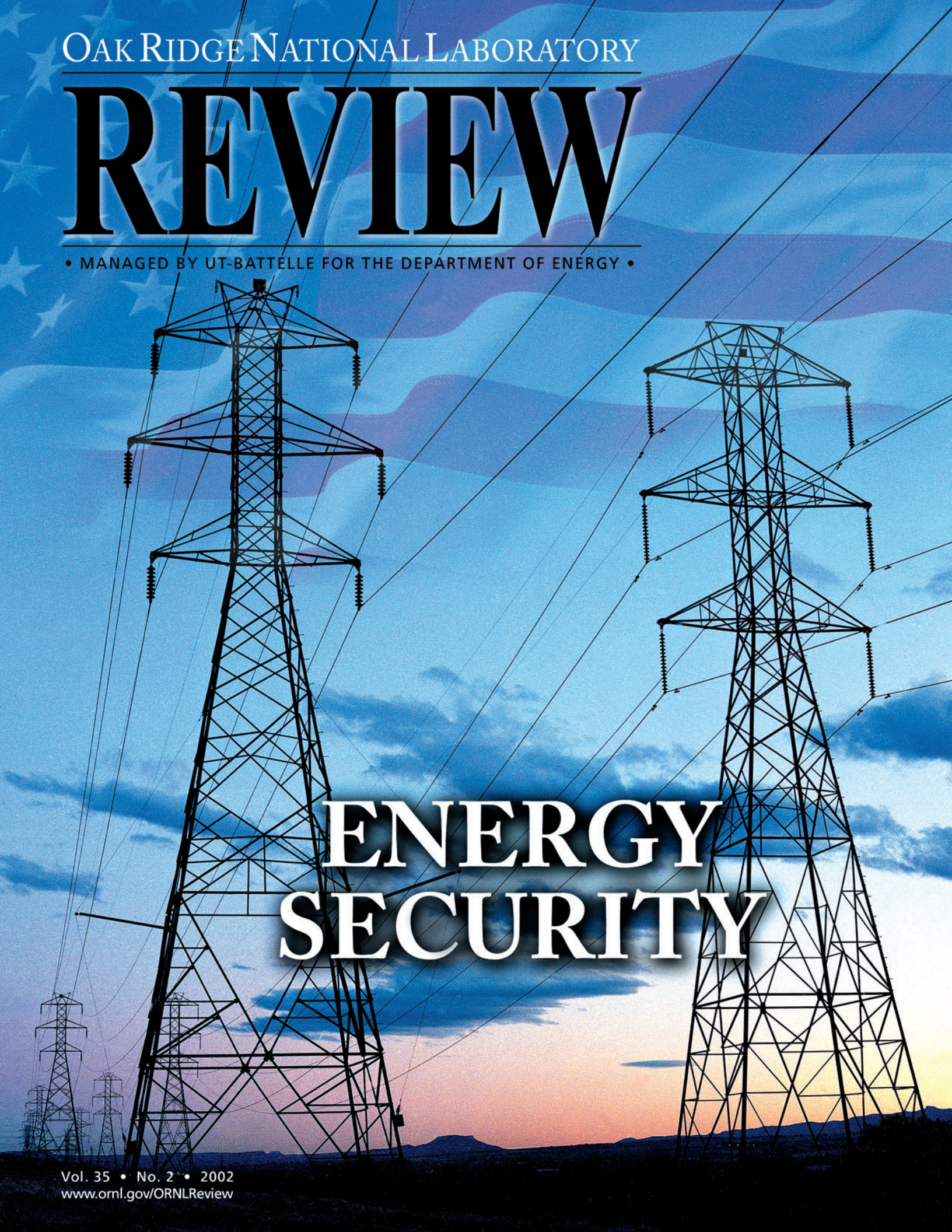
OAK RIDGE NATIONAL LABORATORY

REVIEW

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

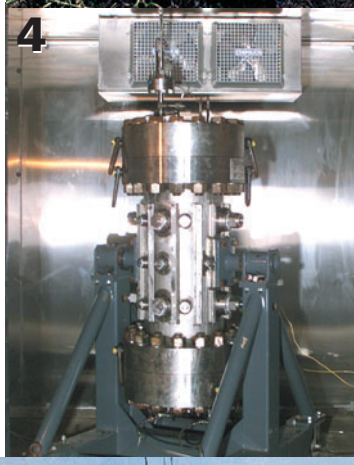


ENERGY SECURITY

Vol. 35 • No. 2 • 2002
www.ornl.gov/ORNLReview

OAK RIDGE NATIONAL LABORATORY
REVIEW
Vol. 35, No. 2, 2002

Features



COVER: *These twin electrical transmission towers at sunset near Golden, Colorado, symbolize the electrical power grid of the United States. The grid is part of the national energy infrastructure whose reliability must be assured because energy is the engine that drives our economy. ORNL researchers are working on this and many other projects related to the nation's energy security; the work is featured in this issue of the* Review. **Photograph by Warren Gretz for the Department of Energy's National Renewable Energy Laboratory.**

EDITORIAL: Energy Security—Providing Secure Energy Supplies and Protecting Our Energy Infrastructure

R. G. Gilliland

The terrorist attacks on the World Trade Center and the Pentagon using hijacked commercial airplanes on September 11, 2001, aroused concerns about the vulnerability of the U.S. critical infrastructure to future threats, whether natural, accidental, or deliberate. The Department of Energy responded to this threat by commissioning a senior-level committee to identify and evaluate the Department's capabilities to help power producers and energy developers assure the reliability of the nation's energy infrastructure.

What is energy security? Broadly defined, it includes three critical components of our energy systems: A sustainable energy supply, energy infrastructure assurance, and international efforts to develop and provide energy technologies to help developing nations improve their standard of living.

ORNL is committed to a science and technology research program that provides affordable and reliable supplies of energy from environmentally benign sources to meet our nation's growing needs, which include avoiding economic recessions and ensuring our national defense. We import 53% of the oil we use for propelling transportation vehicles (including U.S. fighter jets), heating and cooling buildings, and producing electrical power, and some of this oil comes from potentially unstable Middle Eastern countries (e.g., Iraq) that are supporters of or havens for terrorists. Therefore, a key component of energy security is reducing our reliance on imported oil and gas. We have many options. We could burn coal more cleanly, use alternative fuels (e.g., ethanol from biomass crops), extract methane from ocean hydrates and coal seams, increase use of other sources of energy (e.g., nuclear power), and develop new sources for the long term (e.g., hydrogen fuel cells and fusion energy).

In this issue of the *Review*, we describe ORNL's research and development (R&D) work in support of increasing the nation's energy supplies using a variety of sources. All of ORNL's energy-related research is consistent with the goals of the President's energy plan, as described in the *Report of the President's National Energy Policy Development Group*.

After September 11, protection of our energy infrastructure from natural, accidental, or deliberate threats that could disrupt energy services has moved to the forefront of our R&D agenda. Our energy infrastructure includes coal and uranium mines, oil and gas wells, electric transmission lines and oil and gas pipelines, petroleum refineries, and power plants, as well as information technologies that operate and control these systems. This issue of the *Review* discusses ORNL technologies that could identify vulnerabilities in the energy infrastructure and offer ways to prevent, detect, mitigate, or recover from natural, accidental, or deliberate threats or actions.

Components of the U.S. energy infrastructure include electrical transmission towers and nuclear power plant cooling towers.

Power grid technologies developed at ORNL can help provide energy security by assuring both energy supplies and the reliability and protection of the energy infrastructure. ORNL's work on transmission-grid-reliability issues has been nationally recognized.

ORNL researchers have analyzed how people respond to emergencies in many types of events related to disruptions of the energy infrastructure. This work may result in ORNL becoming a leading laboratory in emergency management.

Our nation's energy security will also be increased by improving global energy supplies and use to help lift developing countries from poverty and provide employment to young people (so they are less likely to become terrorists and so their countries are less likely to become havens for terrorists). ORNL's programs that are providing advice to developing countries on how to increase their energy supplies in the face of rising demand and a changing climate are also covered in this issue of the *Review*.

Visionary thinkers from ORNL's new Oak Ridge Center for Advanced Studies (ORCAS) will meet this summer in Washington, D.C., with researchers from the National Academy of Sciences (NAS) and key universities and industries to address energy infrastructure assurance. Results from this ORCAS symposium should help us understand energy assurance implications for future energy systems.

Clearly, ORNL has much to contribute in imaginative new concepts and technology developments that could help boost energy security in the United States.

R. G. Gilliland, Associate Laboratory Director for Energy and Engineering Sciences

OAK RIDGE NATIONAL LABORATORY
REVIEW

Editor and writer—Carolyn Krause
Assistant editor—Deborah Barnes
Editorial Board—Lee Riedinger (chair), Fred Bertrand, Robin Graham, Eli Greenbaum, Russ Knapp, Stan Milora, and Thomas Zacharia
Designer and illustrator—Jane Parrott
Photographer—Curtis Boles

The Oak Ridge National Laboratory *Review* is published two or three times a year and distributed to employees and others associated with or interested in ORNL.

Editorial office address:
Building 4500-North, M.S. 6266,
Oak Ridge, TN 37831-2008
Telephone: (865) 574-7183;
FAX: (865) 241-9787;
Electronic mail: krausech@ornl.gov
ORNL *Review* Web address:
www.ornl.gov/ORNLReview/

The *Review* is printed in the United States of America and is also available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161

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

ISSN 0048-1262

Oak Ridge National Laboratory is a multiprogram, multipurpose laboratory that conducts research in energy production and end-use technologies; biological and environmental science and technology; advanced materials synthesis, processing, and characterization; computing and computational sciences; and the physical sciences, including neutron-based science and technology.

Nuclear Energy: Assuring Future Energy Supplies

ORNL is doing its part to make nuclear energy for power production safer, less expensive, and more efficient.

Nuclear power produces one-fifth of our nation's electricity. However, no nuclear power plants have been ordered in the United States since 1978 because of concerns about waste storage, radiation, accidents, and costs. Yet, nuclear power is poised to make a comeback, partly because of concerns about a possible shortage of power plants (suggested by the inadequate power supply in California in early 2001) and the long-term effect of coal-fired power plants on world climate. (Replacing coal plants with nuclear plants will reduce greenhouse gas emissions.) Also, the nuclear industry surpasses the coal power industry in lowering electricity production costs and boosting actual output compared with potential output.

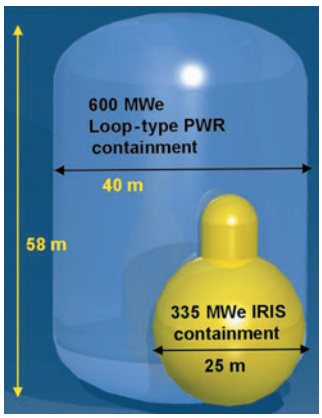
Whether the nuclear power industry will experience a resurgence will probably depend on three factors. First, our nation must find an acceptable way to isolate nuclear wastes from the environment, including the growing amount of radioactive spent fuel stored under water at commercial nuclear power plants. The U.S. government now sees this problem as an energy security issue. ORNL researchers have analyzed the environmental impacts of nuclear waste disposal at two proposed sites. Second, the public must be convinced that reactors are essentially safe. Third, nuclear power must become economically competitive with natural gas, the fuel of choice for most new power plants. If new reactors are designed to cost only $1000 for each kilowatt of generating capacity, then nuclear power may enjoy a revival in our nation.

Three American companies—Exelon, Entergy, and Dominion Resources—are seriously considering building new nuclear power plants, ranging from pebble-bed modular reactors (PBMRs) to gas-turbine modular-helium-cooled reactors (GT-MHRs)—both advanced reactor concepts on which ORNL will be working. Also, the licenses of some of the nation's 103 nuclear power plants are likely to be renewed, allowing them to operate for another 30 years.

ORNL, which pioneered the design of the core, fuel elements, and helium coolant systems for high-temperature gas-cooled reactors (HTGRs), is already playing a role in engineering nuclear energy's comeback. In February 2002 the Department of Energy designated ORNL and the Idaho National Energy and Environmental Laboratory (INEEL) as the lead laboratories for gas-cooled-reactor technology.

SECURE NUCLEAR PLANT DESIGN

Recognizing the importance of nuclear power as part of a diverse energy portfolio that will allow us to reduce dependence on imported fuels, DOE's Office of Nuclear Energy is leading a road-mapping activity involving 150 persons from industry, universities, and national labs. The goal is to draw up and select the best designs for next-generation nuclear power plants that will be built over the next 30 years. DOE has declared that these designs must provide improvements in economic competitiveness, safety, and proliferation resistance, while showing a reduction in radioactive waste production. In February 2002, DOE announced its "Nuclear Power 2010" initiative—a new public-private partnership aimed at building and operating new nuclear power plants in the United States before the end of this decade.



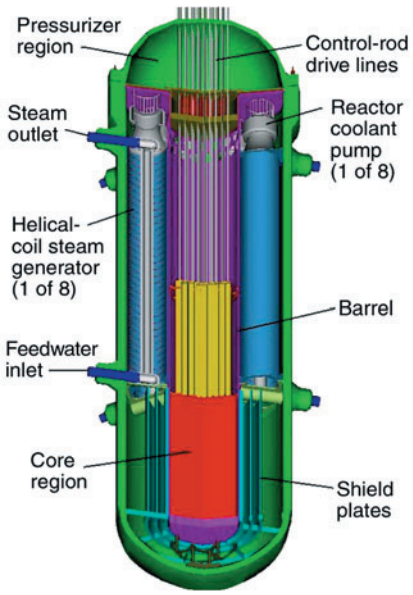
The diameter of the IRIS containment is 25 meters, compared with 40 meters for today's pressurized-water-reactor containment. An IRIS power plant could be expanded through the addition of modules.

In the quest to design a near-term advanced reactor that is cheaper to build and quicker to license, an international consortium of researchers from universities, industrial firms, utilities, and laboratories in nine nations is developing the International Reactor Innovative and Secure (IRIS) nuclear power plant. ORNL is the only DOE national laboratory participating on this team led by Westinghouse Electric Company.

"IRIS is a pressurized-water reactor with safety features that have eliminated five out of six most extreme possible nuclear accidents," says Gordon Michaels, manager of ORNL's Nuclear Technology Program. "Our researchers are developing computational methods and assessing options for the safe and efficient control of the reactor core and for plant surveillance and diagnostics. They are also preparing a probabilistic risk assessment tool to determine the safety of the conceptual design."

According to Dan Ingersoll, leader of the Radiation Transport and Physics Group in ORNL's Nuclear Science and Technology Division (NSTD), the IRIS concept meets DOE's strategic goals in several ways. "It will be more economical because it is more compact," he says. "Whereas today's large nuclear power plants generate 1500 megawatts of electricity, a single IRIS module would generate 100 to 300 megawatts. IRIS is small and simple enough that it could get the reactor operation cost down to $1000 per kilowatt and may be built in developing countries.

"IRIS is an integral reactor, which means that the steam generators will be inside the reactor vessel rather than outside, as is the case with



This schematic of the innovative and secure reactor, or IRIS, design shows the components of the reactor and steam generator in a single vessel. ORNL plans to seek funding to build a first-of-a-kind, power-producing IRIS reactor in East Tennessee in 10 to 12 years.

conventional light-water reactors. This design avoids the risk of a large pipe break because the large pipes that typically connect the vessel and the steam generators are eliminated entirely. The small pipelines that carry steam from the reactor vessel to the turbine are inside a pressurized containment.

"If a small pipe were to break and release steam and water, the water pressure in the reactor vessel would drop and the air pressure in the containment would rise until the pressures were equal inside and outside the vessel. As a result, the reactor core stays covered with enough water to keep it cool, despite the earlier water loss. Also, the vessel is designed so that natural circulation of water occurs even if the power to the water pumps is lost, making this reactor even safer."

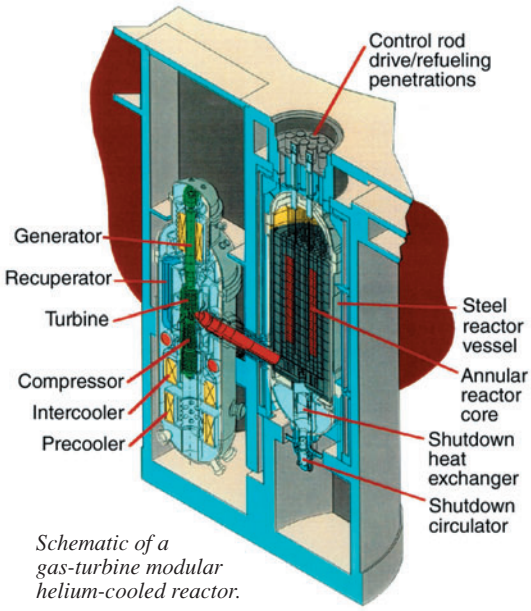
IRIS will be more resistant to proliferation because potential terrorists would have much less access to the fuel. Today's reactors are opened up every 18 months to remove and replace fuel. This shuffling of fuel makes it more susceptible to theft. In an IRIS reactor the fuel residence time is 5 to 8 years. Then the fuel will be pulled out and sent to a repository or reprocessing plant. Because IRIS is designed for high burnup of fuel, the spent fuel will contain less usable fuel and thus be less attractive for diversion.

CHEAPER NUCLEAR PLANT CONCEPT

One way to reduce nuclear power plant costs dramatically is to build a reactor that more efficiently converts its heat into electricity. The route to efficient energy conversion is to operate a new reactor at higher temperature than current reactors. Two industrial teams, backing two different reactor concepts, propose to do just that. An international consortium involving British Nuclear Fuels and Eskom plans to build the world's first pebble-bed modular reactor in Koeberg, South Africa, using technology developed in the 1950s and 1960s by ORNL and German teams. And a U.S. industrial team led by Entergy, a Southeastern utility that operates 10 commercial power reactors, is evaluating the deployment of a gas-turbine modular-helium-cooled reactor.

The fuel elements for the helium-cooled PBMR would be mobile tennis-ball-sized, graphite-coated spheres—or "pebbles"—that slowly move though the reactor. The GT-MHR is powered by stationary fuel elements in the shape of prismatic blocks. Both fuel forms are built up from tens of thousands of coated TRISO particles—particles that employ a dense layer of silicon carbide to trap radioactive fission products. Both reactors would operate at gas temperatures of 900°C with an efficiency in excess of 43% (compared with 31% for today's pressurized-water reactors); in other words, more than 43% of the energy in the fuel core would be converted to electricity.

"ORNL is the lead laboratory for providing technical support to the Nuclear Regulatory Commission in licensing reviews of the pebble-bed reactor," Michaels says. ORNL and INEEL jointly manage a new DOE-NRC program for irradiating German pebble fuel in the Advanced Test Reactor at INEEL. The post-irradiation test program, headed by Gary Bell of ORNL's Fusion Energy Division, will probably involve examination and accident-simulation testing of the fuel.



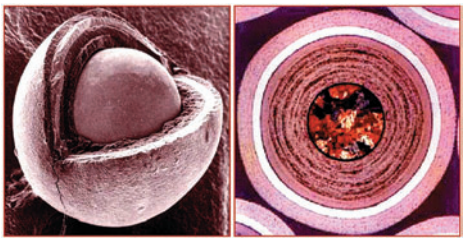
Schematic of a gas-turbine modular helium-cooled reactor.

"The Entergy-led consortium has also expressed interest in ORNL's research and laboratory capabilities," Michaels reports. "We are being told that our ability to re-establish the technology for fabrication of gas-reactor fuel may be essential to deployment of a new U.S. GT-MHR."

NUCLEAR FUEL FABRICATION

In a new fuel fabrication research and development (R&D) program, ORNL is collaborating with General Atomics Company to produce TRISO fuel, a type of fuel similar to what ORNL researchers developed for HTGRs and what is now proposed for GT-MHRs and PBMRs. The work, led by David Williams of NSTD, involves finding the best ways to produce uranium-oxide and plutonium-oxide kernels, using an internal gelation process similar to the sol-gel process developed years ago at ORNL, and to coat them to prevent the escape of the particle fuel's fission products. The coatings deposited on the kernels consist of pyrolytic carbon, silicon carbide, and a porous carbon buffer. The resulting product resembles black beads the size of salt grains.

The goal is to create fuel beads that allow reactors to operate at higher temperatures so that they can more efficiently convert their heat to electricity. The coated fuel should also be meltdown proof—that is, it should act as a miniature containment system that would prevent the release of fission products to the environment during a highly unlikely loss-of-coolant accident.



These micrographs show the structure of the coatings of TRISO-coated particles incorporated into pebbles for the proposed pebble-bed modular reactor. ORNL researchers have developed coatings for nuclear-fuel particles that better contain the radioactive fission products within the particles.

TRISO fuel would also be used in the Advanced High Temperature Reactor, a long-term concept being developed at ORNL under the leadership of NSTD's Charles Forsberg. Using molten salts as a coolant, this highly efficient, power-producing reactor would deliver heat at a high enough temperature to produce hydrogen from water more cheaply than electrolysis. Hydrogen will be used for automotive and building fuel cells.

ORNL researchers recently helped design and manage a nonproliferation program to test "mixed-oxide" (MOX) reactor fuel fabricated from depleted uranium and plutonium extracted from both U.S. and Russian nuclear weapons. "Now, we are helping the Russians design and build a MOX fuel fabrication plant to provide fuel for Russian fast reactors," Michaels says. "We are also assisting DOE and industry in preparing MOX fuel for use in four U.S. commercial reactors."

ADVANCED MATERIALS FOR REACTORS

"In a reactor, neutrons and heat must be controlled," Michaels explains. "Materials used to construct reactors must survive neutron irradiation and heat and still have the right properties to allow reactors to be run at higher temperatures. You must get heat out of the reactor and take it to where you want it to produce power. Toward that end, we are developing advanced materials for future reactors."

Modern ferritic and other steels have been developed for use in advanced reactors operating at temperatures of up to about 600°C. If the operating temperature were raised 200°C to increase reactor thermal efficiency, these materials would become deformed and eventually rupture. ORNL and Japanese researchers recently discovered that a high density of oxygen-rich clusters uniformly dispersed in steel can greatly reduce its deformation up to 800°C, making this modified alloy suitable for higher-temperature applications. ORNL and French researchers are conducting further research in this area in projects funded by ORNL's Laboratory Directed R&D (LDRD) program and DOE's International Nuclear Energy Research Initiative program. According to ORNL's David Hoelzer, who leads the LDRD project, modified steels could revolutionize the future development of gas-cooled reactors.

