OAK RIDGE NATIONAL LABORATORY

REVIEW

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

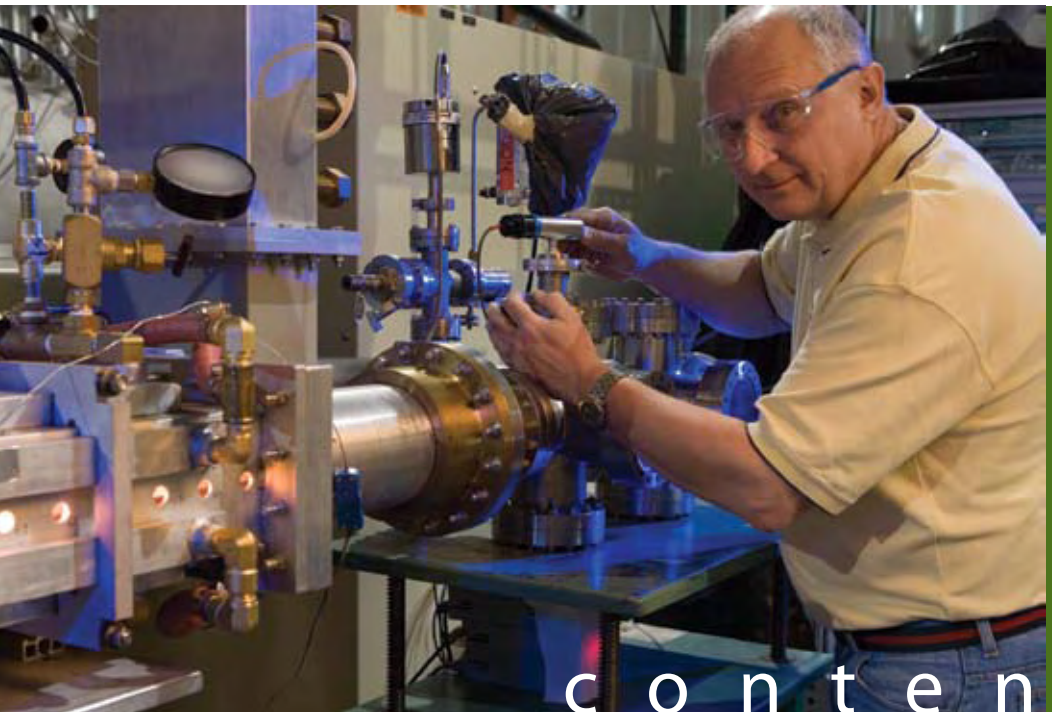
Vol. 40 • No. 2 • 2007
www.ornl.gov/ORNLReview

Greening THE REAL WORLD

Zero Energy Homes

no kidding!

OAK RIDGE NATIONAL LABORATORY
REVIEW
• MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY •
Vol. 40, No. 2, 2007



contents

on the cover

The Lenoir City Habitat for Humanity neighborhood where Oak Ridge National Laboratory has been testing energy-efficient technologies.

ENERGY SOLUTIONS
FOR The Real World

At Oak Ridge National Laboratory, we like to think our mission is "solving the big problems." Increasing numbers of Americans believe that finding lasting solutions to the nation's "energy problem" may be the Laboratory's most daunting and important scientific challenge of the next decade. One can say without hyperbole that the stakes—economic growth, environmental sustainability, even national security—are profound.

In scientific terms, the broad category of "energy" encompasses a variety of disparate activities that involve our daily lives, including the cars we drive and the homes and buildings in which we live and work. The need to develop a comprehensive suite of energy-efficient technologies makes impractical the notion of a solitary dramatic breakthrough or "silver bullet" solution that will generate adequate energy savings. In the same way that obesity cannot be solved by a single pill without diet or exercise, America's appetite for energy cannot be quelled with a single technology that ignores current habits of energy consumption. We use energy in lots of ways, and it will require lots of new ideas to fashion a collective solution for government, business and individuals.

Combining a host of cutting-edge technologies with "out-of-the-box" thinking, ORNL researchers are seeking creative ways to generate these sustainable energy solutions. In this quest, they are guided by a fundamental principle—that the solutions must be applicable to the lives of average Americans. The research required to build a zero-energy house is a wasted investment if the house requires a million dollars worth of gadgets to lower energy costs. Similarly, building a car in the laboratory that gets 90 miles per gallon is pointless if the car's lightweight materials make it unaffordable to the general public. In other words, new energy solutions must be designed for the real world, practical to manufacture and affordable to the majority of American consumers.

This issue of the *Review* is dedicated to energy solutions designed at ORNL for the real world. The theme is captured in the issue's cover image of "zero-energy" homes built for Habitat for Humanity through a partnership of ORNL and the Tennessee Valley Authority. Constructed for about $100,000, the homes use an innovative combination of insulation, solar panels, energy-efficient appliances and innovative heating and air conditioning systems to produce a daily energy cost of only 40 cents. The goal, quite literally, is an affordable home by 2020 that could generate more energy than it consumes.

From cars made of new lightweight carbon fibers instead of steel to modern buildings illuminated by hybrid solar lighting, the Department of Energy has joined with ORNL researchers in a commitment to transfer the discoveries of the Laboratory to commercial products that can both save energy and provide Americans, regardless of income, a chance to sustain their quality of life. In the Buildings Technology Center, the High Temperature Materials Laboratory and the National Transportation Research Center, the challenge to discover new energy solutions at ORNL is undertaken without moral prejudice or an attempt to assign blame. Rather, the researchers are guided by the knowledge that their efforts will be part of what may prove to be the new century's most critical scientific undertaking.

They are, indeed, solving America's "big problems."

Dana Christensen
Associate Laboratory Director
Energy and Engineering Sciences

A GLIMPSE OF THE ENERGY FUTURE

Buildings offer the greatest opportunity for energy conservation.

The cul-de-sac of 40 small houses is everything you might expect in American suburbia. Minivans sit parked in perfectly proportioned driveways. Clumps of kids ride bikes around the neighborhood. Dogs bark behind backyard fences. A nearby four-lane drones in the background. What is not so obvious is that this tiny community offers a peephole to the future—a future in which homes will generate and conserve as much energy as they require.

Most of the time, even resident Kim Charles does not notice the solar panels on her roof, the whisper of her SEER 17 heat pump water heater, the airtight, moisture-managed construction of structural insulated panels, the integrated design that allows most of the home's plumbing to reside within one wall, saving precious energy.

What Charles does notice is a power bill that amounts to less than a daily cup of coffee. Thanks to a 15 cent-per-kilowatt-hour credit paid by the Tennessee Valley Authority for electricity piped back to the power grid, her meter literally runs backwards on sunny days. In 2006, she paid an average of 41 cents per day for electricity.

Charles's home is among five in this Habitat for Humanity community located in Lenoir City, Tenn., and outfitted with the latest in energy-saving technologies as part of a research project designed and implemented by Oak Ridge National Laboratory and co-funded by the Department of Energy and the Tennessee Valley Authority. The project serves as linchpin in a broad array of research programs at ORNL that strive to address America's most energy-inefficient sector: buildings.

Appetite control

Americans work, live and play in boxes of brick, wood, glass, steel and concrete—artificial environments typically kept at constant temperature and lighting levels regardless of season or time of day and notwithstanding the presence or departure of the occupants. The results are obvious. In the United States, buildings command 40% of the nation's overall energy use, ranking above both industry, at 32%, and transportation, at 28%. Buildings demand 71% of domestic electric power in the U.S. and 55% of the nation's natural gas—and produce 43% of U.S. carbon emissions.

"Creating more energy-efficient buildings is not only part of the overall solution but is the number one most cost-effective opportunity to reduce the nation's energy consumption and affect climate change," says Jeff Christian, a buildings technology researcher at ORNL and coordinator of the Habitat for Humanity project. "Yes, we must replace oil with biofuels. Yes, we must pursue other supply-side solutions in an environmentally acceptable manner. But there is enormous potential to reduce energy

demand in the buildings sector, and that is by far the cheapest solution if we really want to address this problem."

Because the nearly 5 million commercial buildings and 112 million households use a collective 38.8 quadrillion BTUs of energy each year, curtailing consumption is a tall order but has enormous potential. Space heating and cooling and ventilation demand most of that power, followed closely by lighting, then water heating. Refrigeration, electronics, computers and other items add up to their own significant and growing slice of the energy pie.

