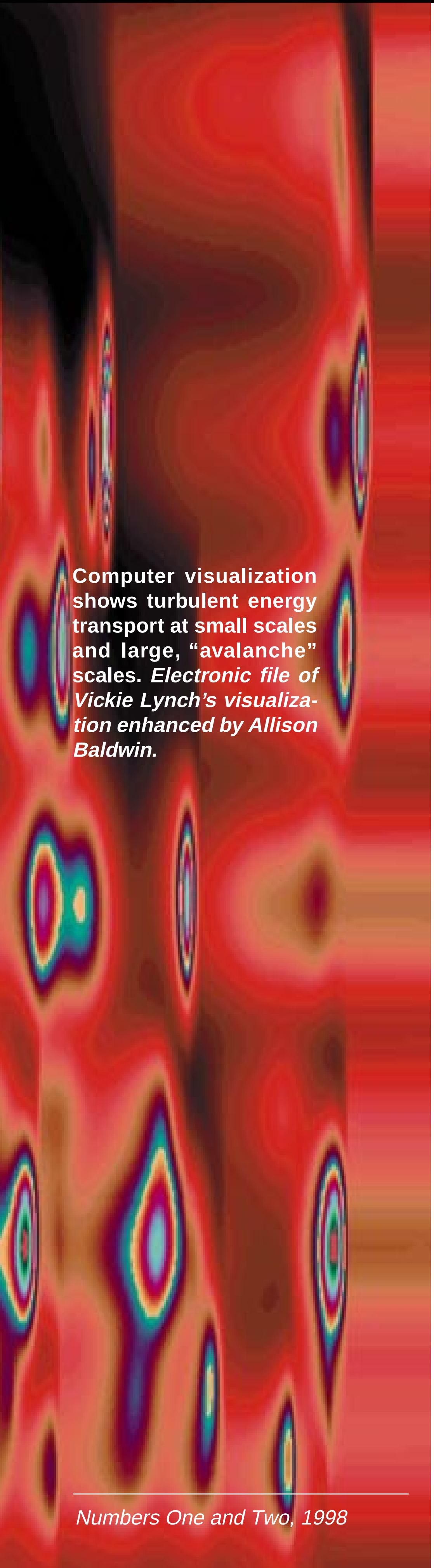
Energy Production and End-use Technologies

Clean, efficient, safe production and use of energy have long been goals of ORNL research and development. At first our focus was fission energy. Then we started research efforts in fusion, fossil, and renewable energy as well as energy efficiency. Among our achievements in 1997 were collaborations with industrial organizations to develop a high-temperature superconducting cable for underground power transmission and a high-temperature superconducting transformer for industry. In the area of transportation, we helped determine the effectiveness of novel catalysts in reducing nitrogen emissions from highly efficient diesel cars of the future. In fusion energy research, we found success and gained recognition at the White House for using the model of a sandpile to better understand and control fusion plasma turbulence and energy losses.

ORNL is one of the world's premier centers for R&D on energy production, distribution, and use and on the effects of energy technologies and decisions on society. As a primary performer of DOE-sponsored R&D in energy efficiency, ORNL applies distinguishing capabilities in materials science, biotechnology, engineering, and technology development and evaluation to transportation systems, biofuels, efficient buildings and building materials, industrial processes, and utilities.

ORNL research on energy technologies applies the Laboratory's strengths in physics and engineering to the improvement of existing systems and the development of new science and technology. Unique facilities for energy-related R&D are used both for technology development and for fundamental investigations in the basic energy sciences that underpin the technology work. ORNL's scientific, engineering, environmental, economic, and social science expertise is integrated to supply the information needed in making decisions that ensure a sustainable energy future.



Computer visualization shows turbulent energy transport at small scales and large, “avalanche” scales. *Electronic file of Vickie Lynch’s visualization enhanced by Allison Baldwin.*

A Sandpile Model for Fusion Plasmas

ORNL is using the model of a sandpile to better understand and control fusion plasma turbulence and energy losses.

To get electricity from a fusion reactor, you must heat charged particles (hydrogen nuclei) in a plasma to a high enough temperature and hold them close enough together using magnetic fields for a long enough time. If you do achieve the right plasma temperature, density, and confinement time, the hot nuclei will overcome their natural repulsion and fuse. Such fusion reactions release enormous amounts of energy that can be converted to electricity. But the energy required to sustain fusion reactions is often transported rapidly from the center of the plasma to the edge where it is lost. This undesirable loss of heat is caused by turbulence, the irregular fluctuations in plasma velocity and pressure brought on by the various mechanisms used to heat the plasma.