Michaels says the United States needs to both attract more American students into nuclear engineering and improve the country's nuclear infrastructure by building advanced reactors, reprocessing plants, and uranium enrichment facilities. "Otherwise," he says, "we risk becoming dependent on foreign nations for nuclear technology. It would not help our nation's energy security if we become a nuclear know-nothing." Fortunately, DOE has a program that aims to revive nuclear engineering as a hot field.

Methane Extraction and Carbon Sequestration

One way to extract methane from underground is to inject carbon dioxide into coal beds, using such equipment as shown here.

ORNL researchers are studying the formation, structure, properties, and dissociation of gas hydrates. The ORNL research will aid the search for ways to extract methane fuel from ocean and permafrost sediments and to isolate from the environment carbon dioxide, a greenhouse gas that many believe could alter the climate. This work could help ensure that our nation has a secure energy supply.

In November 2000, somewhere off Canada's Vancouver Island, the commercial fishing vessel *Ocean Selector* brought to the ocean's surface an unusual "catch." The trawl net that had been dragged near the seafloor to capture fish recovered more than 1000 kilograms of methane hydrates from a depth of 800 meters.

Methane hydrates are ice-like solids in which water molecules form cages around molecules of methane, the chief component of natural gas. Methane hydrates are ubiquitous and found in ocean sediments—especially in continental margins—and the Arctic permafrost.

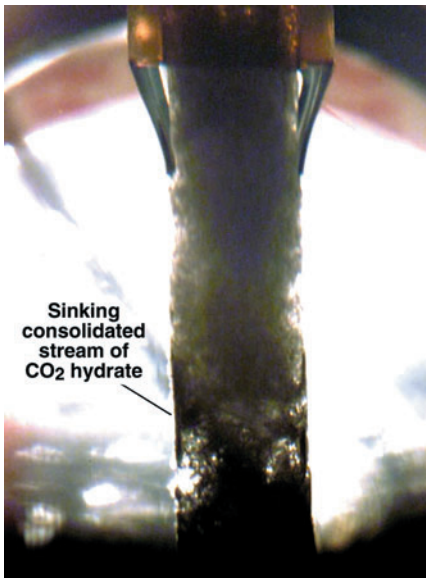
The accidental mining of methane hydrates by a fishing vessel caught the attention of Rod Judkins, director of ORNL's Fossil Energy Program. "This incident may suggest that some methane hydrates can be more easily recovered than we thought," he says. "Also, although these materials could have been broken off of outcroppings, it could indicate that hydrates are not necessarily covered with much sediment, which would imply that their formation does not require as much time as we have previously believed."

Judkins sees methane hydrates as the key to U.S. energy independence, which would give the nation energy security. "We must increase our primary energy sources to make us less dependent on foreign supplies of oil," he says. "One way to do this is to tap the abundant natural-gas supplies in methane hydrates, which offer us more energy than we have in our 1500-year-supply of coal. Estimates by the U.S. Geological Survey and others place reserves of methane in methane hydrates as high as 46×10^{15} m^3. This is an incredibly large potential energy resource, provided it can be safely and economically produced. Natural gas is a versatile fuel that can be used for generating electricity, heating homes, and fueling cars and trucks."

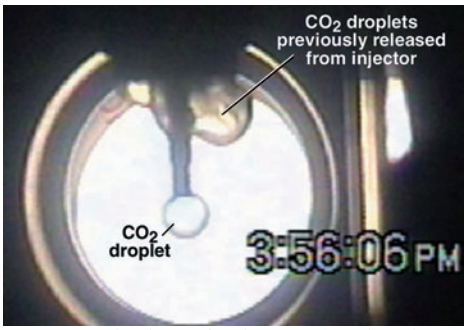
GAS HYDRATE RESEARCH AT ORNL

ORNL researchers are supporting DOE's study of four major issues regarding the ultimate use of methane hydrates for fuel. One issue is resource evaluation—what are both the extent and the nature of methane hydrate deposits in the ocean and Arctic permafrost? Another is seafloor stability and safety: Will the harvesting of methane hydrates disrupt the stability of methane hydrate deposits and become a major safety hazard? For example, should an accidental release of methane gas from a methane hydrate deposit occur during drilling operations, the loss in buoyancy would have the potential to cause losses of expensive oil drilling platforms nearby. A third issue is the potential effect of methane hydrates on climate, especially if methane (a greenhouse gas) were to escape accidentally to the atmosphere as a result of a botched harvesting process. Finally, there is the question of production: How can methane be economically and safely extracted and captured from hydrates?

ORNL and the Idaho National Energy and Environmental Laboratory (INEEL) have commitments for funding from DOE's Office of Fossil Energy to participate jointly in a ship cruise to recover and analyze methane hydrates as part of the U.S. Ocean Drilling Program (see photograph on back cover). An INEEL scientist will take the ship cruise from July through September 2002.



ORNL researchers using the SPS are testing a novel injection technique that makes a paste-like composite of CO_2 hydrate, liquid CO_2, and water that is denser than seawater and, therefore, sinks to the vessel floor. Injecting CO_2 in this paste-like form may improve the efficiency of direct CO_2 injection and reduce the environmental impacts of ocean carbon sequestration.



Current technologies for direct carbon dioxide (CO_2) injections at intermediate ocean depths produce buoyant CO_2 droplets (like the white ball shown in the center at the SPS) that can rise, gasify, and enter the atmosphere—an unwanted result.

"Some methane hydrate samples will be brought back to ORNL for study and for comparisons with methane hydrates produced in our seafloor process simulator," Judkins says.

Libby West of ORNL's Environmental Sciences Division (ESD) is in charge of the day-to-day operations at the highly instrumented pressure vessel called the seafloor process simulator (SPS). She and Tommy Phelps, also of ESD, carry out research there. (See "Methane Hydrates: A Carbon Management Challenge," *ORNL Review*, Vol. 33, No. 2, 2000, pp. 14-15). Experiments have shown that methane hydrates produced in the SPS will dissociate and release methane when the temperature of the water is raised above the temperature at which methane hydrates form when the pressure is right. "But," she said, "depressurizing a methane hydrate field rather than raising its temperature may be a more economical way to harvest methane. We hope to do experiments later in the SPS to determine which harvesting schemes work best."

Some scientists believe that many methane hydrate fields are covered by hundreds of meters of sediment consisting of sand, clay, and other materials. "In our SPS experiments we made methane hydrates in suspensions of geological particles," West says. "We found that our surrogate sediment—silica, which represents sand, and bentonite, which represents clay—has no chemical effect on the dissociation of methane hydrates but may affect their formation."

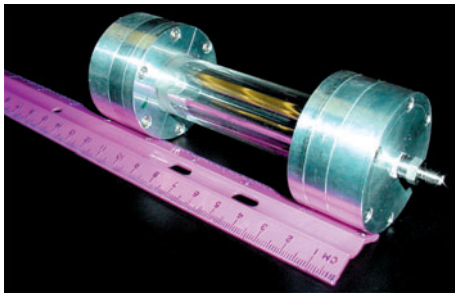
West, together with Costas Tsouris of ORNL's Nuclear Science and Technology Divi-

sion and ESD's Sangyong Lee and David Riestenberg, have conducted experiments in the SPS that demonstrate a possible approach for ocean sequestration of carbon dioxide (CO_2) captured, say, from the stack emissions of coal-fired power plants. Carbon capture and sequestration are considered essential to ensuring the continued use of our abundant supply of fossil fuels for power production without increasing the threat of climate change.

"In a research effort started with a seed money project and now continuing in a program funded by DOE's Office of Biological and Environmental Research, we found that intensely mixing water into liquid CO_2 within a specially designed injector produces a paste-like, cohesive mass that contains CO_2 hydrate," West says. "The presence of CO_2 hydrate, which is more dense than the seawater, caused this cohesive mass to be negatively buoyant, so it sank to the floor of the SPS vessel."

Injecting liquid CO_2 in this paste-like form may improve the efficiency and reduce the environmental impacts of ocean carbon sequestration by direct CO_2 injection. ESD's Liyuan Liang is studying the dissolution of this paste-like material and its subsequent geochemical interactions with the marine environment.

Claudia Rawn of the Metals and Ceramics Division, Bryan Chakoumakos of the Solid State Division, and Adam Rondinone of the Chemical Sciences Division have performed neutron scattering studies to characterize synthetic gas hydrates. Their efforts have been focused on determining how the atomic structure and physical behavior of various hydrates change as a function of temperature. While ORNL's High Flux Isotope Reactor (HFIR) is being upgraded, their experiments are being performed using Japan Atomic Energy Research Institute and National Institute of Standards and Technology research reactors. Once the HFIR upgrades have been completed, the ORNL researchers will use a low-temperature pressure cell, which was constructed at HFIR using Laboratory Directed Research and Development Program funds. It will allow gas hydrates to be synthesized and studied in the neutron beam.



ORNL neutron scientists are building a low-temperature pressure cell at the High Flux Isotope Reactor that will allow gas hydrates to be synthesized and studied in the reactor's neutron beam. Shown here is part of the pressure cell that will be in the neutron beam.

"Neutron scattering is well suited for the study of hydrates because it is sensitive to the hydrogen atoms that are a major part of these materials," Chakoumakos says. "The neutron's large penetration depth allows the use of complex sample environments, which are needed to simulate the conditions at which hydrates are stable."

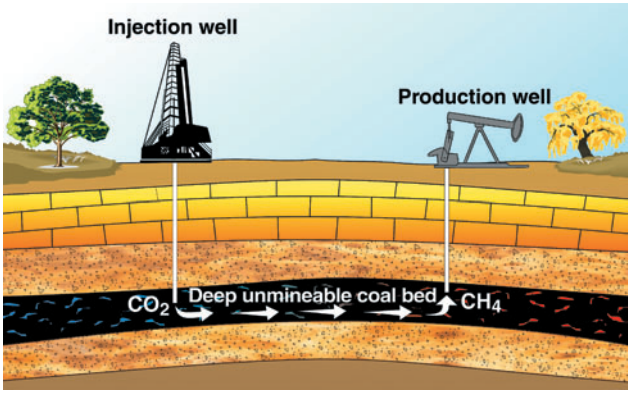
DISPLACING METHANE WITH CO_2

Injecting CO_2 into methane-rich coal seams hundreds or thousands of feet underground could have a double benefit: It could both boost energy production and, at the same time, reduce greenhouse gas emissions. Many unmineable coal seams have associated methane that has been adsorbed on the coal. As recent field tests by oil and gas companies have shown in New Mexico and Canada, CO_2 pumped down an injection well into a deep, unmineable coal seam may be adsorbed on the coal bed, displacing the methane and forcing it to rise up through a production well. The use of CO_2-enhanced coal-bed-methane (CBM) recovery for replacing one stored gas with another would allow long-term sequestration of CO_2, slowing the atmospheric buildup of this "greenhouse gas" while enhancing production of methane, the main ingredient of natural gas. Through reforming processes, this gas could be a source of hydrogen for future fuel-cell-powered cars, which would reduce the need for imported oil for U.S. transportation vehicles.

Recently, Jim Blencoe, a geochemist in ORNL's Chemical Sciences Division, had a revelation when he read that the Alberta Research Council is leading a consortium of Canadian and international companies in field tests of CO_2-enhanced CBM recovery. Because of the basic research he has performed on the mixing of gases such as CO_2 and methane at the elevated temperatures and pressures that exist below the earth's surface, Blencoe believes his findings and analyses could contribute substantially to the development of this technology.

"In my opinion, this is the best geological method proposed for sequestering carbon dioxide," he says. "The value added by CO_2-enhanced CBM recovery is its ability to generate methane that is not recoverable by traditional methods of production."

But, as it is with most technologies, implementation must be done right to ensure that the technology is safe and economical. That's where basic research could provide needed guidance.



Carbon dioxide is injected into a coal seam, causing methane to desorb and mix temporarily with the CO_2 during flow toward a production well. The CO_2 is quickly adsorbed and remains behind, tightly bound to coal surfaces. The methane is recovered.

"If you inject carbon dioxide into coal layers where pressure and temperature are in a certain range, CO_2 will strongly displace methane," Blencoe says. "If CO_2 is injected too rapidly, or the flow of gas toward a production well is impeded, gas pressure could rise enough to blow out seals around the injection well, damaging equipment and posing a serious safety hazard."

Blencoe believes his basic research, funded by DOE's Office of Basic Energy Sciences, is relevant to the DOE mission of developing appropriate carbon management strategies. He has recently received funding from DOE's Office of Fossil Energy to determine experimentally the volumetric properties and viscosities of carbon dioxide–methane mixtures at temperatures and pressures achieved in coal beds buried 100 to 3300 meters (approximately 300 to 10,000 feet) below the earth's surface.

"In 1996," Blencoe says, "we measured the volumetric properties of carbon dioxide–methane mixtures at temperatures and pressures close to those encountered in field tests of CO_2-enhanced CBM recovery. It turned out to be serendipity, because we did not foresee the relevance of the research to a practical application related to energy production and possible environmental protection. A particularly important finding was that, at 50°C and 100 atmospheres of gas pressure, CO_2 repels methane, causing extensive and rapid expansion of the gas mixture.

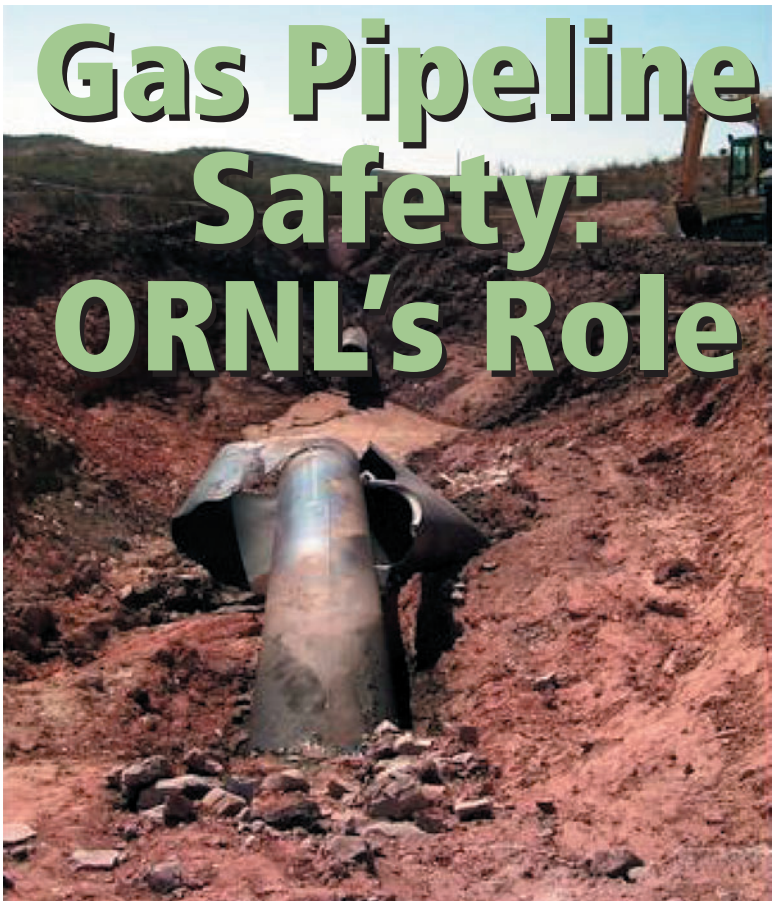
"We will conduct laboratory experiments and develop mathematical expressions to accurately predict this behavior over a wide range of temperature, pressure, and gas composition. In addition to allowing gas pressure to be calculated reliably, this research would lead to more accurate predictions of the rates and levels of CO_2 adherence (adsorption) on coal surfaces, which promotes release (desorption) of methane from those surfaces."

Blencoe also investigates the properties of fluids that contain carbon, oxygen, hydrogen, and nitrogen. At the elevated temperatures and pressures in the earth's crust, these elements form the stable gas species CO_2, methane (CH_4), water (H_2O), and nitrogen (N_2).

"We use special equipment to determine how gas species behave macroscopically and interact with each other," he says. "The properties of pure and mixed CO_2-CH_4-N_2-H_2O gases are represented by equations of state, which describe the behavior of the gases over various ranges of temperature, pressure, and gas composition. I do experiments to determine the thermodynamic mixing properties of gas species and use the results, along with suitable data from the literature, to develop more accurate and comprehensive equations of state."

Thanks to the application of the results of basic research, ORNL scientists are discovering better ways to produce methane, an energy-rich gas, and sequester CO_2, a major greenhouse gas.

Gas Pipeline Safety: ORNL's Role



The natural gas pipeline failure in August 2000, near Carlsbad, New Mexico, resulted in an explosion that killed 12 persons and created a crater 86 feet long (shown at left). One of the missions of personnel in ORNL's Quality Services Division is to monitor pipelines after an accident and help determine the cause.

Natural gas from domestic sources is an important source of energy that reduces our reliance on imported oil and gas. To help Americans get the most out of this resource, ORNL is doing its part to ensure pipeline safety.

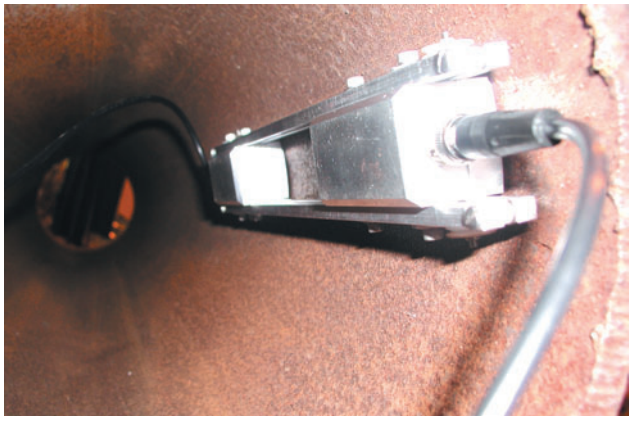
Gas leaking from a natural gas pipeline is an undesirable event. It represents lost energy, lost income for the natural gas industry, and a potential safety hazard. If leaking gas comes in contact with a lit match or a spark from a vehicle, an explosion or fire could result.

Gas pipelines leak or fail largely because of damage from excavation operations; other causes are corrosion, construction defects, material defects, and outside forces. Such forces include earthquakes, washouts, landslides, frost, lightning, ice, snow, and errors or intentional damage by humans. In August 2000, a large natural gas pipeline failed near Carlsbad, New Mexico, as a result of corrosion. Twelve people died in the explosion, which created a 25-meter- (86-foot-) long crater, shown at right.

The natural gas industry keeps a database on pipelines. Each pipe in the database is tracked, and when a pipe is found to have flaws of a certain number and size, a decision is made to replace it. Replacing these pipes is costly in terms of down time, so the industry is looking for better methods by which to obtain more reliable, more accurate data on flaw numbers and size, including the probability that cracks are about to form.

Currently, the pipe characterization technique used most by the natural gas industry is the magnetic flux leakage method. This method induces a magnetic field on the walls of the pipe. When a change occurs in the pipe wall geometry as a result of wall thinning, cracks, or pitting, magnetic flux leaks through these areas, and a sensor detects the leakage. The location and amount of leakage indicate the site and size of the flaw.

Venugopal K. Varma, a mechanical engineer in ORNL's Nuclear Science and Technology Division, hopes to integrate novel hardware and software components to improve a flaw detection method that uses electromagnetic acoustic transducer (EMAT) technology. An EMAT device, designed by Pennsylvania State University, would have no contact with the pipeline. It would electromagnetically induce an ultrasonic horizontal shear wave and measure the amount of sound energy reflected from and the amount transmitted through the pipe walls. An algorithm developed by ORNL's Steve Kercel would then recognize differences in patterns of reflected and transmitted sound waves and correlate those differences with changes in the pipe material caused by corrosion, circumferential and axial flaws, and pittings, for example. In this way, the location and size of each flaw (e.g., its length, width, and depth) could be determined.



Penn State and ORNL researchers have developed and combined an improved electromagnetic acoustic transducer and algorithm for detecting and characterizing flaws in gas pipelines.

This approach also uses wavelet analysis not only to detect flaws but also to reduce the amount of data being stored. This work is being conducted by Kercel and Raymond Tucker, both of ORNL's Engineering Science and Technology Division. Reduction of the data stored during flaw detection is necessary because the equipment for flaw detection must make continuous runs for hundreds of miles before the growing amount of data can be retrieved and analyzed. Although the refinement of this technology is preliminary, Varma believes it would surpass magnetic flux leakage in predicting the formation of flaws along and around pipeline walls.

"I believe our technology will be able to detect small axial and circumferential cracks, metal loss, and corrosion all at once, with one single pass," he says. "If we can prove it works, it should be of interest to the natural gas industry because it would provide more accurate information for its database." This research is being funded through DOE's National Energy Technology Laboratory.

Thomas Thundat of ORNL's Life Sciences Division is developing a method to detect tiny leaks of gas from pipelines using microcantilever technology. A cantilever is analogous to a microscopic diving board that vibrates at a characteristic rate. If exposed to a pipeline that is not leaking gas, it will vibrate at a rate related to air currents. If it is placed in the vicinity of a gas leak, the frequency of its vibration will change. The shift in frequency may indicate the rush of gas through a pipe crack. The microcantilever sensor will be mounted on the EMAT, enabling the detection of both leaks and flaws in the same pass.

Personnel in ORNL's Quality Services Division are monitoring natural gas pipeline construction projects for the U.S. Department of Transportation's Office of Pipeline Safety. According to Barry Oland of ORNL's Engineering Science and Technology Division, ORNL is providing inspectors and technical personnel under subcontract to oversee the installation of gas pipelines running from state to state, to ensure that the installations comply with federal pipeline safety regulations.

Energy from Biomass: Nature's Power

ORNL researchers are examining ways to make biomass energy cost competitive with fossil fuels and production of biomass for energy a profitable agricultural activity.

One way to reduce U.S. reliance on imported oil and environmentally unfriendly coal is to increase our use of renewable energy sources, which tap naturally occurring flows of energy to produce electricity, fuel, and heat. Only about 3% of our nation's energy is produced from biomass, as the result of burning wood and wood residues to produce electricity or converting grains and agricultural wastes to liquid fuels such as ethanol. Thus, the U.S. government is trying to make biomass more attractive economically as a replacement for oil and coal in the production of electricity and liquid fuels.

The President's National Energy Policy Development Group (NEPDG) has recommended, for example, that the President direct the Secretary of the Treasury to work with Congress on legislation to extend and expand tax credits for electricity produced using renewable technology, such as wind and biomass. The NEPDG report notes that, "The President's budget request extends the present 1.7 cents per kilowatt hour tax credit for electricity produced from wind and biomass; expands eligible biomass sources to include forest-related sources, agricultural sources, and certain urban sources; and allows a credit for electricity produced from biomass co-fired with coal."