Buildings' appetite for energy has been on the rise as a result of natural population growth and related development of homes, apartment complexes, shopping malls, schools, office buildings and healthcare facilities. The amount of energy required for each person occupying those buildings is climbing as well. Residential floor space per capita in the U.S. is growing, driven by construction of larger homes as well as a decline in the average number of occupants, and the number of power-hungry accoutrements to be found in today's households—from computers to video games to plasma televisions—is on the rise. As a result, residential energy consumption, unless aggressively addressed, is expected to grow 1% per year until 2025.

On the commercial side, energy use is projected to increase an average annual rate of 2% between now and 2025, driven primarily by use of computers and other office equipment. Such growth has placed stress on aging infrastructure, which, coupled with weather incidents that include the feisty tornado and hurricane seasons and record-breaking heat waves of recent years, result in periods of peak demand and power outages that hamper business and boost energy costs. Soaring prices for natural gas and petroleum also contribute to the problem, and experts believe this combination of factors has created a critical mass, driving the nation toward long overdue adoption of energy-efficient technologies and construction practices.

"If we continue to construct the same kind of inefficient buildings that put high demands on the power grid, we will have to build additional supply-side infrastructure to serve them," says Patrick Hughes, leader of ORNL's buildings technology research program. "What we need is to fundamentally change the way we approach the construction and operation of our buildings. If done right, we, as a nation, can have our cake and eat it too. We can spend less going forward on buildings and supply-side infrastructure and vastly reduce the energy consumption and climate-changing emissions of the built environment."

ORNL researchers are supporting a DOE initiative to develop affordable, net-zero-energy housing by 2020 and zero-energy

commercial buildings by 2025. To achieve this goal, scientists and engineers must break broad new ground in every aspect of building construction and operating practice, Hughes says.

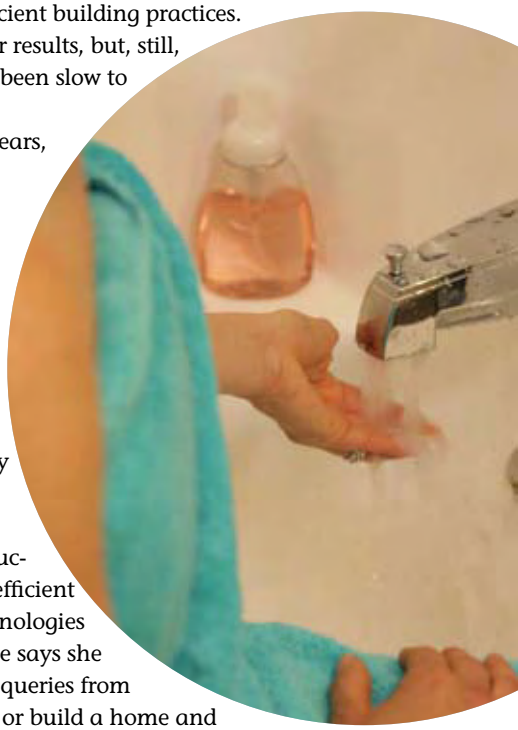
Whenever affordable, these high-performance buildings must be outfitted with renewable sources of energy, minimizing the demand for fossil fuels such as natural gas reserves or coal-fired power plants that supply electricity to the grid. Whether heat pump systems that tap geothermal energy in the ground around the building, solar panels for residential developments such as the Lenoir City Habitat community, combined heat and power systems for commercial buildings or a range of other up-and-coming technologies, the ultimate goal is to construct buildings that can support their own energy needs in a way that is affordable, sustainable and energy efficient.

At ORNL, researchers have been plugging away at the problem since the energy crisis of the 1970s, when DOE predecessors began funding research into energy efficiency initiatives. Through the work of pioneering researchers, whose message regarding the U.S. environmental impact of energy consumption was not always popular, ORNL demonstrated the potential for energy efficiency long before the term became a buzzword.

Today ORNL participates in a number of programs that intersect with builders and suppliers in an effort to bring new energy-efficient technologies and construction supplies to market. Laboratory researchers have worked with industry to develop and demonstrate energy savings benefits of infrared-blocking pigments used to make dark-colored metal, concrete tile and asphalt shingle roofing that is highly solar reflective, reducing the need for air conditioning. ORNL has worked with industry partners to develop low-cost, more energy-efficient second- and third-generation foam insulation materials. The Laboratory has developed software tools to assess the potential for moisture-related damage in construction materials; provide energy efficiency ratings for entire buildings; audit homes for weatherization as part of DOE's low-income Weatherization Assistance Program and perform analysis to support the design of more efficient heat pumps and other equipment. In addition, ORNL has helped guide development of standards related to insulation, materials that make up a building's envelope—that is, walls, floor, ceiling, roof, windows and doors—and moisture design.

how energy efficiency can be incorporated into building design and construction.

"People did not stop by our booth," she says. "They were suspicious of the government. They did not care about energy efficiency. They cared about cost." In the early 1990s, the program began targeting homebuilders rather than homeowners, offering guidance and training on energy-efficient building practices. That effort produced greater results, but, still, many in the industry have been slow to change their ways.



The past three to four years, however, have marked a detectable shift, driven by the very consumers who largely ignored the Laboratory's early efforts. A new demographic, the baby boomers—armed with disposable incomes, looming retirement and a sense of social responsibility remnant from their former hippie days—is creating demand for "green" construction incorporating energy-efficient and renewable energy technologies and building practices. Love says she receives a steady stream of queries from people looking to renovate or build a home and asking questions about energy efficiency.

Building green

Just 50 miles west of ORNL off Interstate 40 near Crossville, Tenn., 6,000 acres of woodland are about to be transformed into the kind of community that Jeff Christian now only dreams of. Developers based in Overland Park, Kan., have reached an agreement with ORNL for collaboration on Walden Reserve, a "green" residential development that would feature technologies tested and developed by ORNL's Buildings Technology Center.

"Yes, we must replace oil with biofuels. Yes, we must pursue other supply-side solutions in an environmentally acceptable manner. But there is enormous potential to reduce energy demand in the buildings sector, and that is by far the cheapest solution if we really want to address this problem."—*Jeff Christian*

While government researchers have been focused on energy efficiency for a number of years, the construction industry and homeowners have been slower to embrace change. Pat Love remembers when the Laboratory began promoting the expertise of DOE laboratories to homeowners in 1980. ORNL serves as the lead national laboratory in communications for the Building America program, a public-private partnership that conducts research and sets standards for energy-efficient homes. In this capacity, Love attends a number of trade shows and seminars each year, armed with educational pamphlets on

The development will be built in five phases and total about 7,000 houses marketed to retired and second home buyers. These homes will feature energy saving and generating technologies ORNL already has utilized in its near-zero-energy Habitat houses including solar technology, geothermal heat pumps, structural insulated panels and integrated plumbing walls. If discussions between the Laboratory and developers bear fruit, the development would serve as a test site for energy-efficient and renewable energy generating technologies, expanding on the work begun with Habitat.

"There are 10,000 baby boomers retiring every day and a significant number of them are 'green' oriented," says Tom Bray, president/CEO of Walden Reserve. "Half of the retirees who choose 'green' would be willing to pay more to live in a green community." Not much more, he adds, saying that incorporating energy-efficient technology and design into what he describes as "mountain/craftsman style" homes will add 5% to 10% to the price tag, with buyers paying $350,000 and up for the homes, and somewhat less for a series of townhouses and condo units also on the drawing board.

As the community is designed and built over the next 20-25 years, Bray says, ORNL researchers would work in conjunction with developers to test and introduce new technologies, serving as a connecting point between Walden Reserve and product manufacturers "to demonstrate the feasibility and marketability" of emerging products. By the time the community is fully built, he says, the newer homes should achieve zero-energy status.

"We think this is a great opportunity for Oak Ridge National Laboratory," Bray says. "We will be developing in conjunction with the Department of Energy. There are so many things we can do together."

ORNL is also working with a Knoxville architecture firm to design and build a near-zero-energy spec house that could be duplicated in communities like Walden Reserve or other, more traditional, suburban and urban developments across the country. In addition to DOE and TVA funding, the state of Tennessee is also contributing to the project.

Elizabeth Eason, owner of the design firm Elizabeth Eason Architecture, says that designing custom homes with energy efficiency and power generating capabilities in mind has become reasonably commonplace and is on the rise. The next step, she says, is to take the concept to more traditional residential developers for easy duplication. Christian is hoping that one of these homes can break ground during this year's festivities for the 25th anniversary of the Knoxville World's Fair. The theme in 1982? "Energy Turns the World."

A change of mind

Approaching construction from a sustainable perspective is nothing new for European nations or countries such as Japan. In the U.S., however, cheap labor and cheap power have allowed traditional "stick construction" practices to remain unchanged for decades.