To better understand turbulent transport processes in fusion plasmas in the hope of controlling them, ORNL researchers Ben Carreras and David Newman are using an unusual model—a pile of sand. Imagine a child dumping a bucketful of sand on top of a sandpile at the beach. When the pile gets too high, it flattens out as avalanches occur, and the sand particles in the center are carried to the edge. The sandpile, a paradigm for self-organized criticality in which complex systems tend to rearrange themselves in a highly chaotic fashion, works especially well as a model for fusion in tokamaks, devices shaped like beach inner tubes. Hot particles pile up in the plasma center as the density and temperature peak, but the turbulence acts like sandpile avalanches, transporting hot particles from the center to the edge.

This new way of understanding turbulent transport processes in fusion plasmas offers possible explanations for universal transport behavior observed in many fusion experiments. These explanations in turn suggest techniques for controlling the performance of these experiments, making fusion as a future energy source more likely.

It was thought that hot particles move from plasma center to edge in random steps, like a staggering drunk. That suggested that the larger the tokamak fusion machine, the longer it would take for hot particles to carry their energy to the plasma edge. Experimental results, however, refute the theory that energy confinement time will be longer if the tokamak is larger. The results instead indicate that, if left uncontrolled, the transport of energy increases with size.

To minimize damage from large avalanches in a sandpile, the best solution is to perturb the sandpile a little, causing only small avalanches. In fusion plasmas, the way to minimize turbulence and its associated eddies is to introduce a radial electric field to apply a sheared flow to the plasma. Each eddy spanning the shear flow is forced to twist more in one direction so it can more easily “eat” its neighbor, causing a decrease in the size and connection of the eddies that can reduce the heat and particle loss. Experiments, in fact, show that when a shear flow is applied, energy transport is minimized and confinement of hot particles improves with tokamak size.

The principle of sandpile perturbations is also being applied to other situations. For example, synchronizing traffic lights to increase traffic flow may actually increase the chances of gridlock if a car blocks a lane because of a flat tire or a collision. Sandpile models suggest it might be better not to synchronize lights but, rather, create little, spaced-out traffic jams to decrease the probability of a larger jam later.

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.

For his work in applying the sandpile model to fusion energy, David Newman received a Presidential Early Career Award for Scientists and Engineers at the White House.

The work was sponsored by DOE’s Office of Energy Research, Office of Fusion Energy Sciences.

ORNL Helps Design Superconducting Transformer

ORNL is working with several organizations to design a high-temperature superconducting transformer for industry.

As utilities replace aging and obsolete equipment, one improvement in the next 5 to 10 years is likely to be the high-temperature superconducting (HTS) transformer. This device, chilled by liquid nitrogen or a refrigerator, will offer several advantages over traditional paper-oil-insulated transformers wound with copper wire.

Transformers are needed at substations and on utility poles to step down high-transmission voltages and raise the current to levels needed for factories, offices, and homes. A transformer consists of two separate coils of insulated wire with different numbers of turns wound on an iron core. The alternating-current (ac) magnetic field created in one coil induces a current in the other coil in proportion to the number of turns. Coil windings are the source of more than 80% of the transformer's energy losses. Thus, DOE has long sought to develop more energy-efficient transformers.

Ben McConnell (left) and Bill Schwenterly shake hands to celebrate the ORNL team's success in completing the cryogenic winding assembly for the prototype 1-MVA superconducting transformer now being tested by Waukesha Electric Systems.

Unlike copper, HTS wires have no resistance to electrical flow. Hence, HTS transformers can greatly reduce heat losses in utility power systems and cut requirements for power generation. (Today's power transformers account for 50% of transmission system losses.) Because oil is a fire hazard and a potential contaminant whereas liquid nitrogen is nonflammable and environmentally benign, HTS transformers will be safer and more environmentally acceptable. In addition, HTS units do not require sprinkler systems and oil-containment devices, weigh less, and require less space, making them ideal for congested cities.

Today's transformers have reduced lifetimes if operated in an overload condition because their insulation is degraded by heat from fault currents and high continuous loads. Therefore, they are typically operated at less than 70% of their full capacity. In contrast, HTS transformers can take both momentary fault currents and continuous operation at their full rated capacity without damage. Using additional refrigeration, they can also accommodate continuous overloads without damage.