Making biomass energy cost competitive with that of fossil fuels and making production of biomass for energy a profitable agricultural activity are goals of the Department of Energy's Bioenergy Feedstock Development Program, managed at ORNL. To track progress in these and other areas, the program supports economic analyses.

"Some 120,000 acres of U.S. land has been planted with hybrid poplar, eucalyptus, sweet gum, and sycamore trees as a result of the DOE program," says ORNL's Lynn Wright, a co-manager of the program. "Over a period of 20 years, DOE invested $48 million in the program, in which researchers learned how to raise fast-growing trees as crops. In one year fiber industry sales of paper products and wood for building construction and furniture produced from these trees equaled $48 million. The return on the government's investment has been good. Jobs have been created in the timber and paper industry, even though restrictions were placed on harvesting trees in national forests."

In the DOE program, researchers bred and cloned fast-growing varieties of hardwood trees. They developed new ways to grow them through the judicious cultivation of land and the use of weed-killing herbicides, fertilizer, and water to get a higher yield in less time. They domesticated this crop, controlled its characteristics, and found ways to harvest it more efficiently.

The key to increasing the production of biomass for energy, however, is the involvement of farmers. They could, for example, make money on bioenergy crops if there were an expanding market for ethanol to relieve the effects of a shortage of imported oil resulting from a war.

The U.S. government is looking at another possible incentive for farmers to grow more bioenergy crops. So, in 2000 the U.S. Department of Agriculture established a Bioenergy Pilot Program and proposed that owners of Conservation Reserved Program (CRP) land work with project managers to grow and harvest bioenergy crops on the land. To make this venture economical and worthy of government financial support, the CRP landowners must plant vegetation that controls erosion and promotes wildlife.

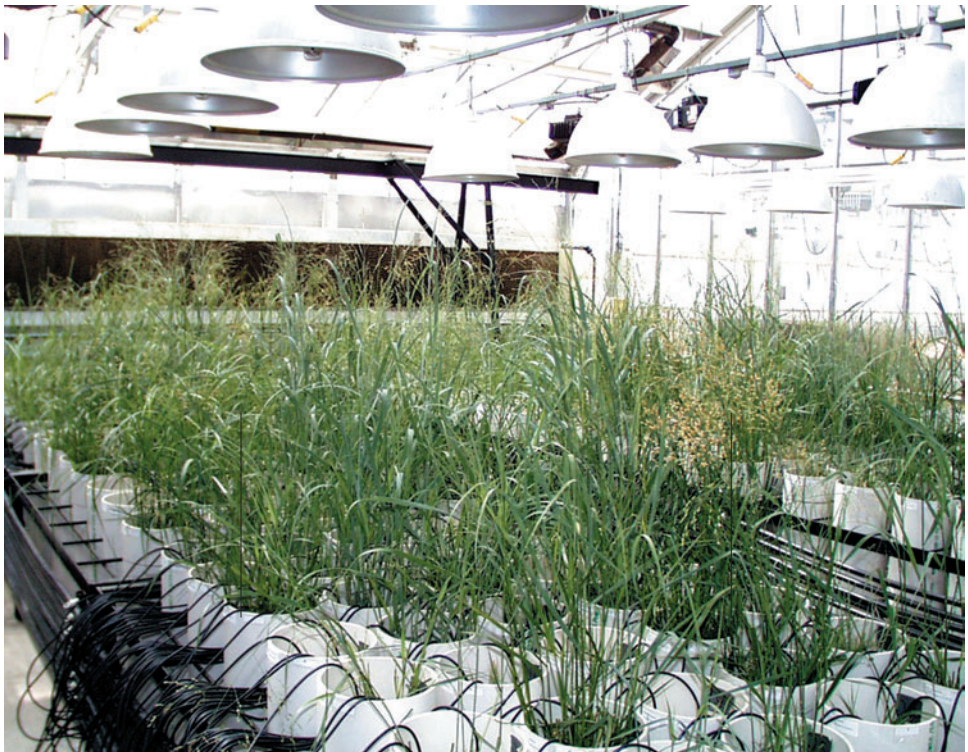
"One proposal is to loosen restrictions to allow harvesting of bioenergy crops such as switchgrass and hybrid poplar trees," says ORNL's Janet Cushman, co-manager of the Bioenergy Feedstock Development Program. "Our studies show that both types of plants control erosion and attract birds. Birds eat switchgrass seeds. Some species of birds that thrive in shrubs like hybrid poplar trees when they are young. When the trees grow taller, other bird species that prefer a forest-like habitat are attracted to the tree plantation."

Ethanol today is produced from corn, grain, potato wastes, and other agricultural wastes that contain sugars or starches. DOE supports projects (including those led by ORNL's Brian Davison) to demonstrate the production of ethanol by using enzymes to degrade cellulose to individual sugars for conversion by bacteria to ethanol.

At least one technology-development company and one waste-management company are interested in demonstrating the cellulose-to-sugar-to-ethanol technology by building commercial biomass-to-ethanol facilities. Other companies are considering building advanced systems to convert biomass into electricity (e.g., a wood waste gasifier and a deep-bed boiler to burn whole hybrid poplar trees). But the final decision on all these projects depends on whether the financial support is there.

For biomass energy proponents, it would help if money did grow on trees.

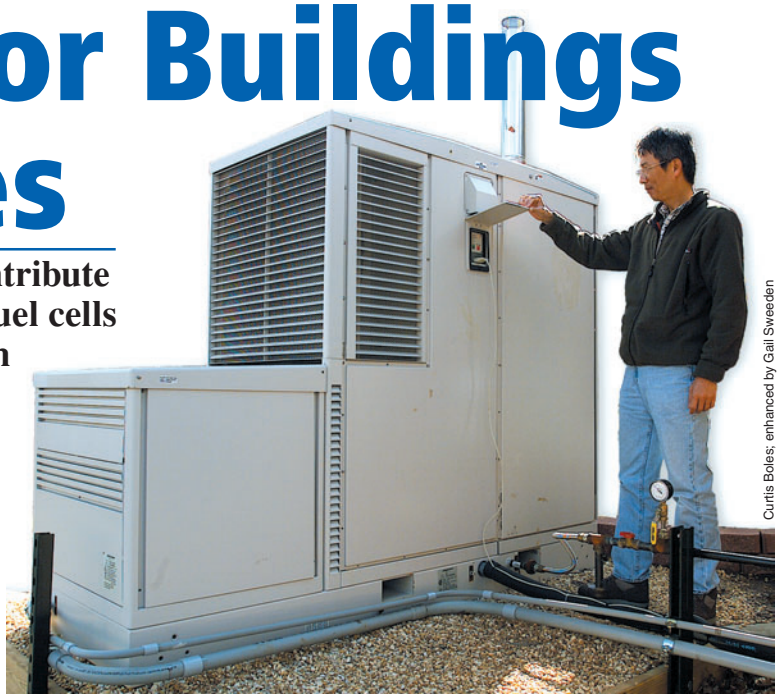
This greenhouse study characterizes the interactions between nitrogen and calcium in the production of switchgrass, which could be converted to ethanol fuel.



Courtesy of USDA-ARS Northern Great Plains Research Laboratory, Mandan, ND

Fuel Cells for Buildings and Vehicles

ORNL's broad expertise is expected to contribute to the development of power-producing fuel cells that are smaller, lighter, and cheaper than today's commercial fuel cells. Improved fuel cells could provide power to clusters of buildings and cars.



Curtis Boles; enhanced by Gail Sweeden

ORNL researcher Fang Chen (shown here) and others are conducting studies on the first packaged proton exchange membrane (PEM) fuel-cell unit for homes that is operating in the Southeast. This PEM fuel cell at a University of Tennessee laboratory off Pellissippi Parkway produces 2.5 to 5 kW of electricity. It will feed directly into the grid. Eventually, a waste heat recovery system will be added to improve the overall system efficiency, providing a source of energy for water heating or space conditioning.

People who envision replacing our fossil-fuel economy with a hydrogen economy see power-producing fuel cells in every home, car, and factory. Because hydrogen can be obtained from almost any material containing hydrogen—such as ammonia, natural gas, domestically produced biofuels, or even water, albeit at a high cost—a society powered by fuel cells will be less dependent on foreign supplies of oil for gasoline. Such a hydrogen economy would be directly benefited by a major indigenous primary energy source, coal, because coal would likely be one of the principal sources of hydrogen through gasification technologies that produce synthesis gas, a mixture of primarily carbon monoxide and hydrogen.

A hydrogen economy will be kinder and gentler to humans because it will greatly facilitate the reduction of emissions of lung-damaging sulfur and nitrogen oxides. If the main source of hydrogen for most cars in the future is natural gas or coal, emissions of potentially climate-altering greenhouse gases such as carbon dioxide will also be lower.

H-Power and other companies are now producing commercial fuel cells that provide electricity to buildings and industrial plants. These fuel cells, which in their housings resemble outdoor heat-pump systems or perhaps tall dumpsters, are becoming less expensive. However, they are not yet cost-competitive with other distributed generation sources such as microturbines.

President Bush has called for the development of fuel cells for use in cars as part of the national FreedomCAR Program. (The term FreedomCAR, in which CAR stands for Cooperative Automotive Research, was coined by ORNL's Kathy Vaughan. The term suggests that this concept will "free" us from being dependent on foreign energy sources.) Right now fuel cells are too large, too heavy, and too costly to be used in cars, so research programs are being funded to develop an affordable fuel-cell car, which may be available in 10 to 20 years.

ORNL fuel-cell research includes experiments with advanced materials and designs that could lead to the manufacture of fuel cells that are small enough, light enough, and cheap enough for use in powering buildings and cars. For many years, ORNL provided only a supporting role to the Department of Energy's program for developing fuel cells, but its activity level has picked up with increased DOE funding since 2000. ORNL has a unique combination of expertise in many different areas related to fuel-cell development—materials development and characterization, reliability of structures, power electronics, catalysts and electrochemistry, thermal management, and computer modeling of systems.

HOW A FUEL CELL WORKS

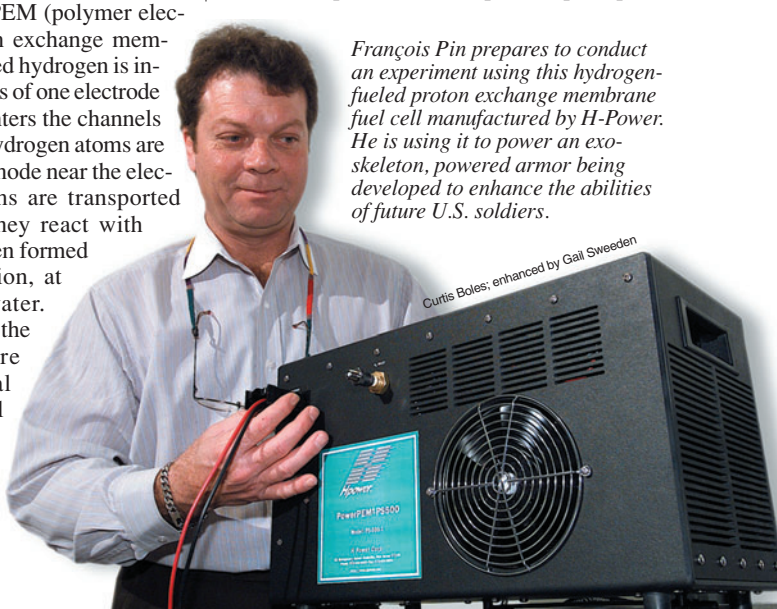
In a fuel cell, water is formed by combining hydrogen (e.g., from natural gas) and oxygen from the air while an electric current is produced in an external circuit. In a PEM (polymer electrolyte membrane or proton exchange membrane) fuel cell, as pressurized hydrogen is introduced through the channels of one electrode plate (the anode), oxygen enters the channels of the other (the cathode). Hydrogen atoms are converted to protons at the anode near the electrolyte surface. The protons are transported through the electrolyte. They react with oxygen ions, which have been formed by electrochemical reduction, at the cathode to produce water. The electrons resulting from the oxidation of hydrogen are conducted in the external circuitry. The fuel cell will generate electricity as long as hydrogen is fed to the anode. To increase the power output, fuel-cell units each consisting of an anode, electrolyte, and cathode, are assembled in an electrical series arrangement to form so-called fuel-cell stacks.

ORNL researchers are now working on several kinds of fuel cells, which are named after their electrolytes. They include PEM, solid-oxide, and alkaline fuel cells (see photographs).

PEM FUEL CELLS

PEM fuel cells use a membrane made by DuPont called Nafion, which could be considered similar to kitchen plastic wrap. This material is a proton conductor that allows protons to pass through it but blocks the flow of electrons. PEM fuel cells are well developed and are strong candidates for cars because engineers have improved their power density so that they could each be as small as a suitcase. (See photographs on this page of PEM fuel cells used in ORNL research.)

Ted Besmann and his colleagues in ORNL's Metals and Ceramics (M&C) Division have developed carbon-composite bipolar plates,



Curtis Boles; enhanced by Gail Sweeden

François Pin prepares to conduct an experiment using this hydrogen-fueled proton exchange membrane fuel cell manufactured by H-Power. He is using it to power an exoskeleton, powered armor being developed to enhance the abilities of future U.S. soldiers.

or interconnects, which connect the individual fuel-cell elements into a fuel-cell "stack" for the PEM fuel cell to make it lighter and more affordable. "We've shown that these carbon composite bipolar plates for automotive PEM fuel cells meet cost and performance goals," says Besmann. "These plates can be made at a low cost. They don't corrode and they show high electrical conductivity and sufficient strength. They are substantially cheaper and lighter than conventionally used graphite."

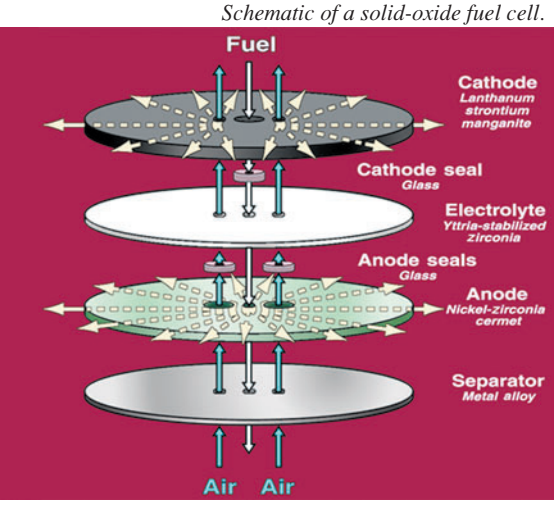
ORNL worked with Los Alamos National Laboratory in evaluating 100-cm^2 single-sided plates. The plates were found to demonstrate good performance and good corrosion resistance. The technology for making these plates has been licensed to Porvair Fuel Cell Technology, Inc.

ORNL researchers are working with industrial partners (e.g., MER and W. L. Gore, Inc.) to make thinner, lighter interconnects and electrodes that offer a good power density. They are experimenting with altering and using alternative materials (e.g., a film of titanium nitride alloy deposited on an iron-titanium base alloy), looking for structure-property relationships, analyzing engineering designs, developing prototype fuel-cell units, and evaluating their performance.

SOLID-OXIDE FUEL CELLS

ORNL researchers are becoming more involved in supporting the development of solid-oxide fuel cells (SOFCs). These fuel cells, which may operate at a very high temperature (1000°C),

Schematic of a solid-oxide fuel cell.



are best suited for stationary power generators that can provide electricity to factories and towns. They not only produce electricity electrochemically but also can operate at sufficiently high pressure that their exhaust gases can drive a power-generating turbine, making the SOFC very efficient at power production.

Rod Judkins (ORNL's Fossil Fuel Program director), Tim Armstrong (ORNL's Fuel Cell and Functional Materials Program manager), and Solomon Labinov (Engineering Science and Technology Division) have conceived a highly efficient power plant. Using static and dynamic computer modeling, they designed a hybrid fuel cell–gas turbine power plant that has an energy conversion efficiency of 80%. This combined-cycle system incorporates a gas turbine, one or two solid-oxide fuel cells, a gas separation device based on the carbon-fiber composite molecular sieve, and a heat exchanger using the graphite foam with very high heat transfer (developed by M&C's James Klett and Tim Burchell).

"We are the only DOE national laboratory doing this type of development," says Armstrong. "This is a real system that an industrial partner could integrate into a working system with components available today."

For SOFCs, ORNL researchers have designed metal alloys for interconnects, are developing materials to improve the electrolyte, and are testing ways to improve and reduce the cost of manufacturing anodes. Using ORNL's Infrared Processing Center, researchers are sintering electrolyte films on substrates to reduce the production cycle time and costs of assembling fuel-cell stacks. ORNL researchers are also doing design work on fuel-cell systems and stacks, as well as computer modeling and mechanical-properties testing to improve the reliability and predict the lifetime of improved SOFCs.

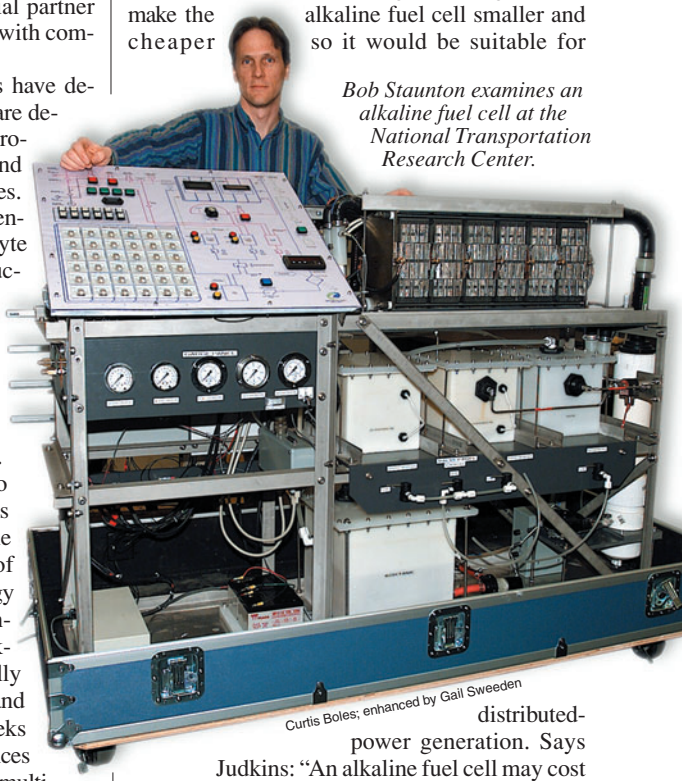
Armstrong and Paul Becher (also of the M&C Division), Doug Lowndes and Christopher Rouleau (both of the Solid State Division), Michael Hu of ORNL's Nuclear Science and Technology Division, and Meilin Liu of Georgia Institute of Technology have been working on an SOFC project funded internally by the Laboratory Directed Reseach and Development Program. This project seeks to develop a fundamental basis for advances in materials for the next generation of multi-stage SOFCs, which must be designed to exhibit exceptionally high energy conversion efficiencies and fuel use. "These systems will require electrolyte and electrode materials made of new oxides that function at temperatures as low as 500°C for as long as 40,000 hours," Armstrong says. "So we are developing nanocrystalline electrolytes by employing ORNL's synthesis expertise."

These ORNL researchers recently showed that a 15-nanometer-thick epitaxial electrolyte film of 10% yttria-stabilized zirconia (YSZ) exhibits the highest ionic conductivity ever reported. It has 140-fold greater ionic conductivity than that of a conventional zirconia electrolyte ceramic at 500°C.

"In our fuel-cell-design activities, we found that power density in SOFCs could be doubled through novel configurations without the need for radically new materials," Armstrong says. "The SOFC fuel-cell size and weight may be reduced to one-quarter the volume and one-half the weight through changes in geometry. The design change could lower the manufacturing cost to $155 per kilowatt, which would have a dramatic effect on overall fuel-cell-system cost."

ALKALINE FUEL CELLS

Alkaline fuel cells have been used in the U.S. space program since the 1960s. They are quite expensive in part because of the reliability needed by the space program and because they use costly platinum for their electrode catalyst. Also, potassium hydroxide, which is used as the electrolyte, has a problem: It readily reacts with carbon dioxide (CO_2), gradually degrading fuel-cell performance and lifetime. But DOE's Office of Power Technologies believes that material substitutions and existing technologies could make the alkaline fuel cell smaller and cheaper so it would be suitable for distributed-power generation. Says Judkins: "An alkaline fuel cell may cost on the order of $100 per kilowatt compared with $1500 per kilowatt for today's fuel cell and have an energy conversion efficiency of 50 to 55%."


Curtis Boles; enhanced by Gail Sweeden

Bob Staunton examines an alkaline fuel cell at the National Transportation Research Center.

To protect and preserve the fuel cell's electrolyte, ORNL's Judkins and a team led by Tim Burchell have developed a regenerable scrubber that removes CO_2 from the air, which is the source of the oxidant (oxygen) for this fuel cell. The scrubber is regenerated by passing an electrical current through it, a process the ORNL inventors have dubbed electrical-swing adsorption. This invention is also useful for capturing CO_2 from gas streams being released to the atmosphere.

ORNL's program will focus on developing high-power-density alkaline fuel cells, and will initially focus on testing and developing more CO_2-tolerant electrolytes and better bipolar plates and electrodes. Researchers will test different materials to find the best candidates to replace the expensive platinum catalyst in alkaline fuel cells to reduce their cost. "One alkaline fuel-cell electrode could be made of carbon, silver, or a metal oxide," Armstrong says. "The other might be made of a nickel-based oxide instead of platinum."

Combining the right materials and designs is likely to result in a better, cheaper fuel cell. That hope is fueling the efforts of ORNL researchers who offer expertise and ingenuity in these areas.

TVA's Bull Run coal-fired power plant in East Tennessee.

Tom Cerniglio

Because it is desirable for energy security reasons that coal remain in our nation's power-production mix for the next century, ORNL researchers are studying ways to make coal-fired power plants cleaner, more efficient, and more economical.

Securing our future energy supply begins at home. The challenge is to develop the technologies needed to help coal remain a viable energy option for the United States in the face of increasing international pressure to reduce carbon dioxide emissions. The events of September 11 further increase the need to ensure that our nation's plentiful supply of coal is not interrupted, especially if imported oil and gas supplies are.

The United States has a 1500-year supply of coal, and 54% of the electricity produced in the country comes from coal combustion, averting the need to use large amounts of imported oil and gas for generating electricity. Although oil was used to supply 20% of the nation's electricity in the 1970s, it is now the source of only 1% of our power, as other fuels have become more available.