The problem, Christian says, is that consumers are unaccustomed to thinking about the energy their homes and offices demand. They simply pay the bills. But Christian says when he describes the Habitat development and the potential impact of even moderate energy-saving measures in the frequent meetings and seminars he attends, audiences respond very personally.

"I have noticed that when I tell people that these new houses have energy costs of approximately 50 cents a day, they tend to think about their own homes," Christian says. "People respond to the idea. They just need education and awareness."

Kim Charles did not ponder energy efficiency until she agreed to become the recipient of the fourth Habitat home in the Lenoir City community more than three years ago. However, since she has moved from her old, drafty house where utility bills sometimes climbed above $200 for a single month, Charles says she, and especially her young son, Brian, take more time to do little things that conserve energy, such as keep the lights off when the sun is coming through the window.

Charles loves her home, not just for the energy savings technologies but also for its cathedral ceiling, the windows that let in plenty of sunlight, the neighborhood that provides Brian a chance to play with friends. "My home is brighter and more cheerful than my old house," she says. "This is just a great place to live."

Charles has also become accustomed to a sort of celebrity that comes with owning a home where one pays as little as 40 cents per day to keep the lights on and the washer running. She'll often look out her window to see parades of students, industry representatives, government officials and media passing by—or knocking on her door … trying to catch a glimpse of the future.—*Larisa Brass*

1 Solar panels: Used to heat water via the solar hot water heater and generate electricity, solar helps offset power use by reducing water heating kilowatt hour use and delivering electricity to the grid. The Tennessee Valley Authority pays 15 cents per kilowatt-hour for the solar power. ORNL solar technology projects include the hybrid lighting system, which pipes light through optical fibers into commercial buildings and will convert the remaining solar energy into electricity. Another ORNL solar project aims to integrate the solar panel's inverter with the collector.

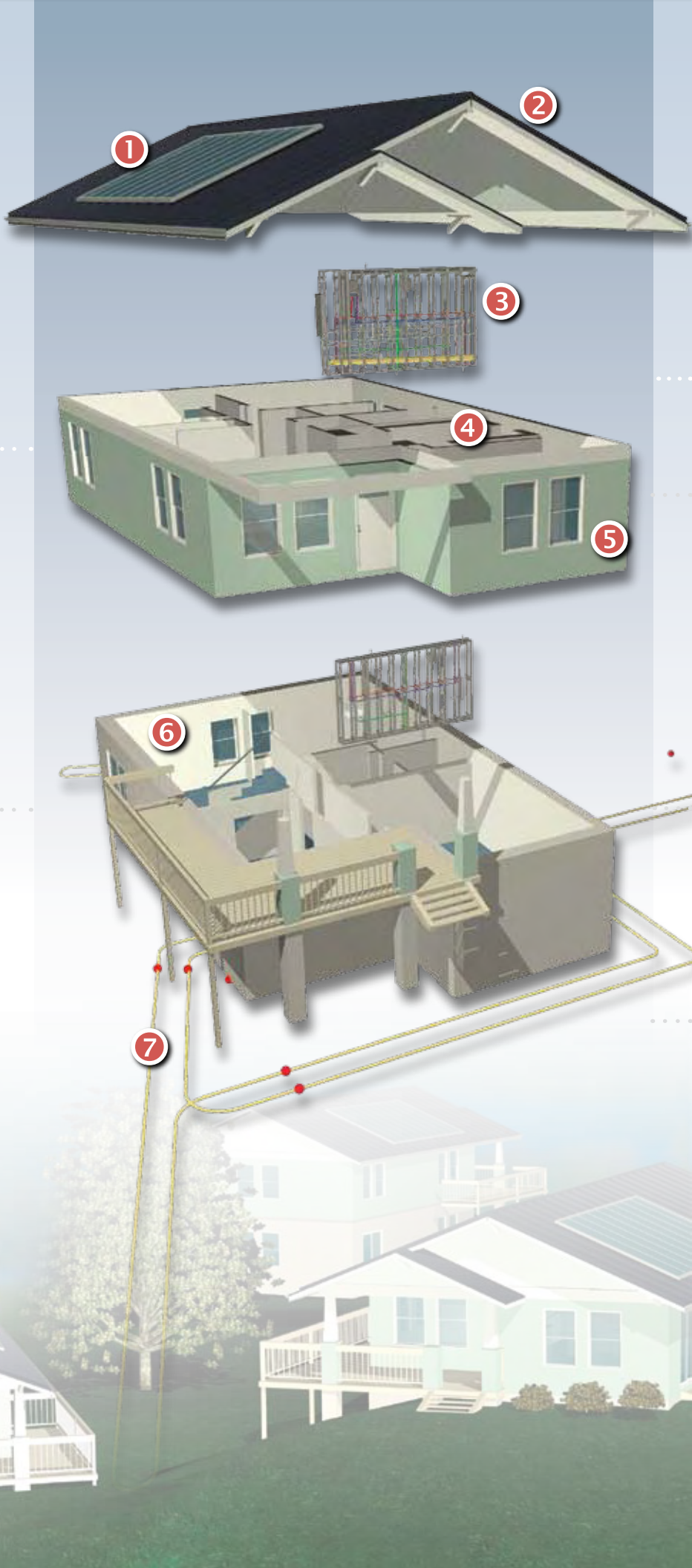
Contacts: *Hybrid solar lighting, Melissa Lapsa, lapsamv@ornl.gov; Inverter integration, Mitchell Olszewski, olszewskim@ornl.gov*

6 Basement: Walls are made of exterior-insulated, termite-resistant, 12-inch reinforced concrete block with $2^{3}/_{16}$-inch fiberglass drainage insulation board on the exterior and an above-grade waterproof covering. They can be painted with an infrared-reflective coating. The interior basement wall provides thermal mass for the building, more uniform interior comfort, annual energy savings and reduced demand during peak periods. Other low-cost foundation systems being studied may provide energy efficiency, moisture tolerance and pest resistance.

Contacts: John Shonder, shonderja@ornl.gov; Moonis Ally, allymr@ornl.gov

7 Geothermal energy: Ground-coupled heat pumps trump air-source units in energy efficiency because the ground is warmer than outdoor air in winter and cooler in summer. Affordability is an issue because the systems typically require extensive below-ground drilling. Recent experience with the Lenoir City homes indicates that use of well-insulated, airtight envelopes; ductwork within the thermal envelope; the interior utility wall; a thermally massive foundation with exterior insulation and other features can be ground-coupled with no additional excavation beyond that needed to construct the home. Using Lenoir City data, ORNL is developing and validating a tool that can size ground loops limited to installation within construction excavations.

Contacts: *John Shonder, shonderja@ornl.gov; Moonis Ally, allymr@ornl.gov*.



2 **Roofing:** The Lenoir City homes feature standing seam metal roofs with "cool colored coatings" that reflect infrared rays, reducing the need for air conditioning. ORNL researchers developed and tested these pigments, also used on the homes' sunlight-exposed foundation areas, in collaboration with manufacturers. ORNL strives to improve the longevity of roofing systems from 12 to 30 years, boost energy efficiency by 150% and identify moisture-tolerant materials and environmentally sound roofing practices. Ongoing R&D focuses on affordable approaches to roof-integrated natural ventilation, radiant barriers, the addition of thermal mass through concrete tiles or through phase-change materials and optimized integration of these concepts. An ORNL computer tool that predicts the energy savings for houses with roofs of different colors can be found at www.ornl.gov/sci/roofs+walls.
Contact: *Bill Miller, millerwa1@ornl.gov; Andre Desjarlais, desjarlaisa@ornl.gov*

3 **Utility wall:** Designed at ORNL, this wall consolidates most of the home's hot water plumbing—with the primary bathroom, laundry and kitchen back-to-back—and enables a home energy savings of 15% over a traditionally plumbed house.
Contact: *Jeff Christian, christianje@ornl.gov*

4 **Interior design and ventilation:** Near-zero-energy homes are designed to limit ductwork and plumbing lines for most efficient energy use. Building interior walls using metal studs rather than wood is more cost effective and sustainable.
Contact: *Jeff Christian, christianje@ornl.gov*

5 **Exterior walls:** To improve the energy efficiency of walls in new construction and renovation, ORNL researchers examine use of exterior insulation finish systems, wall cladding color, thermal mass and air tightness. To achieve affordable energy efficiency and durability, ORNL is investigating passive self-drying wall designs that remove moisture that has either leaked into the wall or permeated the structure by diffusion. ORNL has developed a standardized approach to determining the energy efficiency of entire wall systems, including wall structures, corners, windows and doors. More than 400 walls have been tested in ORNL's Buildings Technology Center.
Contact: *Achilles Karagiozis, karagiozisan@ornl.gov; Jan Kosny, kosnyj@ornl.gov*