ORNL researchers are working with several organizations under a cooperative research agreement to help design an HTS substation transformer that will be acceptable to industry. Studies conducted by the team indicate that over its expected lifetime of 30 years, an HTS transformer's greater energy efficiency can more than pay for increased initial capital costs that arise from the more expensive conductor materials and the refrigeration needed to cool the coil to superconducting temperatures. Both the electric utility and manufacturing industries are seen as potential markets.

ORNL and its partners have built a 1-million-volt-ampere (1-MVA) prototype superconducting transformer that transforms 75 amps at 13.8 kilovolts to 150 amps at 6.9 kilovolts. The prototype is being tested at Waukesha Electric Systems in Wisconsin. Intermagnetics General Corporation near Albany, New York, helped design the cryogenic equipment, manufactured the superconducting coils by winding coils of wire (bismuth-strontium-calcium-copper oxide, or BSCCO-2212, on silver tape) on fiberglass forms, and shipped them to ORNL in January 1997. Waukesha Electric Systems provided the core, the bushings, and the vacuum tank. The utility partner, Rochester Gas and Electric Company in Rochester, New York, provided the utility perspective on many issues, such as the magnitude of fault currents and alternative methods of cooling (e.g., storing occasional truckloads of liquid nitrogen vs cooling with local refrigeration). The team also completed an economic analysis and preliminary commercial designs aimed at a 30-MVA rating.

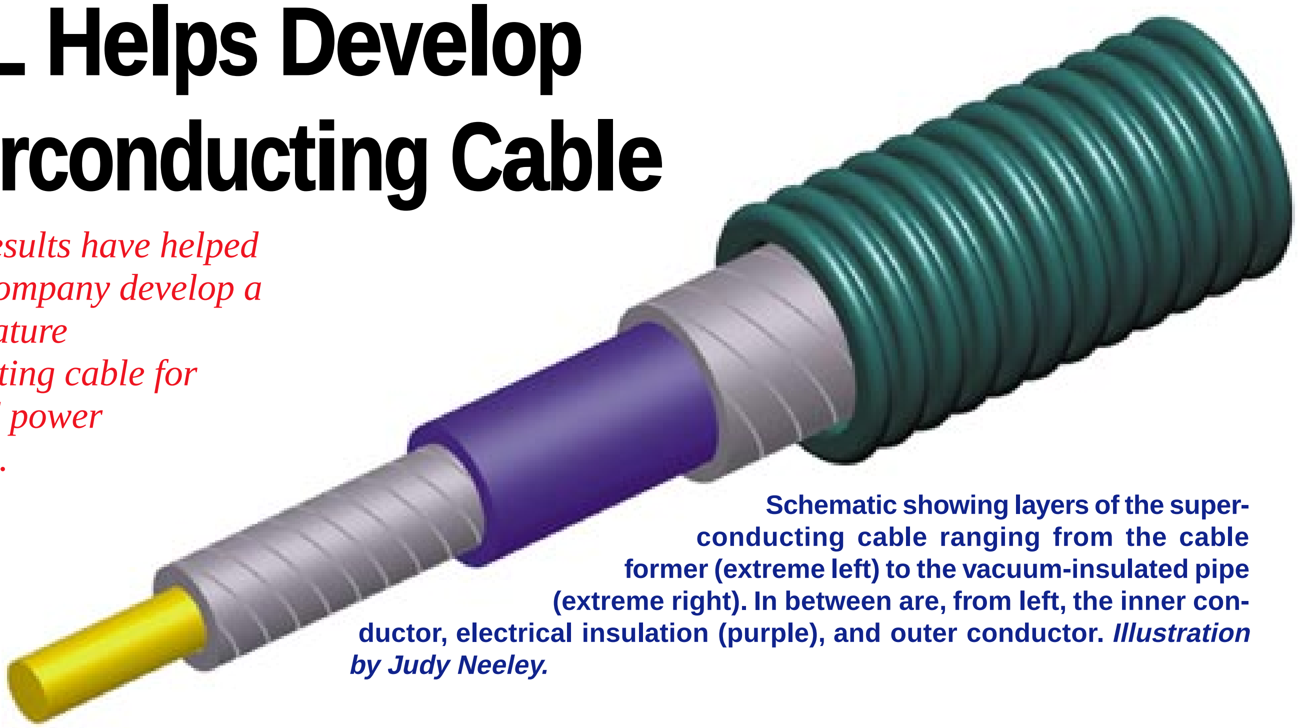
Because it is not beneficial to cool the iron core to the operating temperature of the coils, ORNL researchers designed a cryogenic suspension and cooling system to thermally isolate the chilled coil windings from the room-temperature laminated iron core. They assembled the bulk of the transformer, including the coils and their cooling piping, cryogenic suspension, 30-watt cryocooler, stainless-steel shield, and liquid-nitrogen tank.