Although our nation has many coal-fueled power plants, very few new ones have been built in the past 15 to 20 years. While this may seem strange in a time of ever-increasing energy demands, the reason is primarily economics. Numerous new natural-gas-combined-cycle (NGCC) plants—plants that use natural-gas-fueled turbines as the primary electricity-generating technology and steam-driven turbines as a secondary generating technology in the same system—have been built. Capital costs of these NGCC plants are much lower than for conventional coal-fired steam plants. Other compelling reasons for the trend toward building more NGCC plants are that natural-gas-combined-cycle plants are more efficient and have much lower emissions of sulfur and nitrogen oxides and carbon dioxide (CO_2) than do coal-fired plants. The NGCC plants can also be brought on line in much less time than can coal-fired plants.

The problem is explained this way from the local perspective, according to the Southern Alliance for Clean Energy for the Tennessee Clean Air Task Force: Assume that you purchase electricity from the Tennessee Valley Authority (TVA) and your monthly bill is $100. Without significant investment in pollution-control equipment, meeting your electrical needs each year would result in the combustion of 9 tons of coal and the release to the atmosphere of 335 pounds of sulfur dioxide (SO_2), 177 pounds of nitrogen oxides (NO_x), and 42,197 pounds of CO_2. Both SO_2 and NO_x (through the production of ground-level ozone) contribute to lung damage in humans. Additionally, rising atmospheric concentrations of CO_2 may alter the climate in undesirable ways. Coal-fired power plants also emit hazardous mercury, which eventually is deposited from the air to waterways, where it can be taken up by fish that humans eat (possibly causing neurological damage).

"Because of dramatic advances in pollution-control technology, these emissions from coal plants, except for CO_2, can actually be controlled by commercially available equipment to about the same level as natural-gas electricity generation," says Rod Judkins, director of ORNL's Fossil Energy Program. "These pollution control measures also impact the economics of coal power generation."

TVA, which produces 64% of its power from fossil fuel plants, is the largest single-utility buyer of coal in the United States. The agency has made great strides in reducing its SO_2 and NO_x emissions by purchasing low-sulfur coal and using the best available emissions control technologies. By installing scrubbers and electrostatic precipitators, TVA has cut its SO_2 emissions by 65% since 1977 and plans to reduce it by 75 to 85% by 2005. Through installation of low NO_x burners and selective catalytic reduction systems, TVA plans to increase its reduction of NO_x emissions from 45% (since 1995) to 75% by 2005.

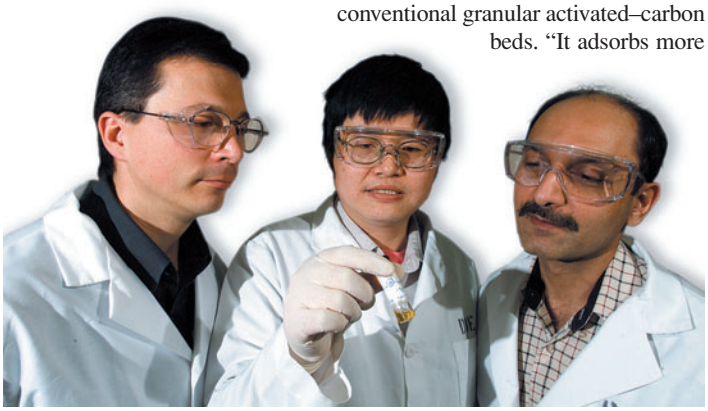
In February 2002 President Bush delivered a speech calling for a reduction of greenhouse gas emissions (including CO_2) by 18% in 10 years. He also asked for an "unprecedented" reduction in power plant emissions of sulfur dioxide, nitrogen oxide, and mercury, which the administration calls the worst air pollutants. Almost a year earlier, President Bush urged the U.S. government to commit $2 billion over the next 10 years to the development of advanced clean–coal power technologies In response, Secretary of Energy Spencer Abraham said, "This country will have a much stronger, more reliable electrical industry if we keep coal in the power mix. New technology is the way to do that."

One possible approach to keeping coal in the nation's energy portfolio is to develop economical methods for capturing CO_2 from the stack gases released from coal-fired power plants. Some of the captured carbon could be used to make marketable products. The rest of the recovered carbon gas could be collected in a vessel for transport to a carbon sequestration site to isolate it from the environment. It could be then injected into an underground coal bed, depleted oil reservoir, or the ocean, although ocean sequestration may be becoming a less preferred approach.

MOLECULAR SIEVES AND DESIGNER SOLVENTS

ORNL and University of Kentucky researchers recently developed a carbon-fiber composite molecular sieve (CFCMS) adsorbent filter that has a great affinity for CO_2 and that is quite effective in separating CO_2 from mixtures of gas containing it. Because the CFCMS adsorbent is electrically conductive, the CO_2 can be removed from the saturated sieve by running an electrical current through it at low voltage.

This CO_2-adsorption technology, developed largely by Tim Burchell of ORNL's Metals and Ceramics Division, has several advantages over conventional granular activated–carbon beds. "It adsorbs more



Curtis Boles; enhanced by Gail Sweeden

David DePaoli (left) and Moonis Ally (right) examine a vial of ionic liquid shown by Sheng Dai, who synthesized it. This ionic liquid will be tested to determine its effectiveness in removing carbon dioxide from a mixture of gases.

carbon and takes it up 5 to 10 times faster," says Judkins. "Also, 2 to 10 times less energy is required to recover the adsorbed CO_2 and regenerate the filter so it can be used again."

In addition to addressing the burning issue of CO_2, another group of ORNL researchers is trying to tackle the problem of hazardous mercury emissions from coal-fired power plants. Using internal funding from ORNL's Laboratory Directed Research and Development Program, they are searching for and trying to synthesize "ionic liquid" compounds that most effectively take up and separate CO_2 and mercury from power-plant stack gases.

Members of the group are David DePaoli of the Nuclear Science and Technology Division; Moonis Ally of the Engineering Science and Technology Division; and Mike Simonson, Sheng Dai, and Doug Duckworth, all of the Chemical Sciences Division. Working with them is Ruth Baltus, visiting from Clarkson University in New York, and former ORNL staff scientist Jerry Braunstein.

Curtis Boles; enhanced by Gail Sweeden

Ruth Baltus, a chemical engineering faculty member from Clarkson University on sabbatical at ORNL, assembles a quartz crystal microbalance, which is used to screen different ionic liquids for their ability to absorb CO_2 from a gas mixture (such as stack gases from a coal-fired power plant). The ionic liquid is coated on a piezoelectric quartz crystal that is electronically excited into resonance. As the ionic-liquid-coated quartz is exposed to varying concentrations of CO_2, the resonance frequency changes because of the uptake and release of dissolved CO_2. These frequency changes are interpreted in terms of the effectiveness of the liquid in removing CO_2.

Dai has synthesized organic "designer solvents" that absorb CO_2. Simonson, Baltus, and DePaoli, using special experimental facilities to reproduce stack-gas conditions, measure their thermodynamic and kinetic properties, including their ability to take up and transport CO_2. In a parallel effort, Duckworth uses mass spectrometry to measure each solvent's affinity for CO_2. Guided by the results of Ally's computer modeling of the properties of CO_2-ionic liquid mixtures, these experimental results are contributing to the design of new solvents for enhanced performance under field conditions.

Dai has synthesized a promising compound that can be impregnated in a glass-fiber or porous polymer membrane. The goal is to work with the coal power industry to create a "reactive membrane" through which CO_2 will flow so that it can be captured for industrial use or carbon sequestration.

"Ionic liquids are ideal for this application because they do not evaporate easily, they are stable in a wide temperature range, and they have adjustable properties," says DePaoli. "We have shown in preliminary experiments that we can design one liquid for which CO_2 has a high affinity and another for which mercury has a high affinity. We hope to find the best compounds that can be used together to extract both CO_2 and mercury from stack gases."

COAL GASIFICATION

Since 1973 when the Organization of Petroleum Exporting Countries (OPEC) embargoed sales of oil to the United States, the U.S. government has explored the use of direct and indirect coal liquefaction to make liquid fuels and coal gasification as a means of producing gaseous fuels such as synthesis gas and substitute natural gas. Most current government-sponsored activities are directed toward coal gasification for power generation in integrated (coal) gasification, combined-cycle systems. Reforming of natural gas (breaking up gas molecules) and gasification of coal are considered excellent approaches to the production of hydrogen. Because the United States has enough coal deposits to last for 1500 years, coal represents a tremendous asset for the production of fuels, including hydrogen, that could be used for transportation and power production.

"Unfortunately," Judkins says, "the economics for these types of plants are poor. We could build an integrated coal-gasification, combined-cycle plant that is 42% efficient. It would produce electricity, partly by using the gas produced from the coal to run a gas turbine for generating power. Its capital cost would be $1000 to $1500 per kilowatt of electricity generation capacity. However, the commercial natural-gas combined-cycle plant commonly being used today costs only about $300 to $500 per kilowatt of installed electricity-generating capacity and has a conversion efficiency of 50 to 58%."

The cost of gasifying coal may become attractive if the U.S. supply of natural gas declines or other factors cause the cost of natural gas to increase dramatically. "We probably have 65 to 120 years of natural gas left, based on known reserves, current consumption rates, and anticipated growth in gas-usage scenarios," Judkins states. "But, of course, if we can get natural gas from methane hydrates, we will have a much larger supply that might last for centuries."

Today, efforts are being made to burn coal at a higher temperature to produce electricity more efficiently, thereby reducing emissions of CO_2 and other pollutants. New technologies, such as selective catalytic reduction, low-NO_x burners, and scrubbers, will help decrease these emissions.

ORNL is a partner with Foster Wheeler, Babcock and Wilcox, and Alstom Power (based in Brussels, Belgium) in developing an Ultra Supercritical Coal Plant. The plant will produce steam as hot as 1400°F. It would have a higher efficiency than the Eddystone supercritical coal plant in Pennsylvania, which operates at 1100°F but was designed to operate (and did) at 1200°F in the 1950s, still a record for commercial operation. This plant was de-rated and required to operate at less severe conditions as a result of materials issues that arose at the higher temperatures.

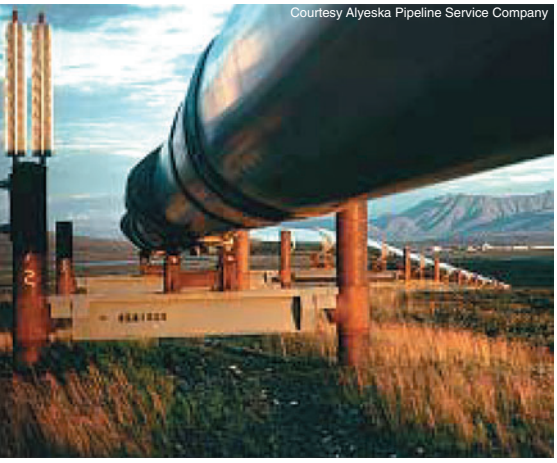
ORNL researchers are also involved in a $5-million program to identify materials that can withstand the 1400°F temperature of this advanced plant's steam system. Materials scientists will focus on modifications of conventional steels and nickel-based alloys for use in a steam system, so that it can stand up to these harsh conditions.

ORNL, which is located near the Cumberland Mountains of East Tennessee where coal is abundant, is doing its part to help demonstrate that coal really can be made clean and can, thus, remain in the nation's energy mix.

Advanced coal-fired power plants, such as this 2544-ton-per-day coal gasification demonstration pilot plant, will have energy conversion efficiencies 20 to 35% higher than those of conventional pulverized-coal steam power plants.

ORNL and

Securing a sustainable oil future for the U.S. transportation and energy production sectors is a difficult energy, environmental, and economic challenge. ORNL researchers are studying ways to reduce transportation vehicles' consumption of oil and to recover and refine oil more efficiently. Other researchers have developed computer models to estimate the cumulative impacts of oil price shocks on the U.S. economy and to assess the potential impacts of significant changes on oil refineries.



Some 13 billion barrels of oil have flowed down the 800-mile-long Trans-Alaska Pipeline (shown above). Two separate incidents of sabotage of the pipeline have each resulted in large spills. Less than a month after the shocking events of September 11, a man fired a hunting rifle at the pipeline 50 times, causing a spill of 6800 barrels of oil onto the tundra. In 1978 vandals blew up a section of the pipeline, releasing 700,000 barrels of oil to the environment. Gate valves have been strategically placed along the pipeline to isolate sections of the pipeline and minimize the size of potential spills in the event of a pipe rupture.

For three decades the U.S. government has had the goal of reducing our nation's reliance on imported oil for our energy supplies. President Bush reiterated this goal in his State of the Union address on January 29, 2002. He said: "Good jobs also depend on reliable and affordable energy. This Congress must act to encourage conservation, promote technology, build infrastructure, and it must act to increase energy production at home so America is less dependent on foreign oil."

Today 39% of the energy used in the United States comes from oil, and 53% of the oil we consume is imported. How we consume this oil has changed, however. In the 1970s, one-fifth of our electricity was produced using oil; today, only 1% of our power comes from burning oil (and one-fifth of our electricity is produced by nuclear power plants). In the 1970s one in four American homes burned oil for heating; today only one in ten U.S. homes is heated by oil (mostly in the Northeast). Most of the oil we import is used for transportation, which accounts for almost two-thirds of total petroleum use in the United States.

ORNL and University of Tennessee researchers at the National Transportation Research Center (NTRC) are working to reduce the need for oil in transportation in several ways. They are studying better and cheaper ways to manufacture lightweight-carbon-fiber composites to replace heavier steel for automotive body parts; the lighter the vehicle, the less fuel it will consume. They are developing smaller electric motors and power electronics modules for hybrid vehicles; hybrid vehicles use less gasoline or diesel fuel because they have an electric motor to help power the wheels during acceleration and stopping. The NTRC researchers are also helping to develop advanced emissions controls for diesel engines (which are 40% more efficient than gasoline engines) to enable diesel engines to meet tougher environmental standards in the next few years.

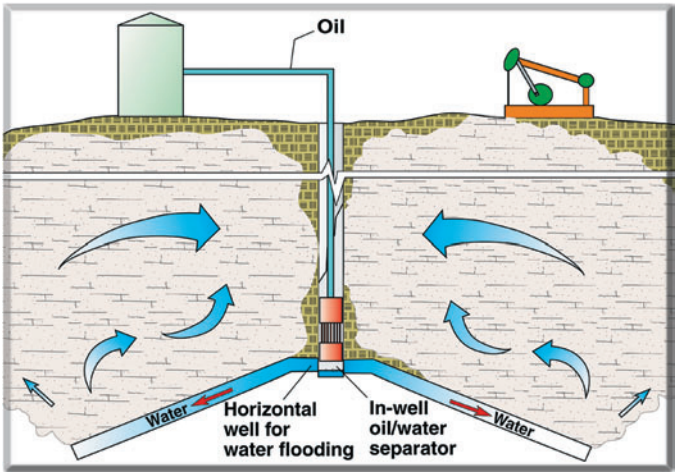
IMPROVING OIL EXTRACTION

About half of the oil being used in the world today and about 8% of the oil used in the United States comes from Saudi Arabia. The oil production cost for the Saudis is estimated at 80 cents a barrel. Oil is harder to come by in the United States; our oil production costs run about $10 a barrel. The Bush administration has proposed extracting oil from the Arctic National Wildlife Refuge (ANWR) in Alaska. However, according to Tom Schmidt of ORNL's Nuclear Science and Technology Division (NSTD), our nation could have access to more oil than exists in ANWR or even Saudi Arabia if it were technically possible to drill at water depths greater than 5000 feet and into the seafloor of the Gulf of Mexico. To achieve this goal, a research program is needed to develop drilling equipment that could withstand extremely high water pressures at such a depth.

One problem that makes oil recovery so expensive in the United States is that, in some cases, 90% of the "crude oil" brought up from a well is actually water, which must be separated from the oil. Considerable energy is required to lift the oil-water mixture from deep within the earth. Today the oil is separated from the water above ground, and the water (which is classified as a hazardous waste under U.S. regulations) must be treated to remove benzene, toluene, and other pollutants before it can be discharged into the ocean.

The proposed solution to making oil recovery cheaper is to separate the oil from the water deep within the earth. NSTD's Joe Birdwell is evaluating the use of a modified centrifugal contactor, originally developed for other Department of Energy applications, as a deep downhole separator that may someday be used to recover oil from underground oil-water mixtures.

The separator contains a rotor that spins so fast that the heavier fluid (i.e., water) is thrown toward the rotor wall and the lighter fluid (i.e., oil) flows in an inside ring. The separated fluids exit the rotor through different channels. If a reliable downhole separator is devised, the idea is to pipe the water back into an underground formation and send only the oil up the well pipe for collection.



ORNL is evaluating the use of a modified centrifugal contactor as a deep downhole separator to recover oil from underground oil-water mixtures. To eliminate the cost of lifting and treating the water, the idea is to pipe it into an underground formation and send only the oil up the well pipe for collection.

Oil Research

"One technical challenge is to make the separator narrow enough to fit into oil well pipes with a diameter of only about 6 inches," says Robert Jubin, leader of NSTD's Process Engineering Research Group (now on military leave). "Another challenge is to get the throughput of oil needed. Still another is to get the device to work for long periods of time without getting gummed up with underground solids such as sand."

ORNL's deep downhole separator contains a rotor that would spin fast enough to separate the heavier water from the lighter oil.

ORNL researchers led by Joanna McFarlane and Debbie Bostick, both of NSTD, have done modeling research to characterize the pollutants in water produced in oil fields. This information will help oil companies decide how to treat the water to make it safe for discharge into waterways.

OIL RESERVE AND REFINERY MODELING

Paul Leiby, an economics modeler in ORNL's Environmental Sciences Division (ESD) has developed computer models, in collaboration with David Greene of ORNL's Engineering Science and Technology Division and ESD's Randall Curlee and Russell Lee, that can be used to estimate the cumulative impacts of oil price shocks on the U.S. economy. "The oil that we buy from the Middle East is not competitively priced," Leiby says. "Oil in the Middle East can be produced and delivered for $3 per barrel, but the world pays around $20 to $30 per barrel. The volatility of oil prices is also a problem. A periodic drop in oil prices makes people lose interest in investing in energy-efficient equipment and domestic oil production technologies."

On the other hand, consumers also at times face the opposite problem of oil price shocks—large spikes in oil prices in response to a 1% decrease in oil supplies. "The United States has experienced 18 oil market disruptions since the 1950s," Leiby says. "These shocks are usually caused by wars between nations; internal conflicts, such as revolutions and civil wars; major accidents, such as the Exxon Valdez oil spill; and intentional economic actions, such as the 1974 oil embargo." [Because of its displeasure with the United States for supporting Israel during the 1973 Arab-Israeli war, the Organization of the Petroleum Exporting Countries (OPEC), dominated by Muslim nations, embargoed sales of oil to the United States, causing gasoline shortages, price rises, and long lines at gas stations.]

According to Leiby, nine of the past ten recessions in the United States were preceded by oil price shocks. Leiby and his colleagues have written many papers that assess the benefits and costs of imported oil. They have also recommended policies to DOE to cushion the U.S. and world economies against oil price shocks.

"First, we need to reduce oil imports by consuming less oil, say, by driving less, traveling in carpools, and driving vehicles designed to go further on less fuel," Leiby says. "Secondly, we need to stockpile oil, as we are doing in the Strategic Petroleum Reserve (SPR), so we can protect ourselves against an oil price shock. We drew oil from the SPR in 1991 during the Persian Gulf War when the military forces of the U.S.-led coalition, expelled the Iraqi army that had invaded Kuwait. Third, we need to invest in producing flexible technologies that will allow fuels to be rapidly switched in response to an emergency."

One example of a flexible technology is an industrial boiler that can quickly switch from oil to natural gas. Other examples are multifuel automobiles now being developed. Their engines can run on ethanol, methanol, or compressed natural gas—instead of gasoline—when an oil crisis hits. Also being developed is the grid-connected, hybrid-electric car. This vehicle can run on both a gasoline-driven (or diesel-fueled) motor and an electric motor. Then if a gasoline or diesel fuel shortage occurs and prices rise suddenly, the owner can connect the car to the power grid to recharge the battery. The car can then be operated as an all-electric vehicle, at least for short trips around town.

"We have characterized for DOE the oil market and the cost to the economy of oil price disturbances," Leiby says. "The problem is that a small group of nations in the Middle East is intentionally influencing oil supply for economic and sometimes political reasons. The geopolitical forces that motivated OPEC behavior in the mid-1970s and is leading to regional conflicts and terrorist activity today could continue to destabilize oil supplies. The U.S. is wise to make preparations."

Leiby and his colleagues have used modeling to assess how much oil should be stored in the SPR, when it should be used, how well it can offset disruptions in our oil supply, and how fast it should be drawn down to keep oil prices stable. Right now, the SPR holds about 600 million barrels of oil in Louisiana caverns, but the ORNL researchers looking into these issues recommend that the SPR be filled to its capacity of 700 million barrels.

The Strategic Petroleum Reserve, located at Bayou Choctaw, Louisiana, and other sites, can rapidly add oil to the market during supply-reduction emergencies.

The ORNL models of the SPR are being maintained for DOE's Office of Fossil Energy. The models help planners prepare for energy security emergencies, such as the blockage of oil tanker traffic by nations or terrorist groups. The models also assess the potential impacts of drawdowns on oil markets and the economy in general.

ORNL's Gerald Hadder maintains U.S. petroleum refinery models that can be used to assess the potential impacts of a significant change for the refinery industry. For example, what would be the gasoline supply impacts of legislative proposals to ban ethers, which may threaten groundwater quality? How would different gasoline types accommodate substantial percentages of ethanol, under proposed renewable fuels standards? How would proposed changes in gasoline driveability (determined by distillation properties) affect refinery operating costs and investments? What will be the refining and transportation-fuel-supply impacts of U.S. regulations that call for significant reductions in the sulfur content of gasoline and diesel fuel by 2005–2006, to ensure the effectiveness of advanced emissions controls in fuel-efficient vehicles? Hadder can also predict the economic impacts of an accident or deliberate attack on an oil refinery.

Other ORNL research focuses on improving oil-refining processes. Brian Davison and Abhijeet Borole, both of ORNL's Life Sciences Division, are modifying bacterial enzymes to make them stable enough in an oil environment to react readily with hydrocarbon and sulfur-containing molecules to upgrade crude oil. Bioprocessing of oil could someday be more economical than using hydrogen at high temperatures in oil refineries to make gasoline and other usable products from crude oil.

An ORNL researcher is modeling potential impacts of changes in the U.S. oil refinery industry.

Water & Energy Security

Water resources and energy production are inseparable; factors affecting one usually affect the other. Where water resources are limited, energy production is likely to be constrained, even unpredictably, as described in ORNL studies.