Heating, cooling, and water heating: Virtually airtight, houses such as the Lenoir City near-zero-energy homes create challenges for behind-the-scenes equipment that must maintain comfortable temperatures and humidity levels and provide hot water when desired. These airtight homes must be ventilated to bring in fresh air, a major source of indoor moisture in humid climates. To be optimally comfortable year-round, homes like these benefit from either a stand-alone dehumidifier or a new kind of heat pump that can provide enhanced dehumidification on-demand. Multiple pieces of equipment used to condition the typical home's air and water lack sufficient integration, wasting energy. For example, the unit for cooling and dehumidification discards heat outdoors while electricity is purchased to heat water in the storage tank. ORNL and industry partners are developing an integrated heat pump that performs all the needed functions through elegant integration with one compressor-bearing unit.
Contacts: *Van Baxter, baxtervd@ornl.gov; Keith Rice, riceck@ornl.gov; Rick Murphy, murphyrw@ornl.gov.*

Structural insulated panels: These make up the walls, floors and roofs of the Lenoir City homes and serve both the structural and insulation requirements, reducing the need for space heating and cooling and enabling contractors to easily build airtight structures.
Contact: Jeff Christian, christianje@ornl.gov

COMPONENTS of a "ZERO-ENERGY" HOUSE

GREEN IS THIS SEASON'S COLOR

Beginning with the nation's largest retailer and spreading to hospital campuses, military bases and private residential developments, going "green" is becoming fashionable in the commercial buildings sector. Oak Ridge National Laboratory has been right there all along.

With the company's stores commanding about 1% of all commercial floor space in the United States and an energy bill in the billions—as well as a well-earned reputation for trimming costs—saving energy has become a priority for the retail giant Wal-Mart. The company has determined that employing energy-saving materials and technologies in its new stores stamps yet another whistling smiley-face—the staple of Wal-Mart's advertising campaign—on the company's bottom line, says Mike MacDonald, a researcher in Oak Ridge National Laboratory's buildings technology program. Wal-Mart has also publicly committed to major reductions in their carbon footprint and increased use of sustainable building practices.

MacDonald has been working with Wal-Mart since 2005 to conduct third-party technical evaluations of technologies the company is employing at one of two "green" Wal-Mart Supercenters—this one in McKinney, Texas. There the company tests a variety of energy saving and generating innovations, from reflective roofing to solar panels to windmills to LED lighting to hybrid solar lighting developed at ORNL. Driven by data from ORNL's analysis, several energy saving technologies have been rolled out in traditional Wal-Mart stores.

"Wal-Mart is trying to push the technology envelope all the time," says MacDonald. "They force the manufacturers to innovate. They are pushing their suppliers to go green in their whole operation. Wal-Mart carries a pretty big stick."

In addition to Wal-Mart, ORNL works with a number of companies investing in ways to become less dependent on traditional energy sources.

One important area of commercial buildings technology research at ORNL includes integrated cooling, heating and power (CHP). Approximately two-thirds of the fuel used to generate electricity in conventional power plants is wasted in the form of discarded heat. CHP allows businesses and industry to use recycled waste heat from power generation for heating and cooling onsite, rather than depending entirely on the electric power grid. CHP systems improve total efficiency of the systems 78% to 85%.

Now being deployed in large complexes such as hospitals and school systems, ORNL researchers believe these CHP systems could service apartment and business office complexes and even multiple homes in a neighborhood setting. Nationally, the systems produce a total of 87 gigawatts of power, close to the Department of Energy's established goal of 92 gigawatts by 2010. ORNL is working with companies including United Technologies, Honeywell and Burns & McDonald to develop and test the systems both in the lab and in the marketplace.

Control over energy sources, energy use and energy management is key to the future of new buildings technologies. New technologies by themselves do not make an energy-efficient future, say ORNL researchers, but integrating those technologies into intelligent, comprehensive systems promises to change the way buildings of the future are designed, constructed and equipped.

This is the thinking behind several new technology strategies ORNL is pursuing in support of DOE's programs to accelerate transformations in the buildings sector that will reduce energy use, climate-changing emissions and environmental sustainability. These pathways include developing new renewable energy systems, building materials, construction techniques and intelligent energy systems.

Under license from ORNL, hybrid solar lighting systems that pipe natural light into buildings' interiors—via fiber-optic lines emanating from dish-shaped solar trackers—are commercially available today. Researchers at ORNL hope to continue technology advancements so systems in the future can satisfy lighting requirements all the way into the core of large buildings and utilize excess solar energy to generate power. Geothermal (or ground-source) heat pump systems for commercial building space conditioning and water heating have been available for several decades, but recent technology advances now enable the construction of buildings so energy efficient that ground loops constrained within the new building's excavation may be feasible, eliminating the expense of extra trenching and drilling for the ground loops the systems typically require.

Another technology pathway aims to make buildings "smarter" about the energy needs of individual building occupants.

This approach involves knowing where the people are and what they are doing, says Jeff Muhs, strategic planner for ORNL's Engineering Science and Technology Division. "We want to focus on the people and provide them with personalized energy services," Muhs says. "In your office you need more light for some tasks than others, and if you are away the office needs none at all. The same is true for temperature, humidity and fresh air control. What we are trying to do is eliminate waste—and we believe we can do that without sacrificing personal comfort or productivity."

Muhs envisions an RFID tracking system that would allow people to interact with buildings and would use anticipatory algorithms to learn occupants' schedules and preferences with respect to lighting and space conditioning. By tapping into ORNL's multidisciplinary pool of researchers, he says, the initiative will use expertise in sensors, controls, computing, wireless communications and machine vision to develop these intelligent systems.

While exciting new systems for buildings lie tantalizingly within reach, other concepts are somewhat more futuristic. New technology called automated free-form construction holds the potential of transforming conventional building practices and architectural design. ORNL robotics researchers envision homes and commercial buildings someday being built using "CAD-to-fab" processes and less expensive, locally available materials made from natural, recycled and/or bio-based sources.

ORNL's capabilities in advanced materials, ultrascale computing and advanced energy systems along with a history of integrating multidisciplinary basic and applied R&D and partnering with research universities and industry, make the Laboratory an ideal place to spearhead such transformational research.—*L.B.*

Walking the Walk

With six new buildings all LEED (Leadership in Energy and Environmental Design) certified, Oak Ridge National Laboratory has made the commitment to practice what its researchers preach about energy efficiency.

Since 2000, when the University of Tennessee and Battelle assumed management of ORNL, six new buildings totaling 750,000 square feet of office and state-of-the-art laboratory space have become home to more than 1,000 of the Laboratory's 4,200 employees. The fact that energy consumption at the new facilities is less than half that of the buildings they replaced is even more significant because they represent a dizzying array of standards that accompany federal, state and privately funded construction projects.

The Joint Institute for Computational Sciences and Oak Ridge Associated Universities have achieved LEED silver certification while, across the street, the Multi-Program Research Facility has achieved gold certification. LEED criteria were developed by the U.S. Green Buildings Council (www.usgbc.org), a building industry coalition that promotes environmentally responsible technologies. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality.

To date, the east portion of ORNL is the only fully LEED-certified campus in Tennessee and the only one in DOE's complexes nationwide. The facilities save more than 5 million gallons of water annually through the installation of low-flow plumbing fixtures. In addition, three-fourths of all occupied spaces receive natural lighting, and hybrid solar lighting units are being installed at the Multi-Program Research Facility. This system, which collects sunlight with 48-inch-diameter dishes and channels the sunshine into buildings through optical fibers connected to hybrid light fixtures, can save up to $1 million per 100,000 square feet over 10 years.

In the first two months of operation, three of the six new buildings saved more than 5.5 billion British thermal Units (Btu). One Btu is the amount of energy required to raise one pound of water one degree Fahrenheit.

The new buildings feature materials selected for their recycled content, low emissions of volatile organic compounds, insulation value and durability, cost and aesthetic value. Carbon dioxide monitors and high-efficiency air filters ensure good indoor air quality. Other features include efficient lights, occupancy sensors, Energy Star office equipment and variable frequency fan drives that keep energy use low.

While these buildings cost more to build, the additional expense is minimal, adding 1% to 2% to the construction cost, according to ORNL facilities guru Lanny Bates, who noted that, "in the end you have a building that will help conserve resources, improve air and water quality, and make a statement."

BUILDING THE Cars OF Tomorrow

Technologies that reduce automotive fuel consumption are becoming a reality.

In March 2007, David Greene—an Oak Ridge National Laboratory corporate fellow, transportation analyst and manager of the web site www.fueleconomy.gov—was invited to address a congressional committee for the second time in two months. In testimony before the U.S. Senate Committee on Energy and Natural Resources and the Senate Committee on Commerce, Science & Transportation, Greene outlined both the challenges of and opportunities for reducing America's fuel consumption through breakthrough technologies. His message was a mixture of concern and hope.

"America's oil dependence costs our economy hundreds of billions of dollars each year and undermines our national security," he told the senators. "The threat to the global environment from human-induced climate change fed by increasing emissions of carbon dioxide from the combustion of fossil fuels becomes clearer with each passing day. With demand for mobility growing rapidly around the world, sustainable sources of energy for growing mobility demands must be found."

Greene testified that in 1975 Congress for the first time established fuel economy standards in response to the OPEC oil embargo, generating a 50% increase in fuel economy over the next 20 years. Although those initial steps saved American consumers more than 50 billion gallons of gasoline annually, in the long term this approach failed to reduce both fuel consumption and the corresponding need for more imported oil.

More than three decades since the first fuel economy standards were established, policymakers find themselves in an even more complicated political context. The economic and security aspects of fuel consumption are joined by growing concerns about the impact of automobile emissions on climate change. According to Greene, the good news is that the issue can be addressed by gasoline-electric hybrid vehicles and cars with clean diesel engines—technologies considered unproven five years ago—that are beginning to penetrate the market. "Today there are a dozen hybrid models to choose from and clean diesels will soon

be available," said Greene. He told the senators that fuel economy for passenger vehicles and lightweight trucks can be raised 30% to 50% by 2017 using proven technologies without reducing the size or power of the vehicles.

Whether Congress chooses to raise fuel economy standards is a policy issue appropriately beyond the purview of researchers. Meanwhile, as the political debate continues, researchers in Oak Ridge are rapidly moving forward in pursuit of energy-efficient automotive technologies that offer options and, one hopes, lasting solutions to one of America's great scientific challenges of the 21st century.—*Carolyn Krause*

Bob Norris and Ronny Lomax examine a carbon-fiber composite preform. Such a lightweight material could improve a car's fuel economy.

LOSING WEIGHT

Lighter materials are one answer to improved fuel economy.

As the U.S. auto industry sought to raise the fuel efficiency of gasoline cars by 50% between 1975 and 1995 to meet government fuel economy standards, one response was to replace bulky cast iron engines with lightweight aluminum engines. Design engineers used a rule of thumb for improving vehicle mileage: reduce vehicle weight by 10% and fuel economy improves 6%. The Department of Energy's current goal for 2020 is to develop materials and manufacturing technologies that, if implemented in high volume, could reduce the average weight of vehicle structure and subsystems by 50%.

"If cars could be made 40% lighter by using advanced materials such as magnesium and carbon-fiber composites, Americans could increase fuel economy by 25%," says Ray Boeman, director of Oak Ridge National Laboratory's Transportation Program and National Transportation Research Center, which includes University of Tennessee researchers. ORNL researchers have developed procedures for evaluating the durability of glass-fiber composites and carbon-fiber composites that have been adopted by industry. As an example of "lightweighting" progress, 11 pounds of carbon fiber replaced 200 pounds of steel in the 2004 Dodge Viper.

Lightweight material tests

While working five years with the Automotive Composites Consortium in Detroit, Boeman initiated at ORNL composite manufacturing and evaluations of the ability of advanced lightweight materials to protect car occupants in collisions. His evaluations used the newly developed Test Machine for Automotive Crashworthiness, or TMAC. Computer models and TMAC tests of auto parts made of carbon-fiber composites reveal that composites can absorb as much or more energy from an impact as steel, enhancing protection of occupants.

"The two materials absorb energy differently," says Phil Sklad, ORNL researcher and technical manager of DOE's Automotive Lightweighting Materials Program. "When steel is struck in a collision, it collapses like an accordion. When a carbon-fiber composite is crushed, the energy is absorbed through multiple fracture processes."

ORNL inherited carbon composite experts from the project in Oak Ridge that developed gas centrifuges for uranium enrichment. Currently, the Laboratory hosts DOE's largest effort dedicated to devising ways of making carbon-fiber composites affordable to the auto industry. Today these composites, which are used in aircraft parts, tennis racquets and wind turbine blades, cost $8 to $15 a pound. DOE funds efforts at ORNL aimed at lowering the cost of composite production to below $5 a pound, a price the auto industry would find attractive.

ORNL researchers are evaluating other lightweight materials for vehicles, such as magnesium and high-strength steel. If regular steel in a car were replaced with only one lighter material,

Amit Naskar observes the plasma conversion line of a pilot carbon fiber processing unit.

Sklad says that the weight of the car's body and chassis could be reduced 60% using only carbon-fiber composites, 50% using magnesium, 35% to 40% using aluminum, and 25% to 30% using thin-gauge, high-strength steel.

"While carbon-fiber composites have the greatest potential, lowering their cost enough will require the most work and investment," Sklad says. "The cost of making magnesium sheet is very expensive because the hexagonal crystal structure makes deformation processes much more difficult. We can easily make cost-effective components using a number of casting techniques, but the processes for producing magnesium sheet for forming specially shaped components are much more costly."

Advanced high-strength steels are so strong that thinner material provides the same strength as regular steel in a vehicle, reducing vehicle weight by up to 30%. The American auto industry has more than a century's experience with steel. "Since Henry Ford's day, the steel and automotive industries have learned how to produce, design, weld and recycle inexpensive steel," Sklad says. This century's challenge is to develop a cost-effective process to produce specially shaped, lightweight steel components.

DOE's lightweighting program also focuses on finding less costly ways to manufacture new "designer" steels, called transformation-induced plasticity steels. TRIP steels are designed to change their properties and microstructure in desirable ways as a result of stresses imposed by forming.

Multi-material vehicle

The DOE does not envision a future car made from a single material. Sklad says DOE national labs are working with the auto industry to design a "multi-material vehicle" that is part aluminum, part polymer, part magnesium, part carbon-fiber composite and part high-strength steel.

"The government's role is to help develop all these materials, remove the technical barriers to their use by the auto industry and, in turn, provide design engineers with the ability to mix and match the materials according to individual needs," Sklad says. "Our task is to choose the right material for the right application. For example, magnesium might be a suitable material for an engine cradle or radiator support but not for a frame rail."

Technical barriers also include joining dissimilar materials, corrosion, disassembly and recycling. Steel is easy to recycle, but carbon-fiber composite parts joined by adhesives are much more challenging.

Joining will be a major issue because dissimilar materials have different properties. "Spot welding would melt plastic," Sklad says. "Fusion welding of magnesium to steel is impossible because each melts and solidifies at different temperatures. In addition, when magnesium and steel come into contact, battery-acid-like galvanic corrosion can result."

ORNL is pursuing funding to experiment with friction stir welding and to develop other methods to address major joining issues involving dissimilar materials. Although a number of issues remain, all agree that a multidisciplinary effort involving materials scientists, joining researchers, engineers and computer scientists will be needed to remove the technical barriers on the road to building an affordable, lightweight, crashworthy, multi-material car.—*C.K.*

ORNL's
Carbon Fiber Pilot Plant

Companies in the United States, the United Kingdom and Portugal are seeking a process for making low-cost carbon fiber for automakers. ORNL has agreements with the companies to compare conventional and advanced processes for transforming petroleum-based PAN and similar materials into carbon fibers. Kline, Inc., estimates that textile-grade fiber, like that woven into carpets, sweaters and socks, can be converted to carbon fiber at a cost of ~$4.70 a pound.

ORNL researchers also are testing the ability of advanced processes to produce affordable carbon fiber from lignin, a renewable material that is separated from paper-mill cellulose and cheaper than PAN. Carbon fiber made from this process is estimated to cost $3.80 to $4.20 per pound, still some distance from the low end of DOE's $3 to $5 per pound target.

Fred Baker heats and spins lignin in a melt spinner. Owing to a purification process developed at ORNL, the tiny holes in the spinnerette through which hair-like fibers are drawn are not blocked by sulfur salts and particles normally present in lignin. ORNL, Pacific Northwest National Laboratory and MeadWestvaco are jointly developing an industrial process for purifying lignin to reduce material cost.

Felix Paulauskas heats bundles of fibers in a controlled manner in a furnace. The microwave-assisted plasma (MAP) techniques he helped develop eliminate the nitrogen and hydrogen atoms in the precursor, lining up the carbon atoms to produce a graphite-like fiber that is stiff and strong. Paulauskas also uses the advanced MAP techniques to reduce the costs of carbonizing and graphitizing carbon fibers.

An orange robot sprays the fibers and a binder onto a form, making a mat-like, carbon-fiber composite preform. In production the form would have the shape of an automotive part, such as a car's body panel.

CLEANER & GREENER

Researchers combine technologies to increase automotive fuel efficiency.

Spinning wheels on a "chassis dynamometer" treadmill, Larry Moore "drives" a 2007 Swedish car that runs in place on an alternative fuel. While conducting an emissions study at the National Transportation Research Center located between Oak Ridge and Knoxville, Tenn., he intently watches a laptop screen outside the windshield, as if playing a computer game. This flex-fuel vehicle (FFV) is highly instrumented and, under the hood, resembles a patient having heart surgery.

The Saab 9-5 BioPower car project at NTRC was highlighted in a speech given by Alexander Karsner, U.S. Department of Energy Assistant Secretary for Energy Efficiency and Renewable Energy at the Washington, D.C., Auto Show 2007 in January. Karsner recognized Oak Ridge National Laboratory's important research to understand the potential performance and fuel economy gains of FFVs. The BioPower, now on the market in Europe but not available in the United States, is the first FFV optimized for ethanol.

Because ethanol has lower energy content than gasoline, tank mileage of typical FFVs drops by 30% when they run on E85, a blend that is 15% gasoline and 85% ethanol. While FFVs sold in the United States are optimized for gasoline and are largely "ethanol tolerant," Saab stresses that the BioPower is optimized for ethanol use, produces more power on E85 than on gasoline and does not lose as much tank mileage as American FFVs, which are being improved to help address President George Bush's ambitious goal of reducing America's gasoline consumption by 20% in 10 years.

"My hat's off to Saab," says Brian West, a researcher with ORNL's Fuels, Engines and Emissions Research Center (FEERC) at NTRC who collects and evaluates data on the car's performance. "The BioPower is very clean on both fuels—gasoline and ethanol. Saab engineers did not sacrifice fuel economy or emissions to get the added performance from ethanol. This finding is important because while U.S.-legal FFVs are emissions certified on both gasoline and E85, the European regulations do not require certification on E85. We really did not know how clean the Saab would be on E85."

The Saab BioPower produces 180 horsepower with ethanol but only 150 horsepower with gasoline. According to West, by accelerating from 40 to 70 miles per hour in third gear, the car using E85 would be two seconds faster than the same model fueled by gasoline. In practical terms, this difference puts the gasoline car almost two car lengths behind on a 500-foot freeway on ramp.

"The improvement provides a clear incentive for people to choose ethanol over gasoline as the fuel for this car," FEERC Director Ron Graves says, noting that about 10% of the gasoline sold in the United States is premium gasoline even though many cars filled with this more expensive fuel do not need it. "Some people will pay extra for a perceived or real performance benefit."

Graves says that engineers hope to exploit ethanol's desirable properties—higher octane number and latent heat of vaporization—to improve tank mileage of ethanol cars like the Saab BioPower.

This Saab BioPower flex-fuel car that ORNL imported from Sweden was first driven on a Maryville, Ohio, track to break it in for ORNL's emissions studies.

Clean diesel engines

Under the U.S. Partnership for a New Generation of Vehicles (PNGV) program in the 1990s, the goal of the Big Three U.S. auto manufacturers, with support of DOE's national laboratories, was to demonstrate clean, efficient vehicles. The program envisioned combining an electric motor with a diesel engine to make a hybrid, family-sized sedan that could achieve 80 miles per gallon. The diesel engine uses at least 30% less petroleum-derived fuel per mile than today's internal combustion gasoline engines.

PNGV evolved into the FreedomCAR and Fuel Partnership, which emphasizes developing, instead of a specific vehicle, technologies from which automakers can choose. The FreedomCAR and Vehicle Technologies program funds research at ORNL and other labs to remove technical barriers that limit the use of these technologies.

The diesel engine, because of its fuel efficiency, continues to be of great interest to automakers. About half of the new cars sold in Europe have diesel engines. In the United States the main technical barrier to market penetration of diesel engines in light-duty vehicles such as sport utility vehicles, vans and sedans, has been the inability of this technology to meet Environmental Protection Agency emissions standards. The primary obstacles are nitrogen oxides (NO_x), which contribute to acid rain and smog, and particulate matter, which threatens respiratory health.

The most elegant exhaust treatment method for diesel engines is the lean NO_x trap (LNT), an absorber-based exhaust aftertreatment system that stores NO_x as nitrates during lean operation. The NO_x is stripped off and chemically reduced when

the engine transitions periodically to a brief, rich combustion mode. The problem is that sulfur in diesel fuel exhaust occupies the NO_x storage sites, rendering the aftertreatment ineffective. The partial solution was a recent ruling by EPA that requires oil refineries to reduce the concentration of sulfur in diesel fuel from 500 parts per million to 15 ppm. Despite lower sulfur in the fuel, LNTs still suffer from sulfur poisoning, so research is focused on mitigating this problem.

EPA's ruling cited data contributed by ORNL researchers. In 1999 West and Scott Sluder conducted transient driving experiments using a Mercedes A170 vehicle they equipped with a prototype LNT.

"We were the first to conduct a laboratory experiment to demonstrate the potential of LNT and other aftertreatment technologies to enable a diesel car to meet Tier 2 emissions standards," West says. "We demonstrated that the LNT helped lower NO_x levels, and that the diesel particle filter effectively removed particulate matter. Using diesel fuel with different levels of sulfur, we also quantified the harmful effect of sulfur on catalysts and tailpipe emissions."

Assisting industry

The Dodge Ram rolled out at a 2007 auto show by Daimler Chrysler has a Cummins 6.7-liter diesel engine and NO_x aftertreatment system that bear the marks of ORNL research. John Wall, vice president and chief technical officer of Cummins Inc., noted in a letter to ORNL's Bill Partridge "the significant contribution you and your FEERC colleagues have made to the research required to introduce this vehicle. The knowledge and tools developed in our cooperative research and development agreement were critical to the R&D efforts that culminated in the release of an aftertreatment technology that meets the 2010 environmental standards in 2007."

Wall credited the mass spectrometer system, called SpaciMS, and pioneered by Partridge, for "changing the way we think about tuning engine combustion." He added that this instrument and "the fluorescence lifetime thermometer your team developed helped us understand the changes in NO_x adsorber catalysts as they aged, critical information for catalyst system design."

Wall also lauded Tom Watkins and colleagues at ORNL's High Temperature Materials Laboratory, who used computer modeling and images produced by the aberration-corrected scanning transmission electron microscope to predict the lifetime of catalysts and particulate filters, such as Corning's honeycomb-like cordierite material, used for diesel exhaust aftertreatment. Durability of aftertreatment technology is an issue because truck drivers expect these systems to last for half a million miles. One study showed that rhenium particles become less catalytically active when they coalesce into nano-sized "rafts" after exposure to diesel exhaust.

Another effective emissions control strategy for diesel engines is exhaust gas recirculation, a process in which a carefully controlled amount of combustion by-products is mixed with the incoming air. "Basically, the exhaust of fuel you burn is dumped back into the cylinder," says researcher Johney Green. "Exhaust gas recirculation reduces the temperature in the cylinder, resulting in less production of NO_x. One challenge we must resolve is that this strategy actually produces more soot until a critical threshold is crossed, resulting in the simultaneous reduction of NO_x and particulate matter emissions."

Larry Moore test drives the Saab BioPower at the National Transportation Research Center. Right, Alberto Lopez Vega adjusts instruments that monitor the car's testing process.

In May 2002 ORNL became the first DOE lab to publicize the discovery of low-temperature diesel combustion. The muted reaction at a Department of Energy program review meeting made ORNL researchers suspect that some automakers and diesel engine manufacturers may have known about the phenomenon but for competitive reasons chose to downplay their reaction.

"Getting this discovery out in the open has helped the diesel engine community move forward faster now that engineers are working on the problem in a noncompetitive way," Green says. ORNL's presentations, he adds, helped redirect the DOE diesel engine portfolio toward increased research on controlling and stabilizing what the agency terms "high-efficiency clean combustion."

Meanwhile, across the ORNL campus various groups are analyzing alternative fuels and materials for engines. Nuclear Science and Technology Division researchers are developing computer simulations of combustion of biofuels, such as B5, diesel fuel containing 5% biodiesel made from soybean oil. The Materials Science and Technology Division is seeking to improve the thermal efficiency of heavy-duty diesel engines in trucks, ranging from tractor trailers to large pickup trucks. Thermal efficiency is

the percentage of a fuel's heat energy value that is converted to mechanical energy to power a diesel engine.

Program manager Ray Johnson says, "In 2006, 150-horsepower diesel engines for passenger cars had a 41.5% thermal efficiency whereas 400-horsepower diesel engines for trucks had a 45% thermal efficiency. The DOE thermal efficiency goals are 45% by 2010 for diesel cars and 55% by 2012 for trucks. With widespread implementation of new improvements, we could realize a fuel reduction of 20%."

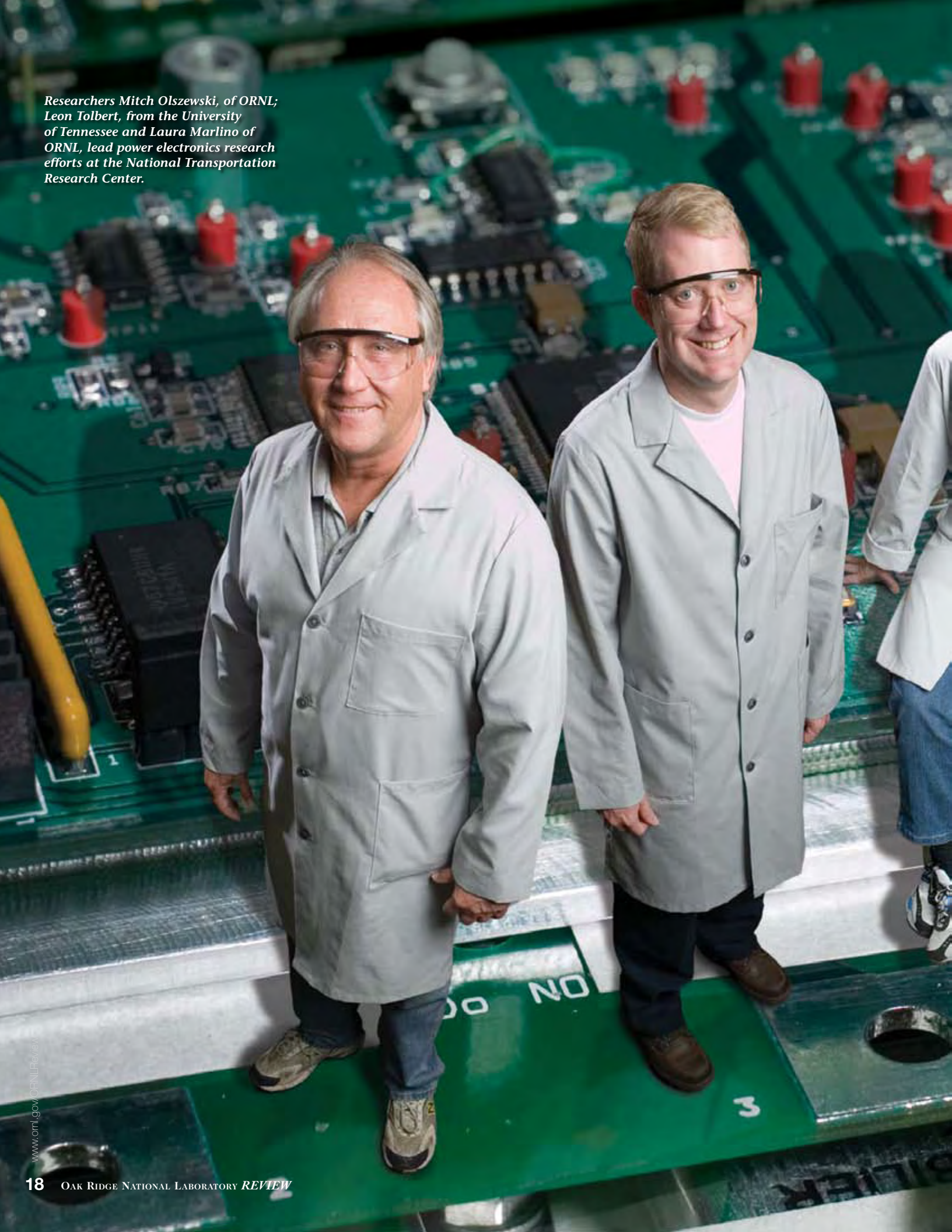
Engine designers working for Cummins, Caterpillar and Detroit Diesel say they cannot achieve these goals without stronger, lighter, higher-temperature, lower-friction materials that ORNL researchers can characterize, synthesize and model. In a new cooperative program involving an industrial partner, advanced materials and components will be tested in a state-of-the-art, heavy-duty diesel engine, allowing researchers to measure the durability of new, advanced materials tested in the engine and also the effects of new materials and components on the engine's performance and efficiency. This initiative builds on a current project in which ceramic and intermetallic valves were tested for hundreds of hours in a stationary natural gas engine and found to be more durable and corrosion-resistant than the standard steel valves.

Capturing waste heat

More than half of the energy value of fuel in current automobile engines is lost to the atmosphere as waste heat. DOE's Solid State Energy Conversion Technology Program is developing technology using thermoelectric modules for waste heat recovery in vehicles to improve thermal efficiency and engine performance. Such a system based on temperature differences not only could convert waste heat directly to electricity to operate the car's electrical accessories, such as pumps and compressors, but also could provide heating and cooling directly. However, the poor efficiency of current thermoelectric materials is a significant barrier to large-scale commercialization.

DOE has asked ORNL to lead a new, computational quantum theory-driven effort to develop practical, high-efficiency thermoelectric materials that would enable commercialization of automotive thermoelectric generators and greater market penetration of solid-state heating and cooling.

Should the initiative result in significant commercialization of thermoelectric modules with a modest 10% efficiency, the impact on America's fuel consumption, and the resulting impacts on security and the environment, would be of enormous and lasting value.—*C.K.*



Researchers Mitch Olszewski, of ORNL; Leon Tolbert, from the University of Tennessee and Laura Marlino of ORNL, lead power electronics research efforts at the National Transportation Research Center.

SIMPLY ELECTRIC

Hybrid electric vehicles are becoming more practical.

Like American car companies and the consumers they seek, the power electronics group of Oak Ridge National Laboratory has taken a critical look at the Toyota Prius. After the Department of Energy purchased one of the Japanese gasoline-electric hybrid cars for the National Transportation Research Center (NTRC), technicians carefully disassembled the hybrid so ORNL and University of Tennessee engineers could determine how the Prius achieves roughly twice the mileage of the average American car.

"We have taken the Prius apart and run its electric motor and power electronics through a complete set of tests so we know what they will do under various conditions," says Mitch Olszewski, leader of ORNL's Power Electronics Integration Group. "We are doing the same with the Toyota Camry Hybrid and the Honda Accord Hybrid."

Laura Marlino, program technical manager, says, "The power electronics in the Prius is a 'brute-force system' in which the most significant innovation lies in the electric motor." The Prius—the benchmark for ORNL's research on vehicle power management—is designed to maximize fuel efficiency and reduce emissions of regulated pollutants and unregulated greenhouse gas emissions. The computerized hybrid sedan can operate on only the downsized gasoline engine or the battery-powered electric motor or both. The car's nickel metal hydride batteries are recharged directly by the engine acting as a generator or by regenerative braking, in which kinetic energy is recovered when the driver depresses the brakes or coasts downhill.

One goal of DOE's FreedomCAR and Vehicle Technologies program is to aid the auto industry in designing a plug-in hybrid electric vehicle with a lithium ion battery that can be recharged by plugging the car into home electrical outlets. Ideally, the car could drive 40 miles on electricity only before relying on the gasoline engine. ORNL leads FreedomCAR research in power electronics and electric motors in support of the auto industry's development of hybrid vehicles and hydrogen fuel-cell cars as well as plug-in hybrids.

To meet DOE's cost targets for the plug-in hybrids, the ORNL group seeks to employ new technologies to redesign or minimize the vehicle's electric motor; the inverter, which converts direct current (DC) from the battery to alternating current to run the electric motor; the boost converter, which raises the battery's voltage to the level needed by the motor and the DC to DC converter, which manages the vehicle's power system in order to operate electric accessories. These accessories include

CD players, seat warmers and electric drives—air conditioning compressors, power steering units and power brakes. The ORNL group calls the combination of the electric motor, inverter and converters the "electric traction drive system."

DOE's cost targets for tomorrow's hybrid vehicles are based on a payback of three years, roughly one-third that of the Prius at today's gasoline prices. Compared with the Prius, the electric traction drive system of DOE's envisioned hybrid cars must be 60% smaller, 55% to 65% lighter and 75% less costly to meet the payback cost targets.

ORNL has several strategies for reducing the volume, weight and cost of the drive system of the hybrid plug-in by 2020. Eliminating Toyota's $185 dedicated liquid coolant loop for cooling the power electronics is one approach. In its place, ORNL researchers propose using an innovative design in which the inverter is flooded with the electrically insulating refrigerant used for air conditioning, providing direct contact cooling of the electronic chips.

To meet the 2020 goal of reducing the size of the inverter by 60%, ORNL researchers are investigating the proposed strategy of replacing the inverter's silicon switches with silicon carbide chips, which are smaller, can operate closer together at higher temperatures and have the potential of using air cooling instead of liquid coolant. The tradeoff thus far has been daunting: silicon carbide devices currently cost 10 times more than silicon devices.

A University of Tennessee team is working with university partners to find packaging materials for silicon carbide devices that can withstand 200°C. Their counterparts at ORNL are gathering performance data from tests of manufacturers' silicon carbide diodes in inverters at high temperatures.

Meanwhile, another team of ORNL researchers is redesigning the electric motor with the goal of making it more powerful, smaller and ultimately cheaper by eliminating the need for the current boost converter. A parallel approach is new electronic topologies that would eliminate bulky components in the boost converter. This strategy seeks to combine the functions of an inverter and boost converter into one multilevel converter and eliminate the magnetics, reducing both weight and cost.

The plug-in hybrid envisioned by DOE and auto manufacturers will have a lithium ion battery because

Chester Coomer and a component of a 16,000 RPM electric motor for electric hybrid vehicles that he is working on.

the specific energy density—three times that of the Prius battery—allows designers to shrink lithium battery weight, increasing the fuel efficiency of the car when running on gasoline. Argonne National Laboratory is leading research on the lithium ion battery for electric vehicles.

To recharge a lithium battery 10 to 100 times faster, the battery must be coupled with an ultracapacitor, an electrochemical capacitor with two carbon electrode plates sandwiching an electrolyte fluid that can rapidly release considerable stored electrical energy each cycle. In April 2007 ORNL Associate Director Michelle Buchanan led a national workshop on electrical storage, including batteries and ultracapacitors, for DOE's Office of Basic Energy Sciences. A novel porous carbon material developed at ORNL is being tested as a candidate electrode for ultracapacitors. The reason: The nanostructured carbon particles have high accessible surface areas and high conductivity, are compatible with the electrolyte and show low degradation at higher cell voltages.

At present the cost of producing carbon-based materials with tailored energy-storage performance for ultracapacitors is $100 a kilogram, five times too high. A number of researchers get up each morning with the goal of bringing down the cost of vehicle components.—*C.K.*

Curtis Ayers with an early version of an inverter he is developing for use in vehicle air conditioning systems.

MORE OR LESS ELECTRICITY

If plug-in hybrid electric vehicles are developed and purchased by consumers for short commuting trips, several studies indicate the vehicles would reduce owners' fuel and vehicle usage costs and cut harmful emissions in half. The studies assume that owners recharge their vehicles overnight when demand for power is low.

ORNL's Stan Hadley recently conducted a different study with the assumption that that plug-in hybrid owners more likely would plug their cars into the electric grid during the day when demand for power is high. "Even at peak power prices, electricity is still cheaper than gasoline for propelling the car," he says. Using a power plant computer model he developed and utility data from Virginia and the Carolinas, Hadley simulated the effects on the grid of a million plug-in hybrids recharged daily for 5 hours at 6 p.m. versus a million plug-in hybrids plugged in overnight starting at 11 p.m. The model indicated the plug-in hybrids feeding on peak power nudged the grid to draw additional electricity from power plants that burn natural gas instead of coal.

"The region has an overall regulated limit, or cap, on emissions of sulfur oxides and nitrogen oxides (NO_x). Because of sales of credits from power plants with emissions below the cap, emissions would not increase throughout the country," Hadley says. "The additional production to meet this regional demand would cost utilities more because of the rising prices of the credits. As drivers shift from gasoline to electricity, more atmospheric carbon dioxide from fossil fuel combustion may be produced because carbon emissions are not yet regulated. In the United States a cap exists for NO_x emissions of power plants but not vehicles. The benefits of transitioning America's vehicles to plug-in hybrids will be lower demand for gasoline and, as a result, air that is safer to breathe."—*C.K.*

ZERO SUM GAME

He is energy efficiency guru and architect of Oak Ridge National Laboratory's unique living lab of energy-efficient and renewable generating technologies. The pursuit of zero-energy housing has no greater champion than

Jeff Christian

In 2002, when the Department of Energy introduced the daunting concept of a house that would produce as much energy as it used, Christian seized the challenge and has not let go. Guided by the belief that energy-efficient homes should be affordable to working families, he partnered with the Habitat for Humanity in neighboring Lenoir City, building five homes to test the latest in renewable energy producing and energy-efficient technologies. The homes feature such as solar panels, geothermal heat pumps, heat pump water heaters, airtight superinsulated walls and roofing panels and advanced ventilation systems. They demonstrate that such technologies, when properly integrated, work in real-life environments with regular people who can then benefit from the resulting cost savings. That accomplished, he is now helping transition the concept—and the technologies—to the traditional construction industry, with plans under way to begin building locally two "near-zero-energy" homes aimed at traditional home buyers. Christian said he hopes one of the homes will be part of the 25th anniversary of the 1982 World's Fair held in Knoxville.

With the zeal of an evangelist, Christian has brought together a diverse group that includes the nonprofit Habitat organization, utilities, suppliers, contractors, architects and researchers to demonstrate today what Christian believes is becoming a model for America's homes of tomorrow.—*L.B.*

Talk about how the zero-energy home concept began.

The idea was introduced to me for the first time in March 2002. I was among three representatives from Oak Ridge National Laboratory to go to Washington, D.C., where we heard the message that the Department of Energy was going to fold all of our buildings research under the umbrella of the zero-energy house. I not only said I thought this was a good idea but I came back and approached the Tennessee Valley Authority and Habitat for Humanity with the idea of being the first on the block to get something that was very near zero-energy and affordable. At first I thought of building something like a carport to get on the ground quickly. It was the Habitat coordinators themselves who said, "The people we serve don't need carports—they need groceries and they need a decent house. Why don't we just make it part of one of the houses we build?" By June, we had a house. I went on my annual pilgrimage to TVA in Chattanooga and proposed that they fund five near-zero-energy test houses. They very quickly pointed out that TVA is in business to sell energy and that "zero" did not sound like a good proposition on the surface. Then they realized the potential benefit of peak load reduction, which could be a strong motive for electric utility interest in the project. Before you know it, TVA committed to funding, with the Department of Energy, five zero-energy houses. Then-chairman Glenn McCullough said he hoped the houses would "propagate across the residential, commercial and industrial sectors."

We are now in the last year of testing the fifth house.

What are the most influential technologies for energy efficiency and energy savings in a home?

The Habitat houses are, in essence, airtight and mechanically ventilated. That is a clear starting point. This is followed by installing the heating and air conditioning ducts inside the conditioned space. From there we go to high-performance windows and—as a result of creating a well insulated, airtight home—downsizing the heating and cooling distribution system and the mechanical equipment. That means a dollar savings generally, although what we have found is we have pushed the capacity so low that there are no systems small enough to help owners achieve the full cost savings potential. That has spawned a focused effort within the ORNL Buildings Technology Center to develop integrated, high efficiency, affordable, smaller-than-commercially available technologies.

What makes a Habitat for Humanity community ideal for this research?

First of all, these homes are very sustainable. You build something, you test and when you are done testing the home is turned over to a family in need, who gets an upgraded, affordable home out of the deal. The houses are small, they are simple, and they can be fairly easily replicated. The community, in essence, gives us a laboratory facility. We have a half-dozen field exposure facilities spread around the country, as well as world-class laboratory facilities, but there are some pieces of information in which we simply need a whole house to conduct our research. This community provides an unprecedented capacity for building research.

What is the impact of actually having people living in the houses?

It is both a blessing and a curse. You have real people and the interface issues are very important. But you also must have things that are ready for prime time. You do not, for example, want to be responsible for cold showers—something I have been accused of. A real benefit is that many people think a near-zero-energy house needs to be occupied by an engineer, tweaking things at every moment to make the house go. To that I simply say, not true. Our research offers a strong testimony that these homes can be easily occupied by average, non-technically oriented residents.

"Many people think a near-zero-energy house needs to be occupied by an engineer.... To that I simply say, not true."

What must happen to achieve the goal of a true zero-energy home?

The first thing that we will reach is zero-energy cost. Currently, the Tennessee Valley Authority buys all the solar power you generate for 15 cents per kilowatt hour. I am very hopeful that will be increased to at least 20 cents, maybe 25 cents, and I'm asking for 30. The Department of Energy has set a target date of 2020 for development of affordable zero-energy homes. To do that, however, we need a couple of things. We need the cost of solar panels to come down. Researchers looking at solar feel like we can reach affordