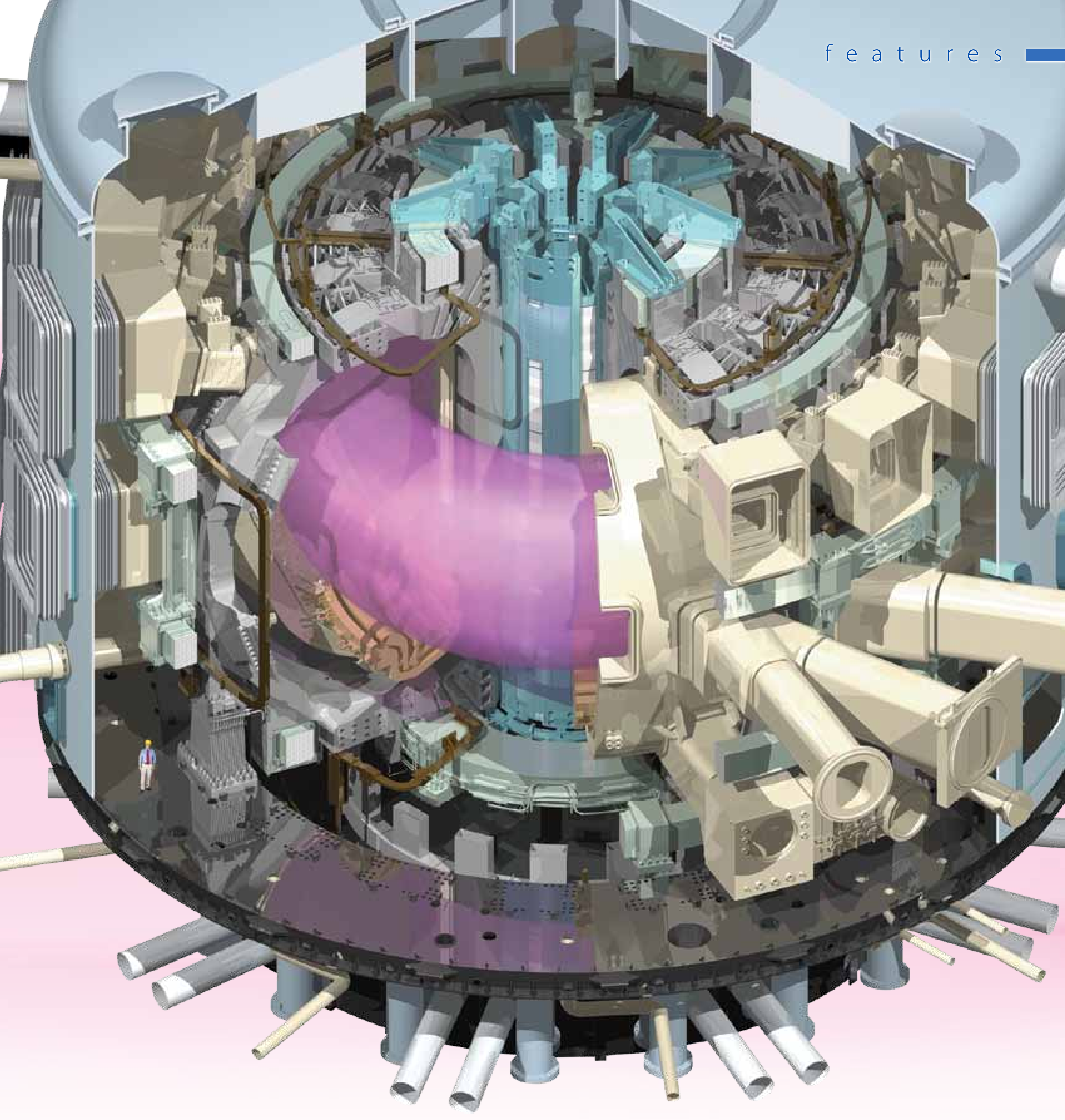
Scientists find themselves in a bit of a quandary, however, when it comes to testing these materials. "The best place to test materials designed to withstand a fusion environment is in the fusion environment itself," Milora says. Unfortunately, no such test facility currently exists. Two proposed facilities are expected to enable researchers to test materials under reactor conditions.

The first of these facilities, the Plasma Nuclear Materials Test Station, would simulate the conditions at the outer reaches of the fusion plasma. Unlike the circulating, self-sustaining plasma of a fusion reactor, the PMTS would continuously generate a column of plasma using radio waves. However, the effect of the plasma on materials would be very similar to that of a fusion reactor.

The second facility, the Fusion Nuclear Sciences Facility, would be a true, small-scale fusion research reactor. The primary purpose of the FNSF would be to test the performance of lithium-containing components, called "blankets," embedded in the walls of the reactor. The blankets will be bombarded by neutrons produced by the fusion reaction. This shower of neutrons will gradually transform the lithium into tritium, which will be recovered and used, along with deuterium, to fuel the reactor. The blankets will also be used to convert the energy of the neutron bombardment into heat, which will then be used to generate electricity. The production of blankets that can tolerate a fusion environment for long periods of time will require new, highly durable, radiation-resistant materials. "That's another aspect that will be investigated at this facility," Milora says.

At ORNL, this materials development work is managed by Roger Stoller of the laboratory's Materials Science and Technology Division. "Research focused on developing tough, radiation-resistant structural materials has been a mainstay of the U.S. fusion materials effort for many years," Stoller says. "New steels and ceramic composites that are being considered for use in DEMO have been developed in collaboration with Japanese scientists." Much of this research has been conducted at ORNL's High Flux Isotope Reactor—a small nuclear fission reactor where materials can be exposed to intense neutron bombardment. This ongoing research will be used to identify materials for use in the design phase of DEMO, although additional studies of these materials using higher energy neutrons may be required to approximate the conditions inside a fusion reactor.

Milora explains that one of the primary drivers for building the FNSF is to expose materials and associated components to neutron bombardment and fusion plasma at the same time. "We could pretreat samples with neutrons in the HFIR and then expose those samples to plasma in the PMTS," he says. "In fact we will do this to guide the selection of the plasma-facing components in the FNSF. However, once the FNSF is completed, we will be able to do both simultaneously under conditions that closely resemble those in DEMO."