The HTS transformer is likely to be more acceptable to utilities than low-temperature superconducting transformers developed in the 1970s and 1980s using helium-cooled niobium-titanium coils. Liquid helium is 100 times more expensive than liquid nitrogen, and these early devices could not handle fault currents properly. Today, utilities are offering warm support for the latest efforts toward developing the next generation of superconducting transformers.

The project was funded at ORNL by the DOE Superconductivity Program for Electric Systems.

ORNL Helps Develop Superconducting Cable

ORNL test results have helped Southwire Company develop a high-temperature superconducting cable for underground power transmission.



Schematic showing layers of the superconducting cable ranging from the cable former (extreme left) to the vacuum-insulated pipe (extreme right). In between are, from left, the inner conductor, electrical insulation (purple), and outer conductor. *Illustration by Judy Neeley.*

A shift in the "underground power structure" in large cities may be around the corner. Electrical power delivered underground in cities normally flows through traditional copper cables in 20-centimeter ducts. But as these aging cables need to be replaced, utilities may be attracted to high-temperature superconducting (HTS) cables in the next decade. Here's why.

An HTS cable offers very little resistance to electrical flow, so it loses little energy in the form of heat during transmission. Thus, a superconducting cable carries three to five times as much electrical current as a traditional copper cable the same size. Utilities can use existing rights-of-way and ducts for new HTS cables. Superconducting cables are more environmentally friendly because they are cooled with safe and inexpensive liquid nitrogen rather than by oil-impregnated paper insulation, which sometimes leaks oil.

The demand for underground HTS cables that can carry double the current of conventional copper cables is expected to grow into a multimillion dollar industry between 2005 and 2020 for several reasons. New construction techniques will cut the costs of installing underground transmission cables as securing rights-of-way for overhead lines becomes more difficult. Underground cables are safer than overhead lines and, because they are hidden, do not contribute to visual pollution. Because fewer superconducting cable circuits are needed to transfer power, they will take up less space and will be easier and cheaper to install. HTS cables also will be able to transmit alternating current (ac) much longer distances than underground copper cables, which are limited to less than 20 miles because of the cable capacitance.

A dozen ORNL researchers are helping Southwire Company in Carrollton, Georgia, design a first-generation, high-temperature superconducting cable that may be used for underground transmission in metropolitan areas and over long distances. In its fusion energy facilities, ORNL has tested nine 1-meter-long HTS cables manufactured by Southwire to determine the amount of current they can carry and the extent of ac losses (based on heat generated, as measured by thermocouples). In another ORNL lab, researchers are testing the ability of the cable's electrical insulation to withstand lightning strikes and switching surges at liquid nitrogen temperatures and pressures; they measured the voltage levels at which holes are punched in the insulation so they could determine the maximum voltage levels that must be accommodated in the design to reduce the risk of short circuits. Results of the ORNL tests have influenced the final cable design.

The HTS cable consists of tapes made by packing bismuth-strontium-calcium-copper oxide (BSCCO) powder in silver tubes and stretching and flattening the tubes into tapes. Southwire has teamed with Intermagnetics General Corporation in New York to develop these BSCCO tapes. ORNL researchers have been measuring the critical current of the BSCCO tapes and the effect of strain tolerance upon the critical current.

The cable is made on a hollow tube called cable former through which liquid nitrogen flows (see figure above). Southwire plans to use a 38-millimeter former over which HTS tapes will be wrapped to make the inner conductor, which carries the cable's electricity. The wrapped tube is surrounded by Southwire's proprietary electrical dielectric tape, called Cryoflex. This electrical insulation is wrapped in BSCCO tapes to form the shield conductor, which prevents external magnetic fields (say, from parallel cables) from destroying the inner conductor's superconducting properties. The outermost part of the cable is the vacuum-insulated pipe, providing thermal insulation to keep the inner temperature of the cable near 77 K.