Water-related limits on energy production are happening throughout the United States, even here in Tennessee, where water availability is generally taken for granted. For example, Governor Sundquist imposed a moratorium earlier this year on the installation of new "Merchant" power plants because these highly efficient, natural-gas-fired turbines require large amounts of water for cooling. Whether some of the proposed power plant sites can provide sufficient water without adversely affecting other water users is questionable.

In the Tennessee River basin, water temperature may limit future energy production. For example, because the Tennessee River runs shallow and warm at Muscle Shoals, Alabama, where cooling water is withdrawn for the Tennessee Valley Authority's Browns Ferry Nuclear Power Plant, the temperature of Browns Ferry intake water occasionally is equal to its discharge temperature limits. Thus, the ability of the river to carry away the reactor's waste heat is limited, necessitating a plan to bring in cold water from elsewhere.

During the California energy crisis in 2001, utilities operating Oregon and Washington's hydroelectric dams were asked to supply California with needed electricity. Unfortunately, the Pacific Northwest region was experiencing a drought, so stream flows throughout the Columbia River basin were very low. Nevertheless, the regulators allowed more water from these reservoirs to be used for power production to help meet California's needs. The net result: the highest number of salmon ever killed in one year in the Columbia River.

Water resources. Energy production. Climate change. Water development effects on endangered species. All of these are intertwined, and a National Research Council report suggests that federal agencies are beginning to recognize that water resources will demand more of their attention so they can better understand this ever-changing web of relationships. For years ORNL's Milton Russell, Mike Farrell, Steve Hildebrand, and Mike Sale [leader of the Water Resources Group in the Environmental Sciences Division (ESD)] have been working to identify water resources research and development needs and to establish a water resources program to support energy research missions.

"Hydropower produces 9 to 11% of the electricity used in the United States," says Sale. "Almost as much water (39%) is used for electricity production in the United States—that is, for power plant cooling and hydropower—as is used for irrigation and other agricultural uses (42%). You cannot produce energy without affecting water resources and aquatic ecology."

The availability of water resources affects how much electricity can be produced; secure energy supplies depend on sure water supplies. For example, Sale notes, each time the flow of the Colorado River is reduced by 1%, the amount of power that can be produced in that river basin falls by 2.5%.

Climate change affects the amount and timing of water inflows to our reservoirs. For example, recently in the mountainous areas of the U.S. western states, there has been more rain and the snowpack has declined. "Less snowpack means less water is being stored and more water is flowing into the reservoirs as immediate runoff," Sale says. "Existing reservoir systems are not able to use the altered flows as effectively, so less energy is produced. The solution to this problem and the salmon problem is bigger reservoirs."

Bigger reservoirs also could provide the nation with more energy security, for example, by generating additional electricity that might be needed if nuclear power plants had to be shut down because of a terrorist attack. ORNL researchers Glenn Cada and Chuck Coutant, both in Sale's group, are working with various partner organizations to develop new, environmentally friendly technology to reduce salmon mortality at dams; ORNL researchers are contributing computer modeling to this effort, which is funded by DOE's Hydropower Program. "Friendlier turbines could make larger dams more acceptable environmentally," Sale says. "Also, bigger reservoirs will provide more water for salmon, as well as for energy production."

DOE does not have a water resources program yet, but its Office of Science is funding a three-year pilot study on the global water cycle; ORNL and four other national laboratories are participating in this study. Using internal funding, Sale and ESD's Randy Curlee are developing a white paper on water and energy security, to help define how water resources research can become part of ORNL's Laboratory Agenda. Sale is also completing a white paper on "Water Cycle Dynamics in the Southeast," to identify unique regional issues. DOE is recognizing the role of water resources in securing our national energy future, but Sale and Curlee believe even more attention is needed at the national level.

Belleville Lock and Dam, located on the West Virginia and Ohio shores, is a stage for competing water uses, including hydropower, navigation, water supply, and cooling for energy and other industrial production.

The Future of Fusion: Meeting National Energy Goals

Fusion energy research holds much promise for securing new sources of energy for the 21st century to answer a critical national need.

Stan Milora, director of ORNL's Fusion Energy Division (FED), has many reasons to be optimistic about the future of fusion energy research at ORNL and in the United States. "Fusion is an attractive long-term energy option," he says. "Fusion energy will rely on virtually unlimited fuel available in the United States, not imported fuels.

"Fuel from 50 cups of water contains the energy equivalent of 2 tons of coal. Fusion can be environmentally acceptable because it releases no air pollutants, including greenhouse gas emissions. Compared with fission its radioactive wastes are short-lived, with a more manageable disposal problem. Fusion is expected to be economically competitive with other power sources when the costs for waste disposal and carbon management are included. The fusion community believes that if fusion research were to receive sufficient support, commercial fusion power plants could start supplying electricity by the middle of this century."

A fusion energy device is fueled by a plasma, an extremely hot state of matter consisting of charged heavy hydrogen ions (e.g., deuterium from seawater and tritium bred in the device) and electrons. If magnetic fields confine the plasma long enough at a sufficiently high density and temperature, sustained production of fusion reactions will result, providing the heat needed to generate electrical power.

What is ORNL doing to advance fusion technology? ORNL's long-time involvement with the Princeton Plasma Physics Laboratory (PPPL) has been strengthened with a focus on developing innovative plasma confinement devices, such as the National Spherical Torus Experiment (NSTX) and a new class of compact stellarators.

The NSTX, which began operation at Princeton in 1999, is based on a very compact high-performance toroidal confinement concept that was advocated by Martin Peng in the mid-1980s at ORNL. Partly inspired by this success, ORNL's fusion theory group began investigating a compact hybrid of the stellarator (pioneered in 1951 at PPPL) and the tokamak. This device relies on external coils (the stellarator) and on a plasma current (the tokamak) for magnetic confinement. The tokamak is currently the front runner in magnetic fusion energy. "Ben Carreras and Don Batchelor of our theory group first started working on exploring the compact stellarator in 1995," Milora says. "PPPL became interested in pursuing the concept in 1998."

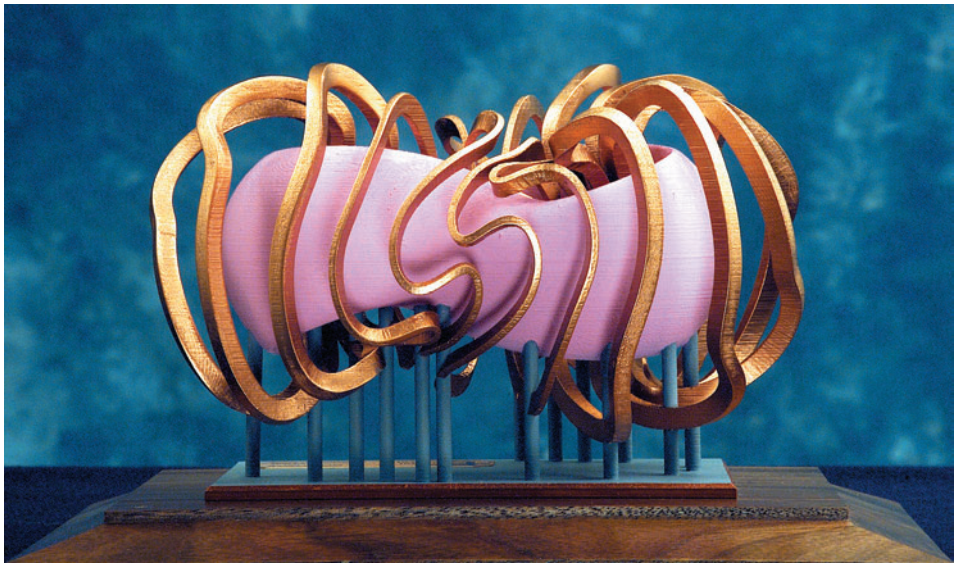
ORNL management enthusiastically supports the collaboration between Oak Ridge and Princeton as co-developers of the proposed National Compact Stellarator Experiment (NCSX) at PPPL, the main element of the U.S. Compact Stellarator Program. The smaller Quasi-Poloidal Stellarator (QPS) at ORNL is a principal support element.

The NCSX is in President Bush's fiscal 2003 budget request, and construction is scheduled for completion at PPPL in 2006. If all goes as planned, the compact NCSX will exhibit the attractive performance levels of the tokamak without some of its engineering drawbacks. ORNL will have several leadership roles through the design, construction, and operation stages. FED's Jim Lyon is deputy project manager, and an engineering team led by FED's Brad Nelson is responsible for design of the stellarator core, including the complex magnet coil system. FED's Steve Hirshman has led the effort to develop coil configurations that are buildable and at the same time deliver the requisite plasma shaping for equilibrium, stability, and confinement at high plasma pressures.

The very-low-aspect ratio QPS was designed by Steve Hirshman, Dennis Strickler, Lee Berry, and Don Spong, all of ORNL, and Andrew Ware of the University of Montana and their PPPL colleagues, using the IBM SP supercomputer at the Department of Energy's Center for Computational Sciences at ORNL. Unlike the tokamak and NSTX, which are shaped like a doughnut, the QPS plasma resembles two linked sausages. This highly shaped configuration is expected to eliminate the violent plasma disruptions common in conventional research tokamaks at high plasma pressures because it will have only a fraction of the plasma current.

"We are using advanced computational tools and terascale computing to design the magnetic field shapes that will ensure plasma equilibrium and stability with good confinement of plasma particles," Milora says. "A new 'optimizer' simultaneously targets these physics goals and the engineering constraints needed to provide feasible, affordable coils. This integration was unimaginable just a few years ago."

The physics and engineering properties of the proposed QPS were validated in 2001 by a technical review committee from the fusion community. QPS is now in the conceptual design phase. If approved by DOE next year, the experiment will be built and ready for operation by 2007 at ORNL. The QPS may be small but it could have a big impact on fusion device design.



Curtis Boles

This model of the Quasi-Poloidal Stellerator shows the combination of magnetic coil geometry and plasma shape that was computed by the integrated engineering and physics optimizer. This configuration meets the QPS researchers' design goal to achieve the desired physics performance objectives using feasible, affordable coils.

ORNL Technologies for Energy Infrastructure Assurance

Some ORNL technologies could play a role in identifying vulnerabilities in and assuring the reliability of the U.S. energy infrastructure.

The Tennessee Valley Authority's Norris Dam is a source of electricity to residents and businesses in East Tennessee. It's an important part of the nation's energy infrastructure.

In September 1998, a natural gas explosion in Victoria, Australia, shut down the area for two weeks, causing100,000 people to lose their jobs and 1.4 million customers to go without gas. The economic loss was estimated at almost $1 billion.

In August 1999, a man was arrested for plotting to bomb the Trans-Alaska oil pipeline on New Year's Day. He allegedly devised the scheme in the hope that oil prices would spike upward after the disruption so that he could reap windfall profits.

In the past decade more than 15,000 infrastructure-related incidents have occurred worldwide in the electric power, oil, and gas industries alone. Incidents like these make governments more aware of their energy infrastructure vulnerabilities.

Three years ago, the U.S. government began funding multidisciplinary research in the new area of "critical infrastructure assurance." Critical infrastructure embraces the physical and computer-based systems that enable the U.S. government and economy to function. Elements of our infrastructure include transportation services (interstate highways, railways, waterways, and airports), as well as energy and water systems. Important also are the electronic networks used for these infrastructure components and also for banking and finance, telecommunications, and emergency services. The purpose of the research funding is to identify weak links and find better ways to help protect and assure the reliability of the country's critical infrastructures.

After the terrorist attacks of September 11, 2001, the Department of Energy was asked to focus on energy infrastructure assurance and define the concept of energy infrastructure assurance and DOE's role in it. DOE staff gathered information on the accomplishments and capabilities of DOE national laboratories in assessing vulnerabilities and developing technologies for prevention, detection, and mitigation of threats, as well as recovery from natural, accidental, and deliberate actions of disruption. As a result, a report was produced that lays out DOE's research role in energy infrastructure assurance. The report indicates that energy infrastructure includes coal and uranium mines, oil and gas wells, oil and gas pipelines, petroleum refineries, electric transmission lines, and power plants (including hydroelectric dams), as well as information technologies that operate these systems.

According to a February 27, 2002, article in the *New York Times* on a conference on the security of the electric system, "The computers that control the electric power system around the nation have been probed from the Middle East, and terrorists may have inspected the physical equipment." The article noted that "government experts identified nuclear power plants as perhaps the most attractive targets but said dams, gas pipelines, and oil refineries were not far behind. Federal officials urged companies that generate, transmit, and distribute electricity to take steps to increase security."

In the summer of 2002, key U.S government personnel will hear a discussion of the DOE report and a report released in May by the National Academy of Sciences concerning the role of science and technology in combating terrorism. Personnel from ORNL's new Oak Ridge Center for Advanced Studies will use the conclusions of these discussions to write a report on how science and technology can help DOE implement its energy infrastructure assurance plan.

Some of the capabilities and achievements of ORNL researchers in this area are presented in this section called "Protecting Our Energy Infrastructure." This article and subsequent articles describe ORNL technologies that could play a role in assuring the reliability of the U.S. energy infrastructure and the protection of people should the infrastructure be disrupted.

Researchers at Oak Ridge National Laboratory have developed a number of technologies that could be applied to identifying vulnerabilities in the energy infrastructure and providing it with better protection. As a side benefit, some of these technologies could be used also for protection against terrorism in particular and for homeland security in general.

ASSESSING VULNERABILITY OF DAMS AND DRINKING WATER

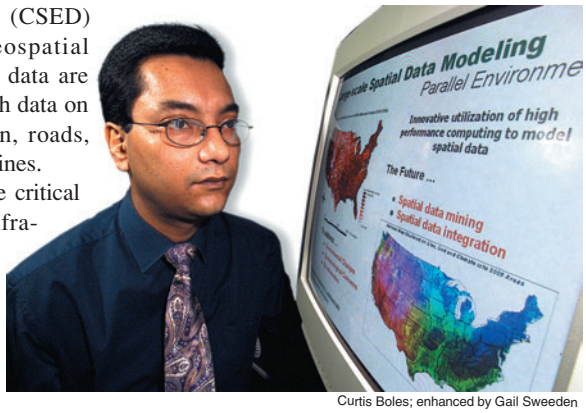
Drinking water is made available to the U.S. population through groundwater and up to 10,000 intakes located at lakes, rivers, small streams, and reservoirs (dams), according to data collected by the U.S. Environmental Protection Agency. Many of these intakes are located at hundreds of the 80,000 dams listed in the National Inventory of Dams. The Geographic Information Science and Technology (GIST) Group led by Budhendra Bhaduri in ORNL's Computational Sciences and

Courtesy U.S. Army Corps of Engineers and NREL

Hydroelectric dams such as Ice Harbor Dam in Washington produce 9 to 11% of our nation's electricity. An ORNL model can pinpoint dams vulnerable to deliberate attacks.

Engineering Division (CSED) has developed a geospatial model in which these data are incorporated along with data on land cover, population, roads, and water supply pipelines.

"These dams are critical to the U.S. energy infrastructure because they supply hydropower and are used for transportation that ships coal and other energy-related supplies," says Bhaduri. "We can use this model to pinpoint dams that might be more vulnerable to attack because they are far from heavily traveled roads and highly populated areas."



Curtis Boles; enhanced by Gail Sweeden

Budhendra Bhaduri examines results of the use of high-performance computing for modeling spatial data. This technique enables researchers to better perceive environmental changes or new patterns of disease outbreaks from large and diverse sets of spatial data.

The model can also be useful for determining the need for mitigation and recovery strategies if a terrorist group were to blow up a dam or contaminate it so that responders must cut it off from the water supply system. The ORNL model can predict how many people might be affected downstream and indicate where sensors should be placed to identify and measure concentrations of toxic chemicals. The measurements could indicate whether it is safe for people there to continue drinking tap water or whether they should switch to bottled water until they are told the water is safe again to drink.

This vulnerability assessment model was developed as part of a national pesticide usage impact modeling project. One purpose of the model is to determine which of the 10,000 drinking water intakes is most likely to receive pesticides used to protect agricultural crops from attack by insects and pathogens. The pesticides get into rivers and lakes from runoff.

"One thing we can look at," Bhaduri says, "is whether pesticides applied in Minnesota that get into the Mississippi River actually make it all the way to New Orleans. Some of the pesticides may decay on the way or get diverted into a tributary or end up in a dam where they eventually are deposited into the sediment."

ORNL's ability to predict whether a substance entering a reservoir can reach a number of people through drinking water intakes can also have homeland security applications. For example, if terrorists were to dump a biological agent such as botulinum toxin or a chemical agent such as cyanide into a reservoir, the model can predict which drinking water intakes might receive the toxic agent in hazardous concentrations. It can also predict the locations and number of people that would likely be exposed to dangerous amounts of the toxin in their drinking water.

HYDROLOGIC TRANSPORT ASSESSMENT SYSTEM

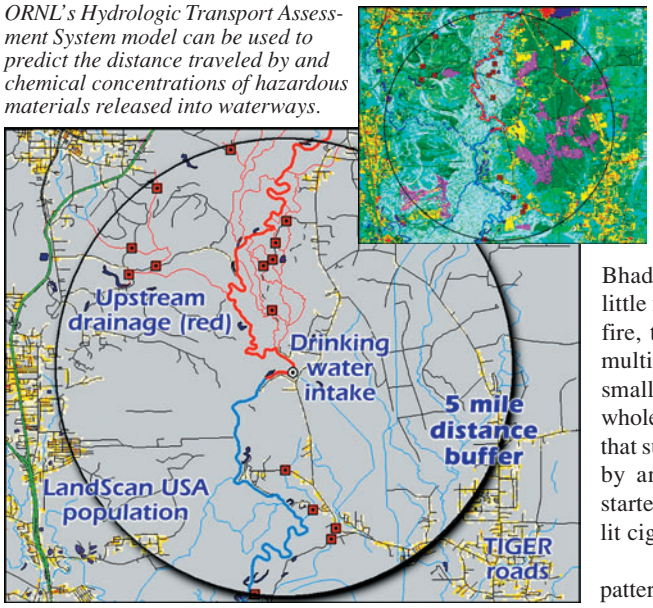
Suppose that a terrorist group were to dump a toxic chemical or disease-causing biological agent or a suitcase full of nuclear materials into the Mississippi River. A witness sees the dastardly deed and reports it to the police. The water and sediments at the point of dumping are sampled, and the dangerous substance is identified by analytical chemists. The local population is informed about the attack and advised to drink bottled water until further analysis determines the water is safe to drink.

Is there a risk to people living further downstream from the site where the hazardous material was dumped? Fortunately, ORNL has developed a numerical model for simulating the transport and fate of nuclear, biological, and chemical agents in water bodies. Called the Hydrologic Transport Assessment System (HYTRAS), the model predicts material concentrations in the water and sediment over time and distance downstream in rivers or lakes.

"HYTRAS includes health effects data and will eventually incorporate population data from ORNL's LandScan USA model," says CSED's David Hetrick. "Thus, the model will be able to predict how many people downstream of the site of a dumping incident are at risk of being exposed to the hazardous substance through their drinking water, the doses they are likely to receive, and the health effects of those doses. This information could be very useful for emergency responders and health care centers."

About 200 rivers worldwide are included in a map database in HYTRAS. A new river database being developed for HYTRAS will have thousands of rivers, including water intakes for the United States. The model was originally developed to help energy production plants and manufacturing firms estimate the health effects of the pollutants they discharge to waterways.

ORNL's Hydrologic Transport Assessment System model can be used to predict the distance traveled by and chemical concentrations of hazardous materials released into waterways.



GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING

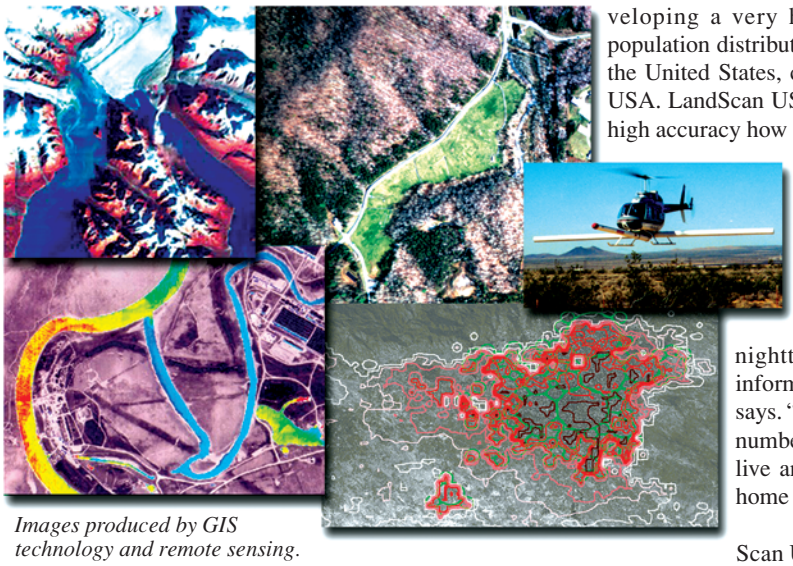
The GIST Group has been a leader in developing, implementing, and applying geographic information systems (GIS), science, and technology since 1969—well before the advent of commercial GIS. The ORNL group is the oldest in the DOE laboratory system to use geographic information systems technology combined with remote sensing information obtained from satellite and airborne imagery.

"Every incident has a geographic nature," Bhaduri says. "We can display, for example, the spatial relationships between an oil refinery, the plume of pollutants that are spewed out as a result of an accident or deliberate attack, and the number of people who may be affected."

Satellite images and video taken from aircraft can vividly show plumes from volcanoes and smoke from forest fires. But satellite imagery combined with ORNL's GIS technology can provide insights about whether destruction of a field of green plants is the result of a natural, accidental, or deliberate action.

"Take a forest fire," says Bhaduri. "If satellite imagery shows many little fires combined to make a large forest fire, that suggests the fire was caused by multiple lightning strikes. But if only one small fire by a road was spotted before the whole forest eventually erupted into flames, that suggests that it was deliberately started by an arsonist or perhaps accidentally started by someone who carelessly threw a lit cigarette into the woods."

The ability of GIS technology to find patterns in satellite imagery can be used for



Images produced by GIS technology and remote sensing.

homeland security. "We have the capabilities to demonstrate that GIS technology combined with remote sensing can be used to monitor fields of crops such as corn and cotton to detect bioterrorism," Bhaduri says. "With the bird's eye view of satellite imagery and pattern analysis using GIS, we can detect whether fields of valuable crops are being invaded by killer weeds or insects or pathogens that are destroying them."