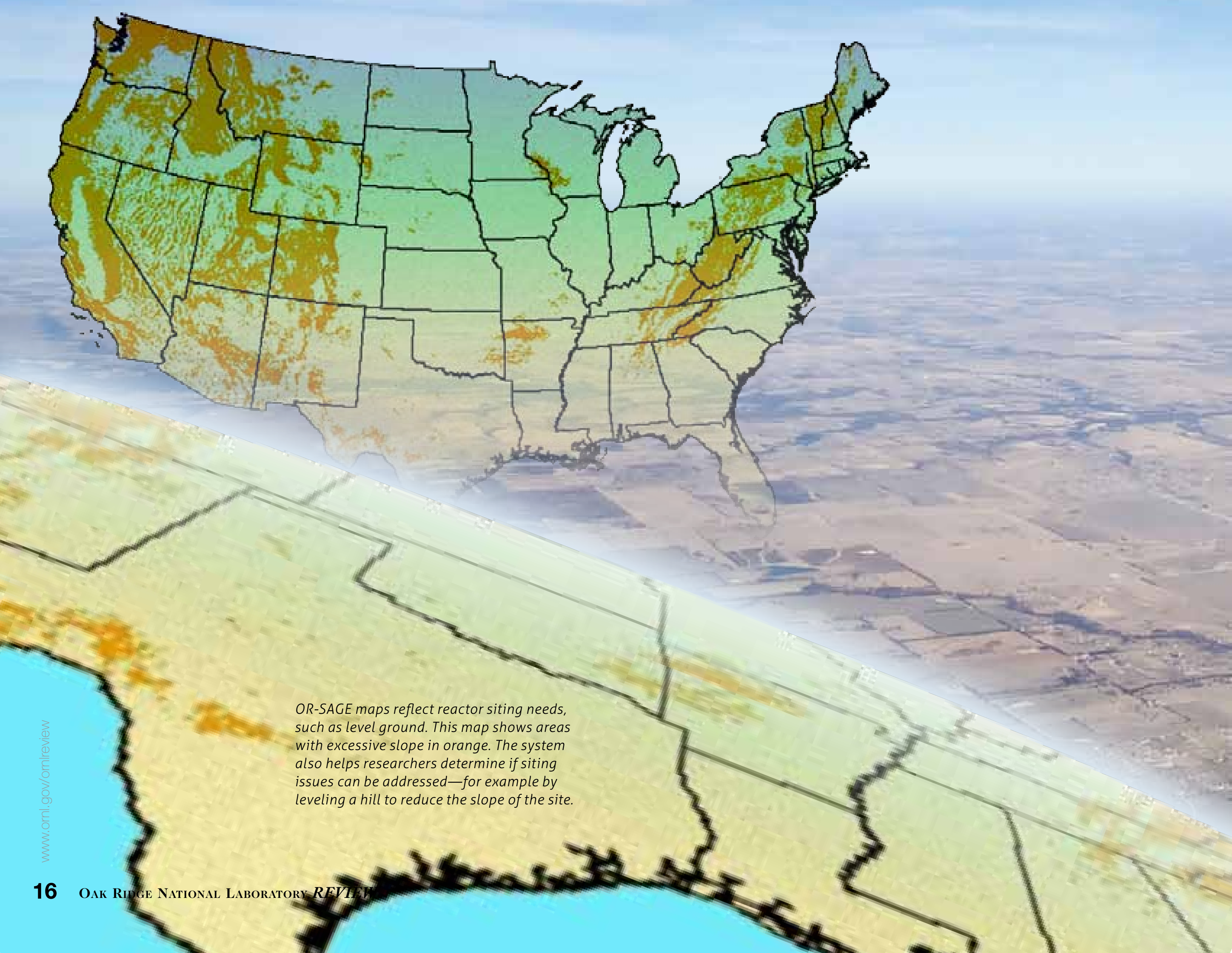
A practical option

Despite the magnitude of the materials challenge and the need to develop two world-class research facilities along the way, Milora is positive about the prospects for both ITER and for fusion energy in general. "Fusion power has many advantages over traditional means of generating power," he says. "It's clean; it produces no greenhouse gases; the technology will be shared with all of ITER's international partners; and its primary fuel, deuterium, comes from seawater, which we have in abundance."

"Once ITER and DEMO demonstrate the practicality of fusion reactors as well as that of fusion power production," Milora says, "generating power with a fusion reactor will be a viable option for utility companies around the world—on a par with nuclear, coal or natural gas power production—and with fewer drawbacks."—*Jim Pearce*

bird's-eye view

ORNL mapping tool identifies suitable land areas for new nuclear plants



OR-SAGE maps reflect reactor siting needs, such as level ground. This map shows areas with excessive slope in orange. The system also helps researchers determine if siting issues can be addressed—for example by leveling a hill to reduce the slope of the site.

Constructing a layer cake with 22 tiers would be a baking experiment of epic proportions—an architectural balancing act worthy of a pastry professional. Although Olufemi Omitaomu would not call himself a chef, he and his ORNL colleagues are concocting a multilayered cake of their own, except instead of being on a cake stand, it's on a computer screen.

Instead of flour and sugar, Omitaomu deals with data—and lots of it. Twenty-two datasets known as layers make up an ORNL tool called OR-SAGE, short for Oak Ridge Siting Analysis for power Generation Expansion. The mapping tool, developed from a wide array of geographic information systems (GIS) data sources, is designed to support siting evaluations for power plants of all shapes and sizes.

The development of the OR-SAGE tool, which is being used to support a project funded by the nonprofit Electric Power Research Institute, was prompted by a 2008 ORNL internal study that examined the key issues associated with the country's future energy needs. A principal finding was that 300 gigawatts of new nuclear electric-generating capacity would be needed by 2050. What was not clear, however, was where those power plants could be located.

"We don't know if we have enough land area to support that analysis," says Omitaomu, a research scientist in ORNL's Computational Sciences and Engineering Division. "That's not a single power plant. It's hundreds."

Identifying candidate sites

An EPRI siting guide, based on guidelines from the Nuclear Regulatory Commission, formed the foundation for the OR-SAGE tool. The written criteria, representing factors such as population density, seismic activity and proximity to cooling water sources, were matched with appropriate datasets to provide values for each criterion. The ORNL team assembled the datasets from diverse sources, including the U.S. Geological Survey, the U.S. Census Bureau, the Department of Transportation, the Federal Aviation Administration and the Federal Emergency Management Agency.