After ORNL completes a variety of tests of 5-meter-long HTS cables in a single facility in 1998, Southwire will install a 30-meter (100-foot) cable to provide power from its local utility to two manufacturing plants at its Carrollton complex. The 12.5-kilovolt, 1250-ampere HTS cable will be demonstrated by the end of 1999. If officials of electrical utilities like what they see, our infrastructure may soon be wired in a different way to bring power to the people.

The project is funded by DOE's Office of Energy Efficiency and Renewable Energy, Office of Utility Technologies.

Prototype catalytic converter installed in engine test cell at Advanced Propulsion Tech Center. *Digital image enhanced by Allison Baldwin.*

Studying NO_X Catalysts for Efficient Cars

ORNL is helping to characterize novel catalysts and their effectiveness in reducing nitrogen oxide emissions from highly efficient diesel cars of the future.

The lean, clean car of the future proposed by the U.S. Partnership for a New Generation of Vehicles (PNGV) may have an improved diesel engine. This compression-ignition, direct-injection (CIDI) engine today uses 35 to 40% less fuel per mile than gasoline-burning, spark-ignition engines typical of most cars. Because PNGV's goal is to design and produce a car by 2004 that has a fuel efficiency of up to 80 miles per gallon, the CIDI engine is a prime candidate for this vehicle. A second DOE program seeks to clear the way for diesel engines to be used in light trucks and sport utility vehicles to improve their fuel economy by over 35%.

The challenge of today's diesel engines is their high emissions of nitrogen oxides (NO_x) and particulates. NO_x is undesirable environmentally because it contributes to the formation of smog and acid rain. Diesels present a particular NO_x dilemma because their lean-burn operation is incompatible with today's highly effective exhaust aftertreatment catalytic converters that eliminate about 90% of the NO_x from today's cars. Hence, a new type of exhaust catalyst system is needed.

DOE national laboratories (including ORNL) are helping to develop new NO_x control systems specially suited to the diesel engine. They are working with Chrysler, Ford, and GM (through the United States Council for Automotive Research, or USCAR), as well as diesel engine manufacturers, such as Cummins and Detroit Diesel Corporation, under cooperative research and development agreements (CRADAs). Ron Graves has led ORNL's development of CRADAs with engine manufacturers that complement our work with the auto companies.

The search is on for a catalyst that selectively adsorbs NO_x from the exhaust gases passing through the catalytic converter and then chemically reduces the NO to N_2 in an oxidizing atmosphere. For the diesel-propelled car or truck, the new catalyst systems may incorporate either precious metals or metal oxides.

Our role is to apply broad analytical and experimental capabilities to evaluating the performance of the new catalysts. Using electron microscopes, our materials scientists are characterizing the microstructures of these catalysts (e.g., the spatial distribution of platinum atoms or the movements of rhodium atoms) to better understand how they perform. Our engineers, chemists, and physicists at the Advanced Propulsion Tech Center (at the Oak Ridge Y-12 Plant) are identifying and quantifying the constituents of diesel engine exhaust before and after it passes through the catalytic aftertreatment device. Gas chromatography, mass spectrometry, and Fourier transform infrared spectroscopy are used to determine if a test catalyst effectively removes NO_x from the exhaust. One finding is that, for diesel fuel, precious-metal catalysts work well below the desired temperature and metal-oxide catalysts work well above the desired temperature, suggesting that the best aftertreatment may involve the combined use of both catalyst types.

At the ORNL diesel engine test stand, researchers are studying the hydrocarbons from the engine's unburned diesel fuel that may enhance the catalyst's performance. The hydrocarbons react with the nitrogen oxides, converting them to nitrogen, carbon dioxide, and water vapor. ORNL researchers are evaluating techniques that may enable the introduction of the right hydrocarbons to the exhaust system at the right time to optimize the performance of the chosen catalyst.

For the PNGV work, ORNL researchers led by Ralph McGill and their partners from other DOE laboratories and industrial firms received a PNGV Award for technical accomplishment and teaming for lean-burn NO_x catalyst research. But the best prize will be the development in time of a near-zero-emission, energy-efficient car.

The research has been funded by DOE's Office of Energy Efficiency and Renewable Energy, DOE's Defense Programs, and our CRADA partners.

Norberto Domingo and Karren More discuss the ability of the materials in the aftertreatment device catalyst (held by Domingo) to remove nitrogen oxides from diesel engine exhaust. *Photograph by Tom Cerniglio.*