The mission of the GIST Group is to support national energy, environmental, and security programs through research, development, and application of geographic information and analysis systems. The GIST Group can provide advanced digital remote sensing, advanced GIS algorithms, design of decision support systems, advanced image analysis and interpretation, three-dimensional visualization and animation, digital terrain modeling, demographic modeling, and global positioning information.

POPULATION DISTRIBUTION MODEL

Perhaps the most important research project of the GIST Group is the LandScan Population Distribution Model, which shows global population data in the finest resolution yet available (each cell is 1 square kilometer). CSED's Eddie Bright, Phil Coleman, and Bhaduri are developing a very high-resolution population distribution database for the United States, called LandScan USA. LandScan USA predicts with high accuracy how many people are present in any given area (90-m cell) during the night, as well as the day. "The U.S. census provides nighttime population information," Bhaduri says. "It is based on the number of people who live and sleep in each home in a city block."

To develop LandScan USA, the ORNL group conducted a pilot study in a 29-county area in southeast Texas around Houston and Port Neches. The goal of the study was to develop needed algorithms and to identify and resolve issues surrounding the development of LandScan USA.

When the World Trade Center twin towers collapsed after being struck by two hijacked airplanes, it was estimated that as many as 10,000 people were in these buildings. It was later determined, based on missing person reports and injury reports, that fewer people were present. The GIST Group is determining average daytime populations for buildings such as the Sears Tower in Chicago, where the nighttime residential population is zero. Bhaduri believes that by using real-time remotely sensed data around busy city business districts, reliable information about the dynamic daytime population can be effectively estimated.

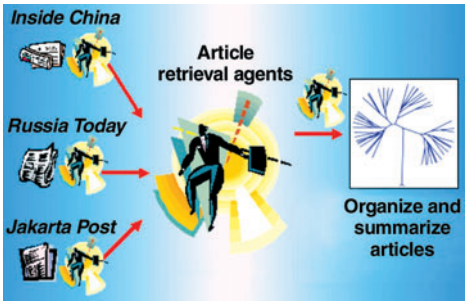
LandScan USA includes demographic attributes (age, sex, race), as well as spatial distributions for both nighttime and daytime populations. "The combination of both residential (i.e., nighttime) and daytime populations will provide the best estimate of who is potentially exposed to ambient pollutants from, say, an industrial facility," Bhaduri says. "We can also use the model to determine how many women in a certain age group are more than 15 miles away from a health care center that gives mammograms. The National Cancer Institute is interested in this kind of information."

The GIST Group at ORNL is currently developing LandScan USA, which details both the daytime (left) and nighttime (right) population distribution at a resolution of approximately 90 m. As seen in the images, during an average work day, about 160,000 people move into the U.S. census tract containing the downtown district of Houston, Texas.

LandScan USA could be useful for homeland security. The GIST Group has applied this population model to a spatio-temporal simulation in which a terrorist releases smallpox germs in Neyland Stadium during a University of Tennessee football game attended by more than 100,000 people. "Suppose that 72 hours after the game a season ticket holder who feels very ill goes to a Knoxville hospital emergency room, where he is diagnosed with smallpox," Bhaduri says. "Because of our GIS-based data modeling, we can efficiently locate people inside the stadium as well as in the surrounding region (where they might have come from) to predict the possibility of an epidemic attack originating in the stadium. We may be able to determine the extent of the epidemic, as well as the zip code locations of the people who are ill and the hospitals that should be notified that they must be prepared to receive many smallpox patients soon."

THREAT ASSESSMENT AND MODELING

Suppose that an airplane crashes into an American nuclear power plant as a result of an accident or deliberate attack. The U.S. response might be to shut down all nuclear power plants to protect them against possible additional attacks (until the cause of the crash is determined). What will be the consequences of this massive shutdown? How will it affect the electrical power grid and the many users—from elevators to subways, from homes to hospitals, from mines to manufacturing facilities—that depend on the nation's electricity (20% of which is supplied by nuclear power)? If a plume of radioactivity is released from the crash site, where will it go and how many people might be exposed to it?



This schematic shows part of ORNL's spatio-temporal threat assessment and modeling system.

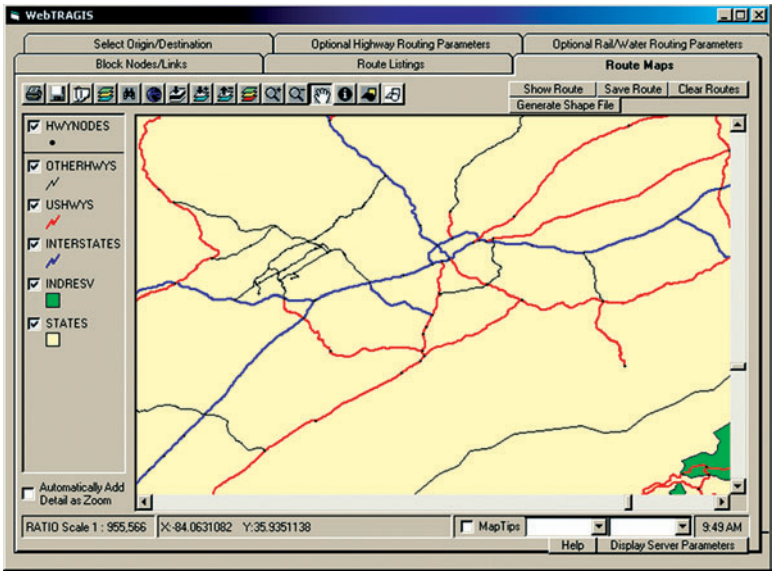
The consequences of the crash and the effects of the shutdown decision can be modeled at ORNL by a threat assessment and modeling system that combines several ORNL modeling technologies. One technology is the Virtual Information Processing Agent Research (VIPAR) system, developed by CSED's Collaborative Technologies Group led by Thomas Potok. "VIPAR consists of intelligent agents, or software robots, that can retrieve open-source infor-

mation, including vast stores of government data, from the Internet and other electronic archives," Potok says. "These software robots can help model various effects and predict consequences of various actions."

VIPAR also can be linked to ORNL's GIS and remote sensing technologies for determining, say, the geographical distribution of impacts from a shutdown of nuclear power plants. CSED's Hazard Prediction and Assessment Capability (HPAC) code can accurately predict the direction and fission product concentrations of the radioactive plume emanating from the nuclear plant crash site, as well as the size and location of the population at risk of being exposed.

"VIPAR's intelligent software agents can gather related data about a certain problem from the Internet," Potok says. "Other software agents store the most relevant data, fetch updates for data that frequently change, and integrate all the data, which initially came in different formats. VIPAR, which has a friendly graphic user interface, then analyzes the data and displays relationships among crucial pieces of information as a visualization that is meaningful to the user. A picture is worth a thousand words. VIPAR minimizes the time needed to communicate possible solutions to a problem. For example, one possible solution might be to get hydroelectric dams to generate more power to compensate for the temporary loss of electricity from the nuclear plants."

ORNL's threat-modeling system provides various levels of user access so that only people who have a need to know receive all the pertinent data. Other users are sent only selected data that allow them to perform their particular tasks effectively. The modeling system could improve data exchange among government agencies and departments, allowing a more coordinated response to threats to homeland and national security.



ORNL's Transportation Routing Analysis Geographic Information System (TRAGIS) model can generate highway routes that meet Department of Transportation regulations for shipping radioactive materials by truck. TRAGIS can also select alternative routes if a selected route is blocked, say, by a landslide or terrorist action.

TRANSPORTATION ROUTING MODEL

If a road is blocked by a landslide or a railroad bridge is blown up by a terrorist group, a computer tool built over 20 years ago at ORNL could quickly calculate an alternative route, say, for trucks or trains carrying spent nuclear fuel. As a result, they could get to nuclear waste disposal sites as fast as possible.

The routing tool is called the Transportation Routing Analysis Geographic Information System (TRAGIS) model. Developed by CSED's Paul Johnson and Richard Michelhaugh of ORNL's Nuclear Science and Technology Division, TRAGIS can determine the fastest highway, railroad, or waterway transportation routes between a starting point and a destination. It also provides information on population distribution counts and densities along each route. These data are of value to government users who wish to select a route that minimizes the risks to people in the unlikely event of a transportation accident. The route and population information is also used for health risk assessment models and environmental impact statements.

"TRAGIS can generate routes that meet Department of Transportation regulations for shipping radioactive materials," Johnson says. "DOT requires that trucks carrying certain types of radioactive materials must take the shortest distance to the nearest interstate highway, the quickest interstate routes, the interstate exit closest to the destination, and the shortest route there from the exit. Another rule is that trucks carrying these materials must take beltways around large cities rather than pass through them."

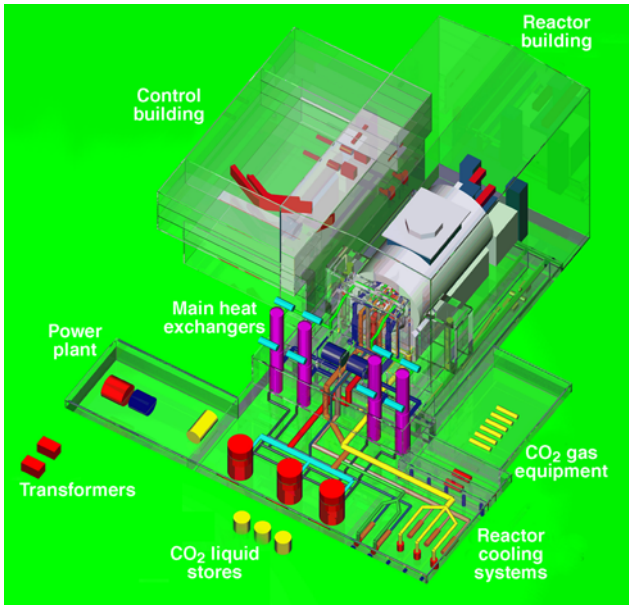
TRAGIS databases identify the nuclear power plants and coal-fired power plants located on the U.S. rail network. Using Department of Defense funding, Johnson is completing the development of a new rail network for the U.S. Navy; it is a 1:100,000-scale network—that is, every centimeter on the network is equivalent to a kilometer in real space. This rail network tool will help the Navy select the fastest routes for getting armored personnel carriers and materials from inland bases to ports in case of an attack. According to Johnson: "Our rail model can tell you which rail lines crossing each other are interconnected and which ones may be separated, as in the case of a railroad bridge crossing over a ground-level rail line."

The ORNL model also has been used in environmental impact statements for predicting how many spent fuel assemblies are likely to be delivered from nuclear power plants to nuclear waste repositories by rail and by truck. The model has been used to calculate the routes likely to be used for delivery of these assemblies to the proposed Skull Valley site in Utah and the proposed Yucca Mountain site in Nevada.

The TRAGIS waterway database, which is a 1:2,000,000-scale network, represents the inland waterway system and interconnections among U.S. deep-water ports.

PREDICTING INDUSTRIAL AND NUCLEAR FACILITY VULNERABILITIES

A terrorist group drives a truck loaded with explosives into a building at a nuclear power plant. The building houses a pool of water



This graphical representation of a nuclear power plant is the result of modeling by ORNL's Visual Interactive Site Analysis Code (VISAC). VISAC can predict the probability that a portion of a facility would be destroyed (say, by a terrorist attack) and the probability of an undesirable side effect, such as a release of radioactive material. It can provide an estimate of the length of time that the whole facility would be shut down.

covering spent nuclear fuel. What is the probability that an explosion will cause the release of radioactive fission products from the spent fuel into the atmosphere?

At another nuclear power plant, a disgruntled employee who has received a termination notice leaves a "briefcase bomb" next to a heat exchanger. If the bomb goes off, what is the probability that the explosion will "kill" the heat exchanger? If the heat exchanger is destroyed, what is the probability that a core melt might result, causing a release of radioactive fission products to the environment?

These are two make-believe scenarios that CSED's Robert H. Morris, Robert L. Sanders, and C. David Sulfredge and their colleagues might use to test their new computer code for predicting vulnerabilities at nuclear power plants and nuclear reprocessing facilities. Their Visual Interactive Site Analysis Code (VISAC) is of interest to the U.S. Nuclear Regulatory Commission and other governmental agencies because the code can determine and analyze nuclear facility vulnerabilities to natural, accidental, and deliberate threats.

VISAC is a Java-based expert system that provides mission planners with a coordinated capability to predict and analyze the outcomes of various accidents or incidents at nuclear and industrial facilities. "Our code can also predict the outcomes of accidents at industrial facilities that use chemicals, such as nuclear reprocessing plants," Morris says. "For these industrial facilities, VISAC can calculate the initial direction of the plume and its chemical concentrations. This information is then fed to HPAC, which predicts how far the plume will go and where and how much of the plume's hazardous chemicals will be deposited on the ground."

VISAC also has the capability to model any nuclear facility, such as power or research reactors, and simulate the results of various incidents. Simulated incidents have ranged from simple equipment sabotage to complex sorties involving military weapons, truck or car bombs, or satchel charges.

By using fault-tree methodology similar to that employed in probabilistic risk assessments, VISAC calculates the probability of facility destruction and undesirable side effects, such as a chemical or radiological release. It also estimates how long the facility will be out of service for repairs. VISAC has access to a library of models that can be customized by the user in both geometry and logic to approximate a number of facilities of interest.

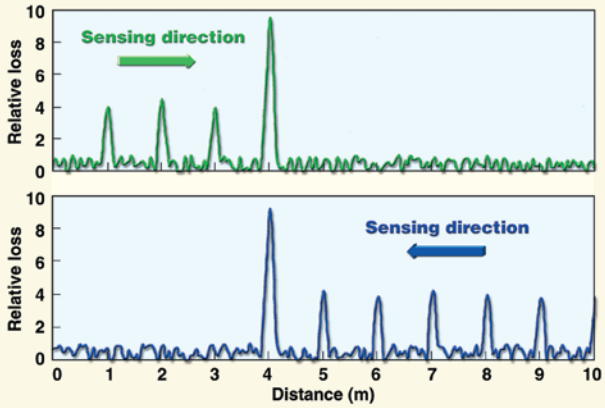
According to Morris, "Our code can be used by utilities to guide them in determining which parts of their nuclear power plants need better protection."

OPTICAL SEALS FOR CONTAINERS

ORNL researchers working with researchers at the Oak Ridge Y-12 National Security Complex have developed an active seal technology that immediately indicates when a container has been breached. This optical seals technology, which is used at the Y-12 facility to protect stored weapons-grade nuclear materials, has saved the facility hundreds of thousands of dollars in materials control and accountability costs. The patented technology, known as the ReflectoActive™ Seals System (RAS), was invented by Jeff Muhs, Barton Smith, and Duncan Earl, all of ORNL's Engineering Science and Technology Division, and Y-12's Chris Pickett.

Oak Ridge researchers have developed an active optical seals technology that is used to protect weapons-grade nuclear materials stored in containers, like these above.

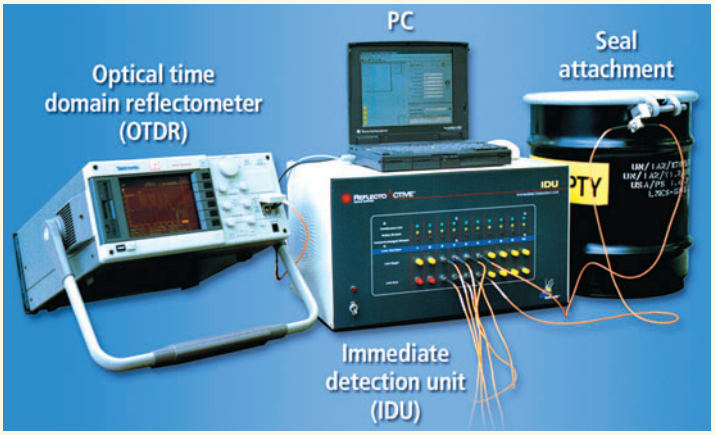
Instead of passive seals that must be checked manually, large arrays of storage containers can be continuously monitored using active seals consisting of optical fibers, thin strands of glass that conduct light. Light of varying frequencies travels in opposite directions through a fiber-optic loop that may have 150 to 200 seals. An optical-time-domain reflectometer sends light pulses through the optical fibers. Light is reflected back from each closed seal and detected by an immediate detection unit. If the seal is breached or opened, the light signal reaching the detector will register as a much taller peak, setting off an alarm and indicating which container has a seal problem.



If a container seal has been breached, the light signal reaching the detector will register as a much taller peak.

RAS provides continuous surveillance of the containers even during a breach or opening. It verifies in real time that the seals on individual containers are intact. The fully automated system is controlled from an intuitive graphical user interface. It can be used with a variety of container closure designs and container configurations. One RAS system can monitor up to 2000 seals or containers.

RAS provides continuous tamper indication for large numbers of containers at a significantly lower cost than other active seal technologies. RAS is self-powered and requires no electrical components, so little maintenance is required. The RAS technology is expected to be commercialized soon.



This active seals system, which uses a light source, computer, detector, and optical fibers, instantly indicates when a container has been breached.

Responding to Energy-Related Emergencies

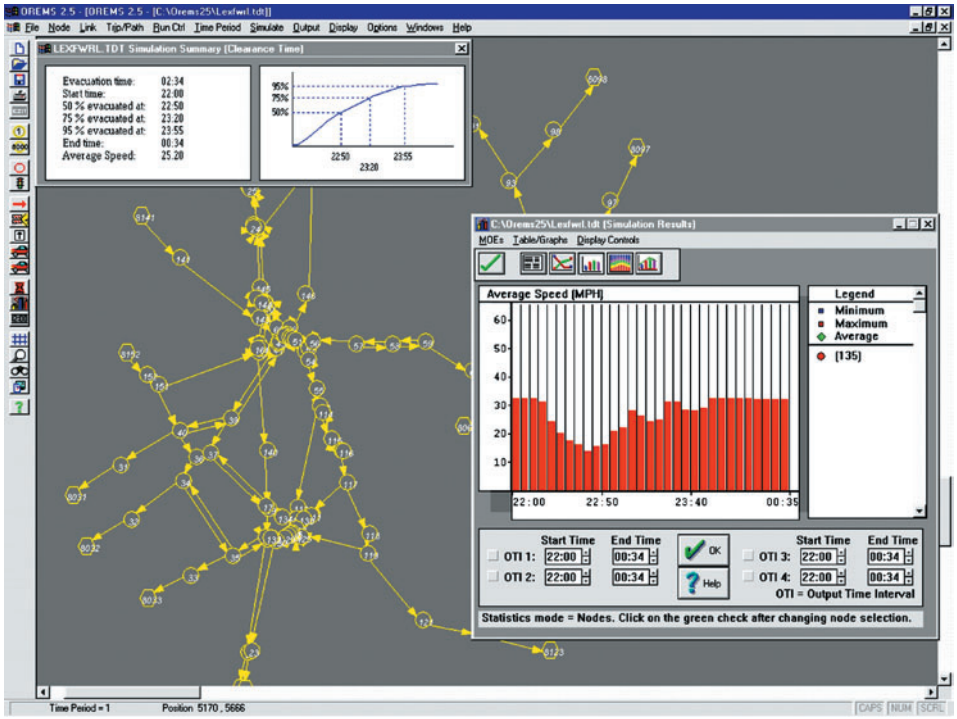
Evacuation planning is important for utilities that operate nuclear power plants.

ORNL researchers have been investigating how people respond to emergencies and warnings about hazards. An ORNL-developed computer tool is being used to guide emergency preparedness and to determine which evacuation strategies work best for a given incident.

Imagine that a hydroelectric dam burst or a large amount of radioactivity was accidentally released from a nuclear power plant? Suppose that a plume of toxic, flammable gases was released from an oil refinery fire or a gas pipeline explosion? Where would people living near the site of any of these incidents go, and how fast could they leave? If a terrorist group threatened to detonate a weapon of mass destruction in the center of a city, would it be feasible to evacuate the population at risk before the onset of damage (that could also affect the energy infrastructure)? Answers to these questions are being sought by ORNL researchers.

EVACUATION PLANNING TOOL

An ORNL-developed computer tool called the Oak Ridge Evacuation Modeling System (OREMS) is being used to help emergency responders develop plans for moving people quickly and safely away from the site of most any disastrous event. Various scenarios can be tried using this state-of-the-art, evacuation-planning model to determine which evacuation strategies would likely work best. These scenarios can range from a natural event, such as an earthquake or hurricane, to a deliberate attack on part of our energy infrastructure, to an accidental release of hazardous materials.



The display screen of the Oak Ridge Evacuation Modeling System shows results of the model's calculations of the time required to evacuate a community, based on the population and average speed of the moving cars.

"The 1984 accident in Bhopal, India, that killed at least 5000 persons sparked interest in the problems of hazardous materials releases in populated areas," says John Sorensen of ORNL's Environmental Sciences Division (ESD). "The Three Mile Island accident in 1979 dramatically increased public awareness of the need for emergency planning for nuclear power plants."

OREMS was developed by a team led by Sorensen. He and his colleagues have conducted research to assess community preparedness for dealing with an industrial accident that resulted in the release of toxic chemical plumes or radiation.

OREMS is based on data obtained from actual experiences and events, such as dam failures in Colorado and Wyoming and explosions at chemical plants. OREMS can be used to estimate clearance times for evacuating an area, predict traffic bottlenecks, and evaluate traffic control strategies.

"Evacuation planning has become very important for utilities that operate nuclear power plants," says Sorensen, noting that OREMS is being used for four such facilities. "The Nuclear Regulatory Commission (NRC) requires that utilities use 2000 census data to estimate the time needed to evacuate the population around all nuclear power plants in case of a natural, accidental, or deliberate threat. Also, each nuclear utility

Traffic congestion is a consequence of evacuation from communities exposed to a natural, potentially destructive event (such as a hurricane) or an accidental or deliberately destructive action (such as the release of a toxic agent into the environment).

must provide evacuation estimates as part of its application to renew its license to operate a nuclear power plant after its current license expires."

Sorensen and his colleagues can offer experience and expertise in this area. For nuclear power plants, these ORNL researchers have studied evacuation planning issues, as well as the adequacy of warning systems, emergency plans, and public information programs. This work has been funded by DOE, NRC, the Federal Emergency Management Agency (FEMA), and the Three Mile Island Public Health Fund.

OREMS is also being used by planners in Las Vegas, Nevada, to evaluate evacuation scenarios there. A city department in Florida has requested it to use in making evacuation plans in the event of a hurricane.

"We have added a user interface to make it easier for a lay person to operate the OREMS model," Sorensen says. "We expect this ease of use will increase demand for our tool."

OREMS models the flow of vehicles over a network of roads around a source of hazardous material, as could result from an accident at a plant in which a plume of toxic chemicals is released. Most road network data are available from local departments of transportation, and local population census data are available from the U.S. Census Bureau.

Sorensen has a colleague in Florida who for a number of years has studied the evacuation of people after they were warned about an approaching hurricane. His studies show that the occupancy count for cars during evacuations consistently averages 3 to 3.2 people per vehicle.

"So if you know the population in the area of the disaster," Sorensen says "you can estimate the approximate number of vehicles that will be on the network of roads. Using traffic-loading curves to calculate the distribution of cars over time, you can predict how long it will take for the local population to evacuate the area."

The OREMS tool can be used to predict how fast a town can be evacuated if lanes are reversed—for example, turning a two-way, two-lane road into a one-way, two-lane road. For example, OREMS was used to illustrate the best way to evacuate a small town in Kentucky that can be accessed only by a two-lane road.

"We found that the town could be evacuated in less than three hours by reversing one lane and making the whole road one way," Sorensen says. "It would take a lot longer if the road remained a two-way street."

Use of OREMS might have prevented the congestion that resulted when people drove away from Florida and South Carolina in an attempt to escape Hurricane Floyd in 1999. "Part of the highway was made into a four-lane, one-way road to speed the evacuation," says Sorensen. "But when the four lanes were merged into two lanes, terrible traffic congestion and delays resulted—more of a problem may have been created than would have happened with better planning."

OREMS is the only evacuation simulation model that uses state-of-the-art traffic simulation codes derived from U.S. Department of Transportation (DOT) models. Furthermore, it is the only model of its kind endorsed for use by DOT in regional evacuation planning. OREMS was developed to replace obsolete technology used in other evacuation simulation approaches.

EVACUATION vs SHELTER IN PLACE

How do people normally respond to an emergency involving a release of hazardous material? Sorensen and his wife Barbara Muller Vogt (also of ESD) studied the responses of people to an actual accident—the explosion of a pesticide repackaging plant that occurred May 8, 1997, in West Helena, Arkansas. In this accident, clouds of foul-smelling smoke spewed from the plant. "We found that 90% of those who were told to evacuate did so, but only 27% of those told to shelter in place stayed in their buildings," Sorensen says. "At least 68% of those people advised to shelter chose to evacuate instead."

Evacuation is not always wise. You could leave your house and unknowingly move closer to a plume of hazardous material rather than away from it. If the air initially is more contaminated outside your home than inside, studies by Sorensen and Vogt suggest it would be better to stay in an interior room and cover the doorway with duct tape and plastic sheeting—not a wet towel—to prevent contaminated air from infiltrating the "safe" room. "You are 10 times safer if the doorway is sealed with these materials than if it is not," says Sorensen. He recommends also that you take a battery-operated radio with you into the interior room to find out when it is safe to re-enter the area outside the room. After a few hours, the concentrations of the hazardous vapor infiltrating buildings may exceed those of the airborne toxic materials outside. Then it would be smart to leave your house until experts agree that it is safe to live there again.

This advice also applies to a plume of biological or chemical warfare agents. Sorensen made a video showing how people can protect themselves from these weapons of mass destruction for FEMA, from which he gets most of his funding. (The rest comes from the Department of Energy.) The video, available on tape and digital video disk (DVD), is called "Residential Shelter in Place." One of the points made in the video is that people who shelter in place have more pro-

ORNL researchers found evidence of caring behavior but not panic among people evacuating the World Trade Center on September 11, 2001. Here, firefighters and rescue teams search for victims amidst the rubble of the collapsed twin towers.

Courtesy Andrea Boohe/Federal Emergency Management Agency

tection against toxic airborne agents if their homes have been weatherized to reduce energy use.

The results of Sorensen's studies of people's responses to emergencies were borne out by the reactions of occupants of the World Trade Center's twin towers in New York City after they were hit by hijacked airplanes in the terrorist attack of September 11, 2001. "We found no evidence of panic," Sorensen says. "Most people evacuated the twin towers and ignored the announcement after the first tower was hit telling them to stay in their offices. We found evidence of people helping people, an emerging therapeutic community. For example, two men carried out a woman who was wheelchair-bound."

One thing that has changed in recent years is the speed of communication in response to an emergency, thanks to cell phones, electronic mail, and informative Web sites on the Internet. Sorensen's study of the evacuation following the eruption of the Mt. St. Helens volcano in 1980 showed that it took 4 to 8 hours for people in eastern Washington to learn they could be covered in volcanic ash if they didn't leave the area.

In the case of the fourth hijacked airplane that crashed near Shanksville, Pennsylvania, on September 11, communication by cell phone made some passengers aware that the hijackers of their airplane were on a suicidal mission to crash into an important American building filled with people. As a result, some of the passengers organized a response and took action to wrest control of the plane away from the terrorists. Their response to the perceived danger, says Sorensen, shows an "unprecedented speed of adaptation to the situation."

HAZARD WARNING SYSTEM

In his "Hazard Warning Systems: Review of 20 Years of Progress," published in the May 2000 issue of *Natural Hazards Review*, Sorensen writes that the United States has no comprehensive national warning strategy that covers all hazards in all places. "Since 1975," says Sorensen, "forecasts for floods, hurricanes, and volcanic eruptions have improved most significantly, with public dissemination of warnings improved the most for hurricanes. However, a 100%-reliable warning system does not exist for any hazard."

ORNL's Emergency Management Center staff are studying public response to emergency warnings.

He also lists the myths about public responses to warnings about impending disasters: The public will panic. People will become overwhelmed with too much information. People won't respond if false alarms have been issued earlier. Emergency information should come from a single spokesperson. People will take action and follow instructions immediately after a warning. None of these beliefs are true, Sorensen says.

Sorensen (as chair of the Subgroup on Prediction, Forecast, and Warning) and Vogt both contributed to the recently published book, *Disasters by Design,* edited by Dennis Mileti. Sorensen wrote about warning systems and Vogt wrote about the vulnerability of physically challenged people to emergencies and disasters and the need to identify which people need assistance and how to ensure that they get help.

Sorensen's expertise in the area of planned and actual responses to natural and accidental disasters has been sought recently by the news media and the National Academy of Sciences because of the September 11 terrorist attacks. There is a need to determine how to plan effective responses (e.g., rapid evacuations, clear communication about sheltering in place, and the best ways to perform personal decontamination) to intentionally created disasters, in order to save lives and prevent injuries as much as possible.

DISRUPTION OF OIL AND GAS PIPELINES

If an oil or gas pipeline or distribution facility were blown up by a terrorist attack, how long would it take to restore service?

This question was studied in the mid-1980s by Sorensen and his ORNL colleagues L. W. Rickert, J. H. Horton, and W. Reed, in collaboration with M. M. Stephens at Tulane University. They published a report entitled "Emergency Response to Saboteur-induced Damage to Oil and Gas Distribution Facilities."

For this report, they presented engineering calculations for many scenarios, including blowing up a pipeline running across a river and blowing up a terminal for offloading oil from a ship to a pipeline.

"We found that for the damage scenarios considered, most systems could be jury-rigged into at least partial operating capacity within a short time," Sorensen says. "Depending on the situation, permanent replacement of pumping or compressor stations would take from 12 to 18 months because of the time it takes to deliver and install large valves, compressor drivers, and pumps. The federal government could help the pipeline industry by working with it to develop emergency response plans to guide it in jury-rigging repairs, to minimize disruptions in service."

So far, the U.S. government has not followed this recommendation, but there may be growing interest in doing so now that the U.S. Office of Homeland Security exists.

EMERGENCY PLANS FOR CHEMICAL FACILITIES

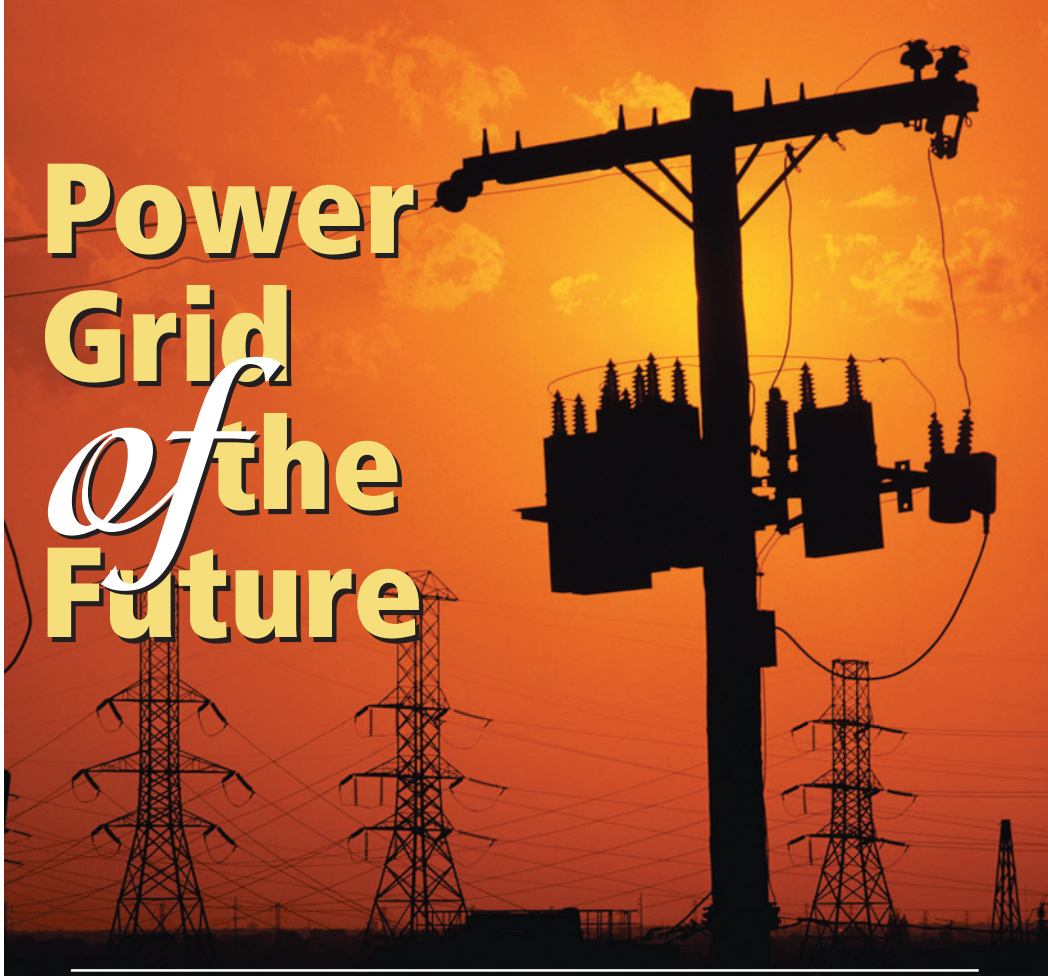
Sorensen and his associates have assessed community preparedness for dealing with chemical accidents. They have identified the technology, procedures, and management practices used to alert the public to a chemical release. They have investigated people's responses to chemical accidents to protect themselves, including such strategies as evacuating, sheltering in place, and decontaminating victims and affected areas.

Shoes and clothing may be disposed of as part of a decontamination regimen following a release of toxic materials.

Sorensen and his colleagues have also provided technical support for the planning, training, and reentry programs associated with the disposal of the nation's stockpile of chemical weapons. The final programmatic environmental impact statement for the disposal program, which involves on-site incineration of the chemical weapons near eight different cities, recommended a community-based emergency preparedness program. ORNL has been providing technical support to the Chemical Stockpile Emergency Preparedness Program, jointly managed by the U.S. Army and FEMA, which has the ambitious goal of achieving state-of-the-art plans with maximum public protection.

Largely as a result of the diversity of emergency management research at the Laboratory, ORNL was identified by DOE as a lead laboratory for emergency management at a recent Energy Infrastructure Assurance Technology Exposition, held in Washington, D.C. Some future ORNL research may be focused on developing plans to better prepare communities to deal with terrorist attacks involving weapons of mass destruction—attacks that could have an adverse effect on not only populations but also energy infrastructure.

Power Grid of the Future



ORNL researchers are finding ways to make the nation's power grid more reliable, responsive, economical, and secure in the face of various threats.

The United States has about 5000 power plants with a total generating capacity of more than 800,000 megawatts (MW) of electricity. Our country also has 254,000 kilometers (158,000 miles) of transmission lines to carry electric power to millions of customers. Over the next 10 years, demand for power is expected to rise by about 25%. Under current plans, electric transmission capacity will increase by only 4%, according to the *Report of the President's National Energy Policy Development (NEPD) Group,* published in May 2001. "This shortage could lead to serious transmission congestion and reliability problems," the report says.

In addition, the report adds, regional shortages of generating capacity and transmission constraints, such as occurred in California in the spring of 2001, combine to reduce supply reliability and quality of power delivered to end users. Uninterrupted power, which is essential to computer users, is becoming an increasingly important issue as our digital economy expands.

The power grid and power plants make up a significant part of the nation's energy infrastructure. After the terrorist attacks of September 11, 2001, the Department of Energy began developing a National Energy Infrastructure Assurance Plan, to identify vulnerabilities in the infrastructure and ways to improve its protection against natural, accidental, and deliberate threats.

TRANSMISSION GRID STUDY

The NEPD report, noting that the United States has three regional power grids that are not synchronously interconnected, directed the Secretary of Energy to examine the benefits of establishing a national electrical grid and to identify major transmission bottlenecks and remedies to remove them. The Department of Energy responded by conducting a "National Transmission Grid Study," to examine both the technical and economic issues resulting from transmission constraints and reduced power system reliability and to provide innovative solutions to reverse these trends.

The Tennessee Valley Authority not only generates electricity from its coal-fired and nuclear power plants, hydroelectric dams, wind turbines, and other resources but also transmits it through a system of transmission lines and towers.

ORNL researchers whose work on transmission-grid reliability issues has been nationally recognized also contributed to this study. The grid study report consists of six issue papers published and released in March 2002. Brendan Kirby of ORNL's Engineering Science and Technology Division (ESTD) is the lead author of one issue paper, entitled "Reliability Management and Oversight," and co-author of a second paper, "Transmission Planning and the Need for New Capacity."

"The study clearly identifies a nationwide decline in transmission system capacity and finds that this decline can be explained by a combination of technology, business structure, and regulatory reasons," says Kirby. "By addressing each of these issues, DOE can help develop the robust 21st century national transmission system that our economy needs. To ensure greater reliability and efficiency of electricity transmission, DOE should continue to encourage the development and demonstration of new technologies, such as advanced cables, including superconducting transmission lines in available rights-of-way. These approaches will help the power industry meet growing demands for energy while reducing the cost of electricity for customers all over the nation."

The grid study report recognizes the increased concerns about providing security to protect the U.S. power system from deliberate attack. It recommends more study of technical and administrative methods of enhancing security.

ADVANCED CABLES

ORNL researchers are helping industry develop and evaluate new technologies that could improve the efficiency and reliability of existing transmission lines. For example, 3M is developing and ORNL is testing designs of advanced

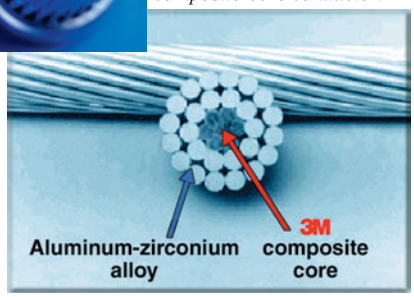
Courtesy Southwire Company

The world's first industrial installation of a high-temperature superconducting cable was performed recently at the Southwire Company facilities in Carrollton, Georgia. The cable, called the Southwire SuperTD Cable, has provided power to the Southwire industrial complex for more than 14,000 hours.

overhead cables with cores made of a metal-matrix composite instead of steel. Such cables could carry up to three times the current of today's transmission lines without the need for tower modifications or additional rights-of-way.

Courtesy of 3M Company

3M's composite-core conductor uses an aluminum metal matrix containing Nextel fibers that can increase the ampacity (current-carrying capacity) of a transmission line by 1.5 to 3 times over conductors currently installed. Inset: View of the end of a composite-core conductor.



"Using available technology to build expensive new rights-of-way and new tower systems will cost well over $1 million per mile," says Kirby. "Upgrading existing transmission lines with composite conductors will significantly improve the overloaded electrical infrastructure at a fraction of the cost."

Today's overhead transmission lines consist of aluminum conductor strands wrapped around a steel core. Because of the weight and properties of the steel, these cables will stretch and sag if they are heated up too much by carrying too much current. Sagging lines caused by excessive current and hot weather triggered a major power outage in 1996 in the northwestern United States. To overcome this limitation, 3M developed a composite consisting of Nextel ceramic fibers and an aluminum-zirconium alloy to make an advanced cable that can carry more current than steel-aluminum lines without sagging at higher temperatures. Vinod Sikka of ORNL's Metals and Ceramics Division and ESTD's Roger Kisner worked with 3M to improve the quality and production of this composite material.

Tom Rizy and John Stovall, both of ESTD, are responsible for testing 3M's advanced cable material to determine how well it holds up over time as it is run through many cycles of current flow. It will be heated by increased current loads to temperatures around 210°C and, every tenth cycle, to 240°C (simulating an emergency load).

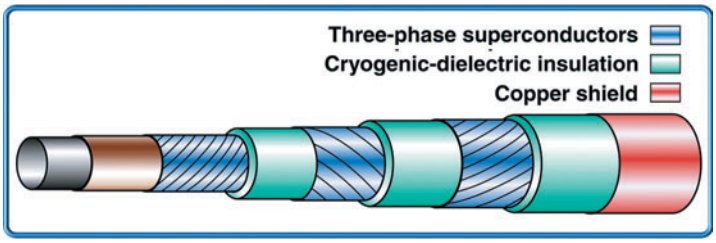
"We have developed instrumentation for detecting the extent of sag as temperature changes in planned tests at ORNL," says Rizy. "We will use this information to write algorithms. We will later collect and analyze data and prepare a report after a planned field test in which a mile of the 3M cable will be strung between transmission towers in North Dakota where icing has caused sagging of conventional lines." All this work by ORNL researchers is being done as part of a cooperative research and development agreement with 3M.

"Another advantage of the advanced composite conductor lines," Kirby says, "is that they can be kept in inventory and put up faster than conventional aluminum-conductor, steel-reinforced lines to replace, for example, a 300-mile line that has been knocked down. Because they are lighter than conventional conductors, composite conductor lines can be quickly strung between temporary towers that are farther apart than the regular towers. After this emergency restoration of power, new lines can be put up on the permanent transmission towers."

SUPERCONDUCTING TECHNOLOGIES

The power grid of the future will include high-temperature superconducting (HTS) cables, which offer much less resistance to the flow of electricity than do copper lines. "A superconducting cable will conduct up to 5 times as much current as a copper cable of the same size," says Bob Hawsey, manager of ORNL's Superconductivity Program. "Because an HTS cable loses little energy as heat, it will cut electrical transmission losses in half, from 8% to 4%."

An HTS cable is more environmentally friendly than a copper cable also because it is cooled with safe, inexpensive liquid nitrogen rather than oil-impregnated paper insulation, which may leak oil. Also, it can be installed in an existing underground duct, where it is better protected against natural, accidental, or deliberate threats than are overhead lines.



In this innovative triaxial cable concept for the Southwire project, the three alternating-current phases are concentric and contained in a single cryostat, resulting in the most compact superconducting cable configuration possible.

ORNL researchers led by Mike Gouge of ORNL's Fusion Energy Division (FED) have helped Southwire Company develop an HTS cable 30 meters (100 feet) long for the company's facility in Carrollton, Georgia. The cable is made of bismuth-strontium-calcium-copper-oxide (BSCCO) first-generation wires that are chilled using liquid nitrogen. The HTS cable has provided power to the Southwire industrial complex for more than 14,000 hours. A new innovation is a "triaxial" cable design first tested at ORNL in 2001. In this concept, all three alternating-current phases of the cable system are concentric and contained in one cryostat (as shown in the illustration), resulting in the most compact superconducting cable configuration possible.

ORNL's patented technology called RABITS™ (rolling assisted, biaxially textured substrates) is being developed for a number of electrical power applications, including cables being made by Southwire Company. ORNL developers of the RABITS™ technology showed that texture introduced to metal (e.g., nickel alloyed with tungsten) by rolling and annealing it into tapes can be transferred to a superconductive oxide coating through buffer layers deposited on the metal substrate. The resulting orientation of crystals in the superconductive oxide allows it to conduct large electrical currents without resistance at liquid nitrogen temperature (77K). Industrial collaborators have made wires of this material that are longer than a meter.

ORNL researchers Bill Schwenterly, Jonathan Demko, and others also have contributed to the development of a superconducting transformer. Unlike a conventional transformer, a superconducting transformer has no oil, greatly reducing the potential for fire damage to a substation if a transformer were to fail. These researchers in FED developed an innovative, compact cryogenic cooling system for an electric transformer made by Waukesha Electric Systems and IGC-SuperPower. Waukesha's HTS transformer will be tested on the Wisconsin electric grid in the fall of 2002.

ORNL has DOE funding to work with General Electric, to develop a 100-million-volt-ampere (MVA) superconducting generator; with Southwire and American Electric Power (AEP), to develop a 300-meter-(1000-foot-) long superconducting cable to be installed at an AEP substation in Columbus, Ohio; and with IGC-Waukesha, to build a prototype, utility-sized superconducting transformer. The goal of these and other DOE-funded partnerships is to advance the introduction of HTS devices into the American marketplace.

Courtesy Waukesha Electric Systems

Location of a 3-phase superconducting transformer that will power Waukesha's factory.

IMPROVING THE GRID'S RELIABILITY, SAFETY, AND EFFICIENCY

Today more and more people are purchasing their own sources of electricity for their homes or businesses. These gas-driven microturbines, fuel cells, diesel generators, solar cells, and wind turbines, called distributed energy resources (DER), can meet owners' electricity needs.

"Providing locally based electricity generation or electricity plus heating and cooling can reduce the reliance on a centralized grid, improving security," says Mike Karnitz of ORNL's Energy Efficiency and Renewable Energy Program. "The grid becomes a less-tempting target to attack. A shift in the electrical grid to more-responsive loads with self-generation improves the resilience of the system. As a result, the vulnerability of the grid to a widespread outage is reduced."

ORNL is one of DOE's leading national laboratories for distributed energy resources (DER) and combined cooling, heating, and power (CHP) systems. At left is a microturbine, an example of a DER. Below is ductwork (being examined by Abdi Zaltash) at ORNL's CHP Integration Laboratory, which has a microturbine power source and absorption chiller designed to use waste heat from power generation to heat and cool a building. A CHP system was developed partly by ORNL at the Chesapeake Building at the University of Maryland. Widely deployed, CHP systems could dramatically improve the U.S. electric grid's efficiency.

Curtis Boles

Because DER can supply owners with even more electricity than they need, they might someday sell their excess electricity to other customers through the distribution system and power grid. But DER presents a potential safety and reliability problem. Electric utility distribution systems are not designed and protected for reverse power flow (i.e., power coming back out of a house or business, potentially causing voltage and frequency problems). Even worse, if an unexpected voltage were introduced to a transmission line being repaired, the line maintenance personnel might face a hazard. To address these problems, ORNL researchers are examining some potential technological solutions.

ORNL researchers led by ESTD's Don Adams and Leon Tolbert are proposing the development of a multilevel inverter to control power distribution and replace the transformer. This system would improve control and reliability of power flow. If excess electrical power from a microturbine could be stored in a battery until needed, the direct current from the battery could be converted by an inverter to alternating current for distribution to other users.

"Most large transformers today are designed for a specific location," Kirby says. "If a large transformer is destroyed, it might take two years to build one to replace it. If the nation were to have a stockpile of multilevel inverters, it would be easy to replace each large, disabled transformer with an inverter. The multilevel inverter would keep the transmission system functioning while a new replacement transformer is being built."

Another technology being studied is the flexible alternating-current transmission system (FACTS), a combination of large-scale power electronics devices that can control the flow of power through transmission and distribution lines.

"FACTS can control the voltage magnitude and phase angle at both ends of the line, as well as the amount of real and reactive power that is passed through the line," says Kirby. "FACTS devices could greatly increase the power-flow capacity and stability of our existing transmission lines.

"A FACTS device can block the flow of power to a line that is about to be dangerously overloaded. It reroutes the electricity to a line that has the capacity to carry the additional current. It could also direct power to another line if a transmission line is brought down as a result of a natural, accidental, or deliberate action."

The problem is that FACTS devices are too expensive to be used widely. So, ORNL researchers are looking at ways to reduce their costs. For example, ORNL researchers Orin Holland, Tony Haynes, and Darrell Thomas, all of the Solid State Division (SSD); Fang Peng, Tim Theiss, Syed Islam, and Leon Tolbert, all of ESTD, and Len Feldman of Vanderbilt University are developing and testing highly efficient power electronics modules based on silicon carbide (SiC), to replace today's silicon-based modules (including FACTS devices). The SSD researchers have made advances in materials processing and synthesis that allow fabrication of SiC devices that will take full advantage of the intrinsic properties of the material without being limited by process-induced defects found in silicon-based counterparts. Compared with silicon modules, the SiC-based electronic modules should operate more efficiently at higher temperatures, voltages, and switching speeds.

Another way to make existing transmission lines more reliable is to control power flow so that it is available to users when and where they need it—even during a fault, such as a power line brought down by a falling tree during a storm. "Electricity transmission today is done by command and control through a centralized system," says Karnitz. "A more effective approach is a layered control system in which distributed, intelligent agents in the form of computers and sensors monitor power lines and other equipment. Like captains and lieutenants reporting the latest news to a commanding general, these inexpensive agents can quickly report faults to a main computer, which could reroute power through another transmission line to avoid an outage."

A line maintenance employee could be injured by uncontrolled voltages from home-based generators.

SHEDDING ELECTRICAL LOADS DURING POWER SHORTAGES

In the winter of 2001, Californians were outraged by spikes in the price of electricity as their bills jumped 50% or more. They were also upset by rolling blackouts that shut down computers, caused traffic snarls, and left some people stuck in elevators.

On August 10, 1996, a major power outage was experienced in the electrical grid in the West, leaving 12 million Americans in nine states without electricity for up to 8 hours and costing an estimated $2 billion. August 10 was a very hot day. The demand for air conditioning and other electrical services was unusually high. The searing temperatures caused transmission lines to sag into trees, forcing the power to shut off. Fewer transmission lines were available to carry the extremely high load of electricity. As a result, the Pacific Northwest's grid was weakened, knocking out four main power highways that send electricity to other states. On that day, lights and air conditioners flicked off in homes and businesses; movie screens and traffic lights went black; factories shut down; and amusement park rides came to a stop.

Crises like these have convinced the Department of Energy that new technologies are needed to decrease price volatility and increase reliability in the U.S. electric power system. So DOE has organized a new Consortium for Electric Reliability Technology Solutions (CERTS), of which ORNL is one of four national laboratory partners.

According to a CERTS brochure, "The U.S. electric power system is in the midst of a fundamental transition from a centrally planned and utility-controlled structure to one that will depend on competitive market forces for investment, operations, and reliability management. Electricity system operators are being challenged to maintain the reliability levels needed for the digital economy in the context of a changing industry structure and evolving market rules. The economic growth of the nation is tied ever closer to the availability of reliable electricity service. CERTS was organized to conduct needed public interest research on electricity reliability technologies."

Current CERTS research focuses on prototyping and demonstrating real-time reliability management tools, developing new system security management tools, and conducting basic research and outreach related to advanced measurement technologies and controls.

How has ORNL contributed to CERTS? ORNL's John Kueck (ESTD), Kirby, and Bob Staunton (ESTD) have written a white paper for CERTS on "demonstrating load as a reliability resource."

"The idea is to make the power grid 99.99% reliable with no fluctuations, to avoid causing interruptions in the digital economy," says Kirby. "By improving the reliability of the electrical grid, we are hardening it against natural, accidental, or deliberate threats."

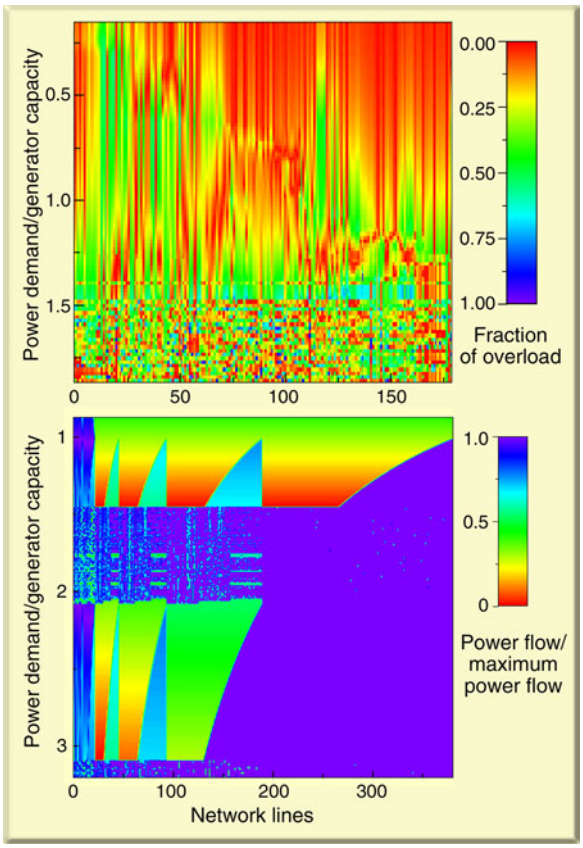
Kirby, Kueck, and Staunton are investigating the benefits of shedding loads when there's a bottleneck. According to Kueck, "Intelligent control technologies and an 'on-line' power market could be used to enable users to voluntarily control their own load in response to market conditions. The residential, commercial, or industrial users would make the decision to curtail their load, based on their own needs and the market-price incentive for reducing load.

"For example, in the summer of 2000 and the early winter of 2001, aluminum shelters shut down several afternoons a month and avoided using 100 megawatts of power in exchange for significantly reduced electric bills," Kueck says. "Aluminum companies contracted to voluntarily shut down their operations whenever the power they used was critically needed elsewhere. The 'reward' for curtailment was sufficiently attractive during times of power shortages to convince them to make this decision for themselves. This approach is much more palatable for industry than having Big Brother come along and flip the switch. The technology for such a real-time, market-and-control system exists today."

HOW VULNERABLE IS A NETWORK TO AN OUTAGE?

CERTS is also supporting research by FED's Ben Carreras and Vickie Lynch of ORNL's Computational Sciences and Engineering Division, who have been analyzing the degree to which a network is vulnerable to an outage. They are also conducting research sponsored by the National Science Foundation in collaboration with Power Systems Engineering Research Center and Alaska University.

"From our analysis of data on blackouts in the United States over the past 15 years, we have found that there is on average a blackout every 13 days," Carreras says. "We have concluded that the probability of a blackout of a given size decreases slowly as its size increases. In other words, the probability of a large blackout affecting millions of people, lasting eight hours, and representing a large loss of power is smaller than the probability of a small blackout affecting thousands of people for an hour and representing a small loss of power. However, the probability is not as small as expected. The situation is different, for instance, in South America, where blackouts are frequent but only very small. In the United States, we have some blackouts that are huge but don't happen very often."



Top: Fraction of overload for each line in a bus network as the demand for power increases. At low demand, the overloading is a continuous function of the power. When the demand for power pushes the system to its limits, power is shed and the solutions become erratic. Bottom: Stress on the transmission lines caused by a continuous increase on load demand.

The problem with the U.S. electric system is that it is overstressed, as is most of its infrastructure, Carreras says. "There is a general tendency for the demand to increase up to the limits of supply," he adds. Because the electric system is pushed to its limits, a small event such as a tree falling on a line or a few lines sagging because of the heat can trigger large cascading phenomena—the domino effect—as was the case in the August 10, 1996, power outage.

Carreras and Lynch developed a dynamic computer model that simulates the management of a U.S. electrical network that is operated close to the breaking point. The model predicts the probability that the network will have a catastrophic blackout. "The probability is lower than you might expect," he says. He suggests that a network's vulnerability to blackouts may be reduced by monitoring demand fluctuations to determine what the peak demands are and how often they occur. "This information will help determine how much generation power must be held in reserve so that peak demands for electricity can be met without bringing the system down," he says. "We are using our model to predict the need for generator reserve on a network. The information we get could suggest a need for changes in operating policy when the electrical system approaches its limits."

The software tool Carreras and Lynch developed is based on ideas from their computer model of a sand pile, originally conceived to describe the loss of energy from unstable fusion plasmas in research tokamak devices. Imagine a child dumping a bucketful of sand on top of a sand pile at the beach. When the pile gets too high, avalanches occur, and the sand particles in the center are carried to the edge. However, the slope of the sand pile remains the same. The shifting sand pile is a paradigm for "self-organized criticality," in which complex systems tend to rearrange themselves to be close to their limits, living at the edge of chaos.

Methods of self-organized criticality can also provide insight into the vulnerability of complex systems such as power grids. This approach can allow researchers to identify the electrical networks that are the most vulnerable to failure in the event of a natural, accidental, or deliberate action.

For large electrical grids, a blown transformer circuit could cause the rerouting of power, possibly overloading an alternate transmission line. To improve the reliability of power distribution and prevent major blackouts, it might be necessary to perturb the system a little, say, by occasionally manipulating circuit breakers to see if the system responds in a healthy or unhealthy way. But Carreras still has more work to do with his model to determine if periodic testing of an electrical network by slightly perturbing it is a good idea.

"Simple solutions to a small problem can cause a much bigger problem that is not anticipated," he says. "In an overstressed network, the probability increases that a small event—like adding a control system, cables, or relays—can make large, cascading events more likely. A small change to a complex system can backfire on you. It also can give you more confidence that you are in control so you are less vigilant and more likely to overlook other, emerging problems that could bring the system down."

ORNL is helping the U.S. electrical industry transform today's transmission system into the power grid of the future.

Improving the Global Standard of Living: Aid From ORNL

Courtesy of Tim Ensminger

ORNL researchers are conducting the first assessment of climate change impacts on the coastal city of Cochin, India, whose backwaters are shown here.

ORNL has been a leader in helping to meet energy and environmental challenges in developing countries for 20 years. This role contributes to reducing the threat of terrorism by addressing many of the roots of terrorism.

Terrorism is generally rooted in perceptions of unfairness, often reflecting feelings in developing countries that their citizens lack economic and social opportunities that are available to others and that peaceful mechanisms for change will not give them satisfactory relief. Poverty is one of the roots of terrorism, and one reason for poverty is a lack of abundant, reliable, and affordable energy services. But poverty alone is not the sole source of the problem, neither is its eradication the ultimate solution. As the events of September 11, 2001, showed, some terrorists are educated and come from upper middle-class families. To address the issues at the root of terrorism, we must also look for ways to assure productive lives for people as they move up the development ladder; and, again, their access to sustainable and affordable energy services is a key.

"Providing energy services is essential to job creation, and energy is the engine that drives economic development," says Thomas J. Wilbanks, an ORNL corporate fellow in the Environmental Sciences Division (ESD). He has led efforts to provide technical assistance to help many countries address their energy and environmental challenges.

For 20 years Wilbanks and his ORNL colleagues have been providing guidance and assistance in energy and environmental problem-solving to 40 nations in Asia, Africa, Central America, the Middle East, and Eastern Europe. The U.S. Agency for International Development (USAID) has supported many of the 70 projects that ORNL has been involved with in these nations.

"Of all the Department of Energy's national labs," Wilbanks says, "ORNL has the most diversified program of research and technical assistance related to energy and environmental needs in developing countries and countries in transition—from the world's poorest countries, such as Liberia, Haiti, Bangladesh, and Sudan, to such high-priority countries and regions as India, China, the former Soviet Union, the Middle East, Central America, and the Caribbean. One national lab promotes renewable energy and another promotes energy efficiency in these developing nations. ORNL is different. Working with local counterparts in each nation, we try to help them determine which energy and environmental pathways make sense for them, considering the whole range of possible strategies."

In the wake of the terrorist attacks on the United States on September 11, 2001, Wilbanks believes that international assistance by the U.S. government (including ORNL) is important for a combination of three reasons: Security, trade, and sustainable environmental management.

SECURITY

It is important that diversified energy sources be put into place in both developed and developing countries, Wilbanks says, so that these nations will be less dependent on oil. Using oil as the chief energy source has several problems: The price can increase dramatically; the source may be unstable in times of war and political conflicts; and the supply may be interrupted by terrorists. Half the oil used in the world comes from Saudi Arabia, the birthplace of 15 of the 19 September 11 terrorists. According to Wilbanks, Japan imports oil and liquefied natural gas from the Middle East to meet many of its energy needs, and it shares a U.S. concern that terrorists might act to interrupt vital energy supplies. Moreover, diversified, clean energy sources are a key element of a strategy to provide sustainable energy services for development over the long run, which contributes to security by shrinking the roots of terrorism.

TRADE

Energy markets in the developing world are one of the most rapidly growing export opportunities in the world. It has been estimated that the total market for clean energy technologies might be more than $200 billion per year by 2015. In order to provide jobs and keep the U.S. economy strong, it will be important to increase our market share

Tim Ensminger

Energy is the engine that drives economic development, which leads to productive jobs for young people, making them less attracted to terrorism.

where the share is currently low and to maintain the market share while the market size increases where our current share is high.

"America needs to be competitive in global energy markets by offering affordable energy products and services that meet the needs of both developing and developed countries." Wilbanks says. "For example, in the 1990s ORNL aided the introduction of energy-efficient refrigerators to India that are suitable for Indian people's homes. As another example, our nation should develop and market clean energy technologies that meet the special needs of tropical countries. Examples are solar cooling devices, diesel generators that work in high heat and humidity, and green buildings that make sense under those conditions."

One important source of information that helps promote worldwide sales of commercially available energy products and services is the Internet-based Green Technologies Information Exchange (GREENTIE). Under program leadership by Marilyn Brown (director of ORNL's Energy Efficiency and Renewable Energy Program) and Melissa Lapsa of ORNL's Engineering Science and Technology Division (ESTD), ESD's Sherry Wright maintains the U.S. part of the GREENTIE database. This database provides information on companies and suppliers of more than 100 technologies whose products or services reduce greenhouse gas emissions. A current ORNL activity focused on trade but relating all three priorities is supporting the development of a Clean Energy Technology Exports (CETE) Program, which has been proposed by the U.S. Senate and supported by the Bush administration. ORNL researchers led by Wilbanks have helped DOE and eight other responsible agencies draw up a strategic plan for CETE, which was submitted to Congress in March 2002.

ENVIRONMENTAL MANAGEMENT

The Bush administration has opposed ratification of the Kyoto Protocol to reduce climate-altering greenhouse gas emissions to below 1990 levels, both because such a reduction would hurt the U.S. economy and because the Protocol does not address growing emissions from major developing countries.

"The President believes that rapidly developing countries, such as China and India, should reduce their use of coal to address their growing emissions of greenhouse gases," Wilbanks says. "The United States must build positive relationships with China, India, and other countries to help them find clean energy pathways without asking them to sacrifice their own economic growth."

Environmental pressures and stresses, including those related to climate change, can result in situations that drastically overtax the financial resources of a region, thus leading to an impoverished standard of living among the region's inhabitants or exacerbating existing levels of poverty. The extended drought in Afghanistan is a familiar example. It has made a poor country poorer. As a result, Afghanistan became more receptive to terrorist groups that bring in money, and farmers there turned to raising opium poppy crops to increase their income. Afghanistan was seen by the United States as a threat because it harbored terrorists and exported illegal drugs.

In a number of USAID projects, ORNL researchers have worked on the environmental side of the development process. For example, in the 1990s they worked in Guatemala, where the largest rain forest north of the Amazon was being cut down because of pressures for economic development. Such deforestation threatened the survival of several endangered species and was eliminating a key "sink" for atmospheric carbon dioxide. Under the leadership of ORNL's Keith Kline (ESTD), USAID, ORNL, and others helped Guatemala reduce its rate of deforestation so effectively that USAID rated this project their most effective environmental project in the world.

ORNL researchers are now conducting the first assessment of climate change impacts on a city in a developing nation. They are studying Cochin, India, a coastal city that could suffer significantly from changes in precipitation quantity and intensity and from a rise in sea level. This project is expected to produce an Internet-accessible approach that will help cities in developing countries perform self-assessments of their vulnerabilities to climate change impacts.

In a project funded internally by ORNL's Laboratory Directed Research and Development Program, Wilbanks, Paul Leiby (ESD), and Bob Perlack (ESD), working with Tim Ensminger (ESD), Sherry Wright, and Stan Hadley (ESTD), have developed a computer model that integrates analyses of costs and benefits of climate change avoidance and adaptation pathways. The model anticipates growing policy attention to adaptation as a way to respond to concerns about climate change impacts.

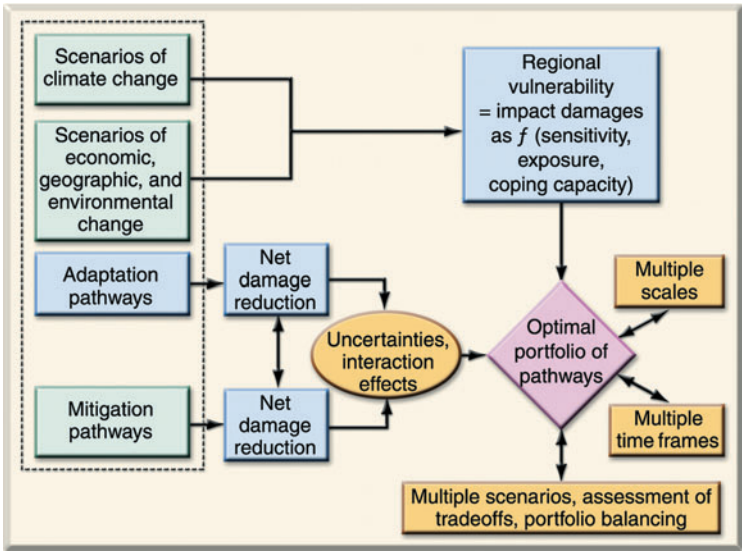
In a talk on integrating mitigation and adaptation as global climate change response strategies at the February 2002 annual meeting of the American Association for the Advancement of Science in Boston, Wilbanks said, "Adaptation has become an important strategy to reduce a region's vulnerability to climate change impacts. Examples include better management of river systems to deal with both drought and heavy precipitation, as well as changes in building codes in coastal areas and floodplains to make houses more flood resistant." But, Wilbanks noted, adaptation is unlikely to take care of all climate change impacts, especially in developing countries, natural ecosystems, and possible instances of abrupt major climate changes.

Tim Ensminger

Low-lying areas on the coasts of developing countries are vulnerable to climate-change impacts such as sea-level rise and changes in storm tracks and intensities.

The Oak Ridge Climate Impact Response Model examines the possibility that global mitigation strategies will be needed for low-lying islands and coastal towns in developing countries for which a rise in sea level could be devastating, while adaptation strategies may be preferable in many other regions. "Common sense tells us that the national and global response to concerns about climate change should include attention to both mitigation and adaptation," he says. "But integrating the two paths is a considerable challenge."

In conclusion, Wilbanks says: "Climate change may increase environmental stresses, such as flooding and drought, that could bring more poverty and trigger terrorism, so efforts should be made to slow climate change and improve capacities to cope with it. In this connection and many others, clean energy systems that reduce greenhouse gas emissions are a key to the kinds of sustainable development that will be needed to make the world a happier and more secure place to live."



Graph by Judy Neeley & Gail Sweeden

The Oak Ridge Climate Impact Response Model compares costs and benefits of adaptation and mitigation pathways and identifies "optimal" combinations of pathways at different scales.

OAK RIDGE NATIONAL LABORATORY *REVIEW*
P.O. Box 2008, Oak Ridge, Tennessee 37831-6266

Thanks to funding from the Department of Energy's Office of Fossil Energy, ORNL and Idaho National Energy and Environmental Laboratory (INEEL) are participating jointly this summer in a ship cruise to recover and analyze sediments containing methane hydrates, a potential fuel source. The research cruise, which is being organized and led by the U.S. Ocean Drilling Program, will focus on collecting geophysical and geochemical data, as well as hydrate-bearing sediment samples from the Cascadia accretionary margin off the Oregon coast. From July through September 2002, an INEEL scientist collaborating with ORNL researchers will be aboard the D/V *JOIDES Resolution* ship (shown here). The *D/V JOIDES Resolution* is a uniquely outfitted, dynamically positioned, scientific research drill ship with a floating laboratory; since 1985 it has been used to investigate the earth's origin and evolution through worldwide ocean coring. Some methane hydrate samples extracted from near the ocean floor will be brought back from the ship and sent to ORNL for study and for comparisons with methane hydrates produced in ORNL's seafloor process simulator. (See article on "Methane Extraction and Carbon Sequestration" starting on p. 4.)

Photograph of the* D/V JOIDES Resolution *ship provided courtesy of the Joint Oceanographic Institutions for the Ocean Drilling Program under the sponsorship of the National Science Foundation.