One source unique to ORNL was LandScan, a population distribution model. LandScan models population distribution at resolutions down to the level of a city block. Unlike census data, which only provides a broad sense of where people are located within a large area, "LandScan is able to tell you exactly where those people are," says Omitaomu.

Finding the appropriate dataset for each written criterion was not a straightforward process. For example, as a rule of thumb, nuclear power plants need to be placed within 20 miles of a large body of water to meet cooling water needs. This required the ORNL team to limit acceptable sites to a 20-mile zone around water sources where plants could be reasonably sited. Locating a plant outside the zone might be prohibitively expensive in terms of water transportation costs.

After tweaking the GIS datasets to reflect the realistic siting needs, ORNL researchers divided up the continental United States into millions of cells, each measuring 100 meters by 100 meters—about 2.5 acres. Each dataset was then computed for every cell to see if the cell met the criteria. "For each cell, I want know how many people are in that cell. I want to know the slope of that cell; I want to know if it is protected land, if there is a stream in that cell, and so on," Omitaomu says.

The high-resolution nature of the 100-meter by 100-meter cell is a critical component of the analysis. If the cell size is too large, then the GIS tool might exclude large swathes of land, missing smaller viable areas within the cell. A cell can be excluded for siting eligibility for a number of reasons: if its slope is too steep, if too many people live within its boundaries, or if it happens to be part of a national forest, for instance. Omitaomu describes the process as looking for holes in the dataset: "You want to see which cell has a hole throughout all the layers. Then you pull all that together to get a base map of those areas that pass all those criteria."

Even if a given cell does not pass all the criteria, the OR-SAGE method can identify the factors behind its failure. This information can help researchers determine whether the reason for its exclusion can be addressed by, for example, leveling a hill to alleviate steep slope issues. Other factors, such as a high risk of seismic activity, may make the area completely unsuitable for siting a power plant.

In addition to identifying siting eligibility for individual cells, the OR-SAGE tool can be used to specify contiguous areas that are large enough to host a power plant. Traditionally, a large nuclear plant has required about 500 acres of land; however, recent small modular reactor designs require only about 50 acres.

Missing the forest for the trees

In the past, utilities looking for a suitable site for a nuclear power plants may have limited their options because they lacked the broad vision and detailed knowledge that OR-SAGE can provide. "Industry has never had a tool that can give them a view of the entire national landscape," Omitaomu says.

Typically, power plant locations are chosen from a pool of predetermined sites, in large part because scouting out new locations with traditional surveying methods can be time-consuming and costly. The OR-SAGE tool, on the other hand, can be run quickly and easily from a personal computer.

Omitaomu emphasizes that the OR-SAGE method is not intended to replace on-the-ground field studies and data collection—a necessary part of nuclear power plant licensing. "This is a screening tool; it does not tell you, go put something here," Omitaomu says. What OR-SAGE can do, however, is broaden the horizons of groups looking to site power plants.

Even if a company or a utility has preselected a handful of candidate sites, the ORNL tool can save them time and money by narrowing down the options. "If you have several areas in mind," Omitaomu explains, "instead of sending people to these areas and doing field analyses, this tool can easily tell you that, perhaps, two out of the five areas are not suitable. So instead of wasting money to do detailed analyses on all five, you can focus on the remaining three."

The icing on the cake

The short answer to the team's initial question—does the U.S. have enough land to accommodate a large increase in the number of nuclear power plants—is a solid yes. Taking into account the need for contiguous land areas, the ORNL team in one baseline scenario assessed that 13 percent of land in the continental United States may be suitable for siting a large nuclear reactor, while 24 percent may be appropriate for hosting a small modular reactor.

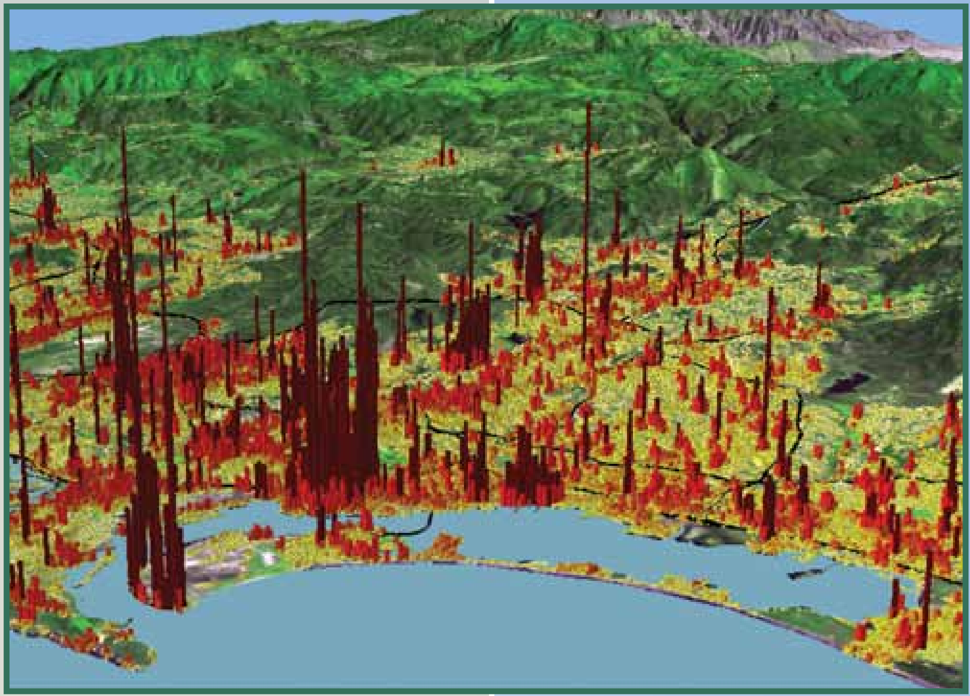
EPRI is using results from the OR-SAGE project as input for economic analyses to explore options for deploying various types of electrical generation plants. As ORNL researchers crafted the modeling system, EPRI realized the value of OR-SAGE for evaluating sites beyond those for nuclear plants. "We started with nuclear, and once they saw it was a good tool, they wanted us to extend it to renewables, like solar, advanced coal and compressed air energy storage," Omitaomu says.

The national scope of the OR-SAGE tool, combined with its ability to analyze areas almost as small as a football field, means that it can be used to help make siting decisions on many different scales. By producing maps that show where different types of power plants can realistically be placed, the GIS model can also help policymakers who want to develop energy profiles or portfolios for a state, a region or the nation as a whole.—*Morgan McCorkle* R

LANDSCAN LOOKS TO THE FUTURE

When tsunamis struck the Indonesian coast in December 2004, the destruction left relief agencies scrambling to locate thousands of stranded people in need of assistance. LandScan, an ORNL-developed global population database that shows geographical distribution of population at 1-kilometer resolution, was a crucial part of the response. Relief workers used LandScan population distribution maps to quickly determine the locations and numbers of potential tsunami victims who would have otherwise been cut off from communication.

LandScan, first developed at ORNL in the late 1990s, has since grown into the community standard for mapping global population distribution. For example, LandScan provides the data necessary for siting reactors away from heavily populated areas as well as providing baseline information for disaster response, humanitarian relief, sustainable development, environmental protection and national security.



LandScan can combine satellite imagery with a range of other information sources, such as census data, as shown in this graphical representation of San Diego's daytime population.

By integrating the best available census and remote-sensing data into a geographic information system framework, LandScan Global describes the total population for a one-square-kilometer area over an average 24-hour period. For the United States, LandScan USA provides even finer resolution, measuring population at the scale of a single city block for nighttime as well as daytime scenarios. In the wake of Hurricane Katrina in 2005, for example, LandScan-produced images were used to brief President Bush about the coast's affected population.

Now, Budhendra Bhaduri, a principal member of the LandScan team, says the award-winning population database is moving into new territory. "The emphasis of LandScan has always been on how many people are where," says Bhaduri, who leads ORNL's Geographic Information Science and Technology group. "We are turning the focus to ask not just how many people are there, but who are these people?"

The answer to this question lies in what Bhaduri calls the "geovisualization of the invisible." By analyzing satellite images, ORNL researchers hope to use geographic indicators such as the structure of neighborhoods, location of marketplaces or construction of satellite towers to understand how people live.

Geographic patterns could reveal, for instance, the economic strength of a given population, which could then be linked to other socioeconomic variables such as level of education, access to information, average size of family or access to services and facilities. Information gleaned from satellite imagery could be used to remotely monitor situations in regions where ground access might be limited. This type of geographic analysis coupled with LandScan's capabilities could be used, for example, to track the living conditions of citizens in Afghanistan and Iraq as U.S. troops withdraw.

"As we start pulling out of Afghanistan, how do we monitor that infrastructure and ensure that things are improving?" Bhaduri says. "That's when we start to look for the sort of indicators we can understand. Are more higher-income neighborhoods, roads, satellite towers, electricity transmission towers and lines being built? Are markets growing or shrinking? All these factors are indicators of stability and prosperity. It all comes down to understanding the patterns on the imagery."—*Morgan McCorkle*

From sand buckets to passive safety

ORNL research supports reactor safety in a new age

Two buckets filled with sand once stood next to the control rod drive system at the Oak Ridge Graphite Reactor, the world's first continually operated nuclear reactor. Each bucket provided a weight on a plunger that could be released if a loss of power occurred—pressurizing a hydraulic drive system and pushing control rods into the reactor to shut it down.

Although crude, this Rube Goldberg–like contraption was part of the original 1943 reactor design, which included not one but three different shutdown mechanisms, providing multiple layers of protection in the event of a runaway reaction. While sand buckets are no longer considered useful safety tools, the philosophy behind them continues to influence the design of modern reactor safety systems.

Defense in depth

"The U.S. nuclear design philosophy is built on a defense-in-depth basis," says George Flanagan, a research scientist in ORNL's Reactor and Nuclear Systems Division. "It means we have system behind system behind system. Defense in depth is a concept that Oak Ridge was involved in from the very beginning."

Today, ORNL researchers continue to support improvements in reactor safety, beginning with the first line of defense—fuel cladding. This layer of protection is found in the reactor core, where fuel pellets are assembled into long fuel rods. Each rod is made of a zirconium alloy, which acts as a wrapper to keep radioactive gases and solids from being released from the fuel. However, under extreme conditions, such as a loss of coolant in the reactor core, the zirconium alloy cladding can react with water and high temperatures to produce hydrogen gas. This sort of reaction is suspected to be the cause of explosions at the tsunami- and earthquake-damaged Fukushima Daiichi reactor complex in Japan earlier this year.

"We are looking at improving the fuel cladding for the current type of light-water reactors," Flanagan says. "This new cladding is made of a ceramic instead of metal, and we are testing it at ORNL's High Flux Isotope Reactor. If it's successful, and we can license it for use in the current fleet of reactors, the improved cladding will reduce the likelihood of hydrogen production in the event of an accident."

Two more physical barriers, the thick-walled reactor vessel and the containment structure that houses the entire reactor, form the next stages of defense-in-depth protection. In addition to these physical barriers, there are a number of other safeguards, including multiple shutdown systems and independent cooling systems, to provide adequate cooling if the normal cooling system fails.

The instrumentation and control components that monitor the reactor operations and provide feedback to the operator are critical to the performance of these safety systems. As the current fleet of reactors transitions from analog to digital instrumentation, ORNL is helping the nuclear industry and regulators make a safe crossover. "There is concern that when facilities upgrade to digital control systems, there might be cross-talk between safety and nonsafety systems or that signals might be subject to interference," Flanagan says. "ORNL's role is to confirm that the digital instrumentation and controls are as good as the analog ones. We play a major role in helping the Nuclear Regulatory Commission make those kinds of decisions."

Passive safety systems

In addition to improving safety measures for existing light-water reactors, ORNL researchers are also involved in analyzing next-generation reactor designs that include new approaches to safety. The current generation of reactors relies on "active" cooling systems composed of pumps, valves and other moving parts. Because each these active components could fail, as the industry looks to the next generation of reactors, designers are rethinking the active approach to safety and are considering passive cooling systems which do not depend as much on moving parts.

These so-called passive reactors are designed to harness water's natural ability to absorb large amounts of heat and include tanks containing millions of gallons of water above the reactor core. If emergency cooling is required, the reactor can be depressurized, allowing the water to drain into the core powered only by gravity. A subsequent cycle of steam production and condensation would substantially cool the reactor without operator intervention or the need for

battery power, diesel generators or moving parts. "The idea is to use basic physics—such things as gravity and condensing steam—to cool the reactor," Flanagan says. "These phenomena occur naturally and don't rely on pumps and valves."

The shift toward a passive safety approach, among other new ideas in reactor design, also requires a rethinking of the traditional license review process. For example, ORNL is helping the NRC prepare to license a small modular reactor for the first time. "The review process that the NRC uses, called a Standard Review Plan, is tailored entirely to large light-water reactors," Flanagan says. "The NRC has decided that they probably can't use that process for this new type of reactor, so we are rewriting the entire review manual for small modular reactors."

Widening the margin

Despite the trend from active to passive cooling systems, Flanagan emphasizes that newer designs still contain the independence, diversity and redundancy that characterize traditional reactor safety plans. "Nobody is considering throwing away the defense-in-depth concept," he says. Passive reactor designs, however, are expected to widen the safety margin by improving upon traditional approaches.

"Calculations show that passive safety systems might be an order of magnitude safer than active systems. It doesn't mean the active systems aren't safe, but there is a margin you gain by going passive," Flanagan says.

This safety margin, in large part due to the defense-in-depth design philosophy, is unique to the nuclear industry. "No other industry has this kind of safety margin built in," Flanagan says. "When a large industrial plant has an accident, there's nothing between the plant and the public other than the site boundary fence. Nobody puts a containment building around these kinds of plants, but the nuclear power industry provides such protection around their reactors and has done so from the very beginning."

—Morgan McCorkle

Nuclear safety has always been based on multiple layers of protection. These sand tanks were part of a gravity-powered backup system for shutting down ORNL's historic Graphite Reactor.

An *Elegant* solution

Rising energy prices and concern over carbon emissions have helped breathe new life into prospects for U.S. nuclear power for the first time in decades. Along with this revival has come intense interest in a new generation of nuclear plants known as SMRs, or small modular reactors. SMRs address many long-standing nuclear safety concerns, while providing power companies with a cost-effective way to match generating capacity to customer demand.

To appreciate why these down-sized, self-contained units are such a vast improvement over traditional reactor technology, it's helpful to look back at the lengthy pedigree of nuclear power in the U.S.

Naval origins

The first power-producing nuclear reactors were pressed into service by the U.S. Navy just after World War II. The earliest units were developed to power ships and submarines in the early 1950s. Later in the decade, when utility companies adapted this technology to power generation, nuclear plants still retained their predecessors' basic design, but applied it on a much grander scale. Where naval reactors had produced tens of megawatts of electricity, their commercial cousins generated up to 1500 megawatts and could power entire cities.

Supersizing the basic naval reactor design turned out to be a mixed blessing for the power industry. While the larger plants were more efficient, their sheer size created more points of potential failure, resulting in a bewildering array of backup systems and other safeguards. "We learned to manage the complexity of this technology," says Dan Ingersoll, head of ORNL's Small Modular Reactor R&D Program, "but it was costly and difficult."

The proliferation of nuclear power plants continued through the 1970s, slowing somewhat as capacity began to exceed demand. "Then, after the Three Mile Island incident in 1979," Ingersoll recalls, "the industry pretty much came to a standstill. In terms of commercial nuclear power, very little has changed since then. Utilities are still operating complex megaplants that are basically scaled-up versions of early reactor designs."

Weinberg's legacy

Although support for nuclear power had all but evaporated by the end of the 1970s, the development of innovative reactor designs was alive and well. Years before Three Mile Island, former ORNL Director Alvin Weinberg left the laboratory and headed up first the U.S. Office of Energy Research and Development and later Oak Ridge Associated Universities' Institute for Energy Analysis. Initially, much of Weinberg's time was spent working with teams of scientists and policymakers considering what the next generation of nuclear power might look like, in terms of basic reactor technologies and power plant design.

In the wake of Three Mile Island and the antinuclear backlash that followed, Weinberg and his colleagues focused their attention specifically on what the nuclear industry would have to do to address its problems and make a strong comeback. "They conducted an in-depth study of the rapid growth in

By the 1970s, Weinberg and others had concluded that small reactors with primary systems inside their containment vessels would be a better long-term option for nuclear power.

the size of power reactors," Ingersoll says. "Their conclusion was that very small reactors would be a better long-term option for nuclear power. In addition, the plants would have to be designed to eliminate vulnerable features by integrating all of the primary systems inside the containment vessel." This compact, integrated design, basically an SMR, was both elegant and robust. If electrical power were lost, the reactor could be safely shut down using self-contained coolant and gravity-driven natural circulation flows. This approach would eliminate both the long stretches of piping linking primary system vessels as well as the need for backup systems to guard against breaks in the pipes.

Unfortunately for proponents of this novel configuration, the 1980s saw orders for commercial power reactors in the U.S. plummet to zero. As a result, the innovative designs developed by Weinberg and his colleagues sat on the shelf for the next 20 years.

A broad resurgence

Today, with the broad resurgence of interest in nuclear energy in the U.S., interest in the small, integrated reactor concepts pioneered by Weinberg and his colleagues has taken off as well. "Several companies are developing designs for state-of-the-art SMRs," Ingersoll says. "They're betting that there will be a large market opportunity for these versatile, small-scale plants."

The big challenge for manufacturers is making small reactors that are as cost-effective as larger ones have been. These companies are calculating that their ability to build reactors on an assembly line, along with the reduced operating costs of SMRs, will enable modular reactors to match the economies of scale enjoyed by traditional nuclear plants.

Ingersoll notes that, in addition to matching the efficiency of larger plants, SMRs are also much more adaptable than their predecessors. "Because their demand on water and other infrastructure resources is comparable to that of coal or gas plants," he says, "modular reactors can be located in a much wider range of locations. This opens up nuclear energy as an option to many more applications, including large business and industrial customers."

In addition to their other benefits, SMRs offer power companies the ability to match their expansion to customer demand. If, for example, a community's need for electricity was growing at the rate of 200 megawatts every few years, the local power utility could add a 200-megawatt SMR to its modular nuclear plant cheaply and quickly. Ingersoll emphasizes that providing the ability to add capacity in relatively small increments is the true value of the modular reactor design.

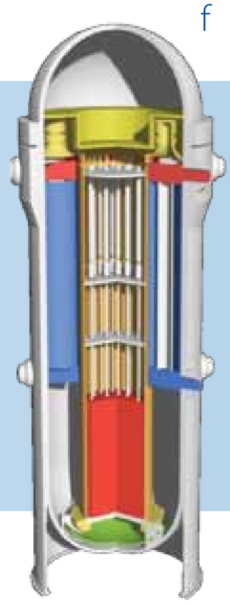
Playing a key role

In addition to his responsibilities at ORNL, Ingersoll, who is also the Department of Energy's national technical director for its SMR program, says the laboratory will play a key role in developing the new generation of SMRs. One reason for this close cooperation is that ORNL is home to research programs that address the technical needs of SMR manufacturers in a number of areas, including sensor development, advanced materials, computer modeling and nuclear fuels research.

"We want to help the industry move the process of siting and manufacturing SMRs forward," Ingersoll says. "Having national labs provide research and development support to modular reactor manufacturers is part of DOE's plan to accelerate the deployment of commercial SMRs."

One of the biggest research and development challenges facing ORNL scientists on the hardware side of the SMR equation will be developing the specialized sensors and instrumentation needed for the new reactor designs. The SMR environment is a particular challenge because most sensors and other instruments will be located in the restricted space of the reactor vessel, and many of them will be exposed to high temperatures, high pressures and intense radiation.

SMR manufacturers will also be working with laboratory researchers at ORNL's Consortium for Advanced Simulation of Light Water Reactors facility, where they will be able to conduct detailed computer simulations of reactor operations. "We're in the process of creating new software that takes advantage of the huge computing capability available through the CASL program," Ingersoll says. "We will be able to model new SMR designs with very high fidelity and reliability." These detailed simulations will enable researchers to simulate the entire life cycle of reactor components and to predict when they will fail. "Knowing where components are in their life cycle is critical to safe and efficient reactor operation," he adds.



Several companies are developing designs for state-of-the-art small modular reactors.

A promising start

Ingersoll says that, until the last few years, small reactor research didn't really attract much attention. Recently, however, there has been an explosion of interest in SMR technology from all quarters.

As evidence of this, Ingersoll notes that, later this year, DOE's SMR program will begin recruiting two companies who want to take on the challenge of designing, licensing and building working reactors. Six months later, they should have the contracts they need to begin the licensing process. Because DOE is shouldering half of the cost of developing these SMRs, the companies that are selected will have to convince DOE that they're worth the investment and that they can deliver results. The goal of the project is to deliver a working SMR by 2020.

While the first SMRs will represent a radical departure from traditional reactor designs, Ingersoll expects that the following generation of SMR power plants will include even more innovative technologies, such as high-temperature, salt-cooled reactors. These novel technologies are significant because they introduce new uses for nuclear energy—like providing both heat and power for nearby high-temperature industrial processes. "ORNL will be doing this kind of advanced reactor research for the foreseeable future," Ingersoll predicts. "We're in this for the long haul."—*Jim Pearce* Ⓡ

Kelly Be

ORNL's Associate Laboratory Director for Nuclear Science and Engineering is responsible for the laboratory's nuclear research and development portfolio, including fuel cycle and isotopes research, reactor modeling and simulation and nuclear security technology. In addition, Beierschmitt is also the Executive Director of the High Flux Isotope Reactor (HFIR) and leads initiatives for a small modular reactor technology, research and licensing ORNL's legacy nuclear and radiological facilities. He also oversees the Department of Energy's first Energy Innovation Hub—the Consortium for Advanced Simulation of Light Water Reactors (CASL).

We asked Dr. Beierschmitt how his organization mirrors the Laboratory's past accomplishments as well as its future aspirations.

ierschmitt

ORNL has a long history of nuclear research and development. How do our current research efforts reflect that legacy?

The laboratory is, in large measure, defined by its materials research. That's how we got our start in the Manhattan Project, working with exotic nuclear materials. The nuclear challenges of the future are, in large measure, materials problems as well. Success in combining our tradition of nuclear research with our more recently developed computational and materials research and development capabilities is what defines us as a nuclear lab today.

We have close to 700 staff members working in areas related to nuclear science and engineering—on projects ranging from nuclear nonproliferation studies to developing materials and components for fusion reactors. These nuclear capabilities are a benefit of our legacy here at ORNL. We want to ensure that these unique capabilities are preserved for our nation's future research and development efforts. To this end, we are currently thinking about what the next-generation high-performance research reactor will look like so that these strategic capabilities are preserved.

We must also ensure that ORNL research and training programs stimulate the next generation of leaders in U.S. nuclear science and engineering in the same way the laboratory's Oak Ridge School of Reactor Technology of the 1950s and 1960s motivated the leaders of the world's first nuclear energy era.

What do you see as the direction of ORNL's nuclear research program over the next decade?

I think our concentration will continue to be largely in the area of fundamental sciences. We do applied work in the areas of nonproliferation and isotope production, but most of our work will continue to be fundamental research. A good example of the need for this kind of research can be found in the 104 nuclear power plants in the U.S. that generate 20 percent of the nation's energy. If we're going to extend the lives of these facilities, we're going to have to do a lot of research on materials to understand what effect another 20 years of operation will have on key reactor components.

Also, in a post-Fukushima world, the nuclear industry is going to want to develop more robust reactor fuel—again a materials problem. Our research programs investigating more durable fuel and fuel cladding are well positioned to help answer these questions. Of course CASL and our related computational modeling tools give us the simulation capability to understand what happens inside a reactor as it ages or when a system fails. This will help drive our experimentation going forward. The combination of these capabilities makes us unique in the world.

How will simulation science help shape the next generation of nuclear reactors?

Simulations allow us to explore what happens at the nanoscale and see the resulting effects on the macroscale. For example, we can look at minute details of how nuclear fuel interacts with its cladding and then scale those observations up and apply them to the reactor as a whole. Not only do we get answers from these simulations, but these studies often help guide the next set of questions—the experiments that allow us to validate what we've seen in the model.

What are the laboratory's contributions to the ITER fusion reactor project?

ORNL has the lead administrative role in the U.S. contribution to ITER. We also have scientists who work on the ITER team on projects like the cryogenic system that injects the fuel into the reactor, plasma control systems and a range of materials development projects. In parallel with our ITER project responsibilities, we expect to increase our long-standing research into the interactions between plasma and various materials since that is one of the challenges in the quest for practical fusion energy.

How have recent events at Japan's Fukushima nuclear facility affected ORNL's nuclear research program?

We are working with the Department of Energy to reevaluate our national research and development priorities to ensure that we're appropriately focused on the challenges that are most urgent and relevant for sustaining and expanding nuclear power as part of our nation's portfolio of clean energy options. We don't think current plans will require a lot of change, but we do see a need to reestablish certain priorities, including developing more robust fuel that can survive reactor system failures, exploring the potential for small modular reactors that may offer enhanced passive safety features, and revisiting issues surrounding the storage and recycling of used fuel.

What do you see as nuclear energy's biggest promise and biggest challenge?

I'm a firm believer that the U.S. economy is going to be driven by the global competition for energy. As emerging countries consume more energy, we're going to be in competition for resources, and cheap fossil energy will be a thing of the past. I support renewable resources like solar cells, biofuels and wind power. However, to get enough power on the grid to meet the demand, nuclear has to be part of our nation's energy equation. It's not a question of if it happens, but when. Our society will decide that we need dependable energy that's not carbon based and not driven by global competition. The sooner we move toward nuclear power in a decisive way, the better off our grandchildren, and their grandchildren, will be. Ⓡ

Unraveling a twister

University of Oklahoma researchers use supercomputing to detail the inner workings of tornadoes

Anyone from Nebraska to Nashville knows a tornado when they see one. And, hopefully, they know to duck for cover. Tornadoes are among nature's most powerful weather weapons.

Just last month, in a span of 24 hours beginning on April 27th, the southeastern U.S. saw a rare outbreak of tornadoes that resulted in a combined 344 deaths, according to estimates by the National Weather Service and the National Oceanic and Atmospheric Administration. Not since 1936 have more people been killed in a two-day period.

Despite their prevalence in a region of the central United States known as "tornado alley," there is still much we don't know about these much-feared funnels from the sky.

For starters, gathering any sort of data from actual tornadoes is risky business, with chasers physically following storms into the heart of harm's way. These chasers might witness a handful of tornados a year, and their mobile radar systems only measure certain variables, such as wind velocity and intensity of precipitation. To truly understand tornadoes, or to predict them, researchers need data that is currently unavailable, such as pressure readings and an understanding of the storms' three-dimensional wind structure. For that, they need far more tornadoes than the atmosphere produces.

"I don't need three, I need three hundred," says Amy McGovern, an assistant professor in the School of Computer Science at the University of Oklahoma, located in the heart of tornado alley.

McGovern is also the principal investigator of a project that is using the University of Tennessee's Kraken supercomputer to better understand, and hopefully one day predict, tornadoes.

In order to do that, McGovern's team uses data from on-the-ground observations and monitoring systems to create a set of variables that describe conditions which may, or may not, create a tornado.

The research is funded by the National Science Foundation's Faculty Early Career Development Program, which offers the NSF's most prestigious awards in support of junior faculty who exemplify the role of teacher-scholars through outstanding research, excellent education and the integration of education and research within the context of the mission of their organizations.

The roots of the tornado project go back five years. Back then, says McGovern, the team used the observational data from a 20-year-old storm and tweaked a few environmental variables to create more than 250 simulated storms, at a 500-meter resolution. Measurements were taken for 40 variables every 500 meters.

The team quickly realized that a higher resolution was needed to achieve the accuracy they sought. Thanks to supercomputers such as Kraken, this enhanced resolution is now possible. Funded by the National Science Foundation and managed by the University of Tennessee's National Institute for Computational Sciences, Kraken is a Cray XT5 supercomputer housed at Oak Ridge National Laboratory.

McGovern's team is now generating 150 75-meter resolution possible tornado-precursor storms, with each simulation creating

Researchers use data from a variety of monitoring systems to better understand tornadoes.

two to three storms and consuming 30 hours and 3,000 of Kraken's more than 112,000 cores. Of these, says McGovern, approximately 50 to 75 of the storms will produce tornadoes, supplying researchers with a sample sufficient to unravel the mysteries of one of Mother Nature's most common terrors.

These simulations delve into the most complex players in tornadic storms, such as rotating updrafts (upward moving currents of air that are tilted and rotating), downdrafts, vorticity (a measure of the instantaneous spin), tilt (how much horizontal vorticity has tilted toward the vertical) and the various relationships among these factors. "The important thing," says McGovern, "is understanding how these variables interact." If a storm does in fact generate a tornado, the team begins the process of "relational" data mining. Whereas in the past these variables have been studied individually, McGovern's relational approach studies the relationships among these variables—more than 40 to be exact—of which 20 are intensely examined. In other words, the team is not looking at individual factors, but how they change over space in time.

Data mining is necessary because each simulation generates approximately a terabyte of data, far too much information to investigate traditionally. For example, while an updraft is just one of the variables being studied, the team will investigate all the variables inside the updraft, such as the pressure gradient and tilt of the updraft itself. With simulations this complex at multiple space and time scales, the amount of data generated is insurmountable without the help of supercomputers to quickly locate important figures in a sea of numbers.

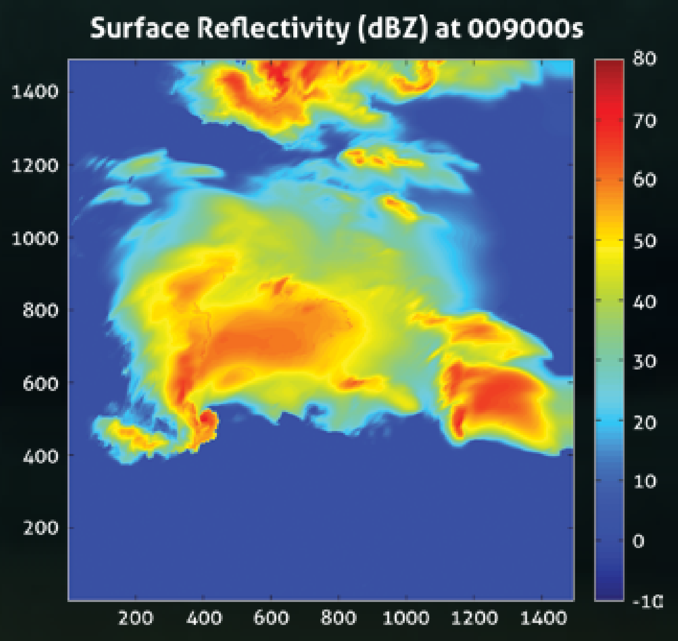
While the simulations are being performed on Kraken, the majority of the data mining is being performed on Nautilus, an SGI Altix UV 1000 system that serves as the centerpiece of UT's new Remote Data Analysis and Visualization Center, which is also located at Oak Ridge National Laboratory. Nautilus's unique architecture provides an excellent platform for relational data mining. "Nautilus is fabulous," says McGovern, adding that the innovative system allowed her team to do three months of work in approximately 12 hours.

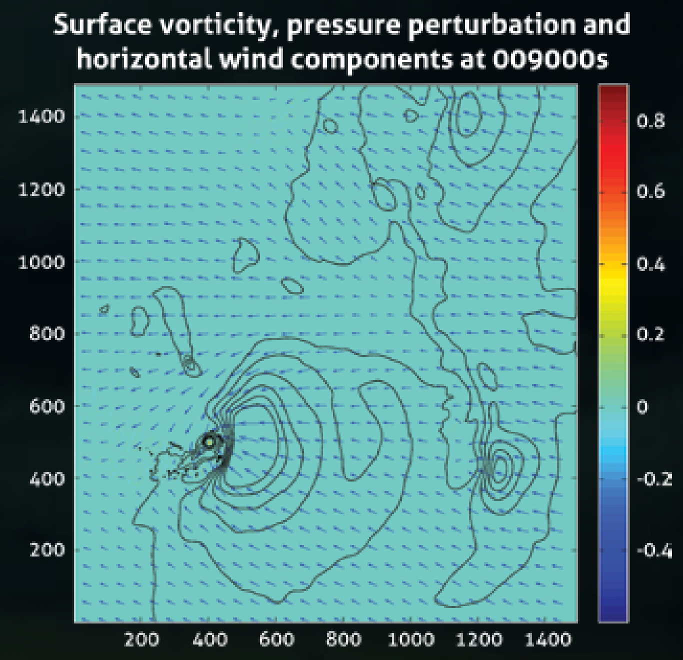
Overall, the team hopes their work will significantly reduce the false alarm rate for tornado warnings, currently about 75 percent, and increase warning lead time, currently around 12–14 minutes. "If we can change our understanding of how tornadoes form," says McGovern, "then, hopefully, that will lead to better prediction algorithms."

For example, if the team's simulations reveal that a certain set of storm conditions usually causes an F5 tornado (among the most powerful tornadoes), then perhaps observers on the ground could watch for those conditions in actual storms. Even if those conditions cause an F5 only half of the time, says McGovern, sounding a warning might save lives.

So far, the team has generated 30 of the planned 150 simulations. With Kraken's recent upgrade to 1.17petaflops, the team should be able to forge ahead even faster than before. But tornadoes are just the tip of the iceberg when it comes to the mining algorithms developed and employed by McGovern's team. They could be used in other fields of science, such as other instances of atmospheric turbulence across the U.S., or even robotics.

For now the team will continue to analyze the enormous volumes of data from their tornado simulations, providing the scientific community with a new understanding of twisters and enabling enhanced predictive capability that could give everyone from Nashville to Nebraska a little more time to duck for cover.
— *Gregory Scott Jones.* R





...and the WINNERS are...

Accomplishments of Distinction at Oak Ridge National Laboratory

Gonzalo Alvarez, **Nina Balke** and **Ezekial A. Unterberg** have received **Early Career Research Program** awards from the **U.S. Department of Energy's Office of Science**.

The five-year awards provide up to $500,000 in funding and are designed to support exceptional researchers during their crucial early career years, when many scientists do their most formative work.

The three ORNL recipients investigate complex problems and phenomena associated with strategic energy research goals.

Alvarez's project aims to advance theoretical modeling capabilities to understand nanoscale phenomena in strongly correlated electronic materials, such as high-temperature superconductors. Understanding these materials could provide insights for the development of new materials for solar cells, lighting and power transmission.

Balke's study seeks to enhance the fundamental understanding of the nanoscale processes that define a battery. Her research will combine microscopy with electrical and structural battery characterization techniques and advanced theoretical modeling.

Unterberg's research focuses on a major challenge for the ITER international fusion experiment and future fusion reactors: controlling the intense fluxes of heat known as edge localized mode, or ELM. These fluxes can seriously damage fusion reactor surfaces.

Stephen J. Pennycook has been named a **Fellow** of the **Materials Research Society**.

Stephen J. Zinkle has been named a **Fellow** of the **Minerals, Metals & Materials Society**.

Andy Wereszczak has been named a **Fellow** of the **American Ceramic Society**.

Carl Burtis has received the **2011 IFCC Henry Wishinsky Award for Distinguished International Services** from the **International Federation of Clinical Chemistry and Laboratory Medicine**.

Ian Anderson has received the **Executive of the Year Award** from the **Volunteer Chapter of the Public Relations Society of America.**

Tina Curry, **LeJean Hardin**, **Lindsey Marlar**, **Mark Robbins**, **Jason Smith** and **Andy Sproles** received awards from **Graphic Design USA** for their work on ORNL promotional materials. Ⓡ

Early Career Research Program award winners Nina Balke and Gonzalo Alvarez (Ezekial A. Unterberg is not pictured).

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Editor—Jim Pearce
Writers—Scott Jones, Morgan McCorkle,
Jim Pearce, Ron Walli
Designer—LeJean Hardin
Technical editors—Walter Koncinski, Debbie Stevens
Illustrator—Andy Sproles
Photographers—Jason Richards and Curtis Boles
Stock images—iStockphoto™
Web developer—Dennis Hovey

Phone: (+1) 865.574.4160
Fax: (+1) 865.574.0595
E-mail: ornlreview@ornl.gov
Internet: www.ornl.gov/ornlreview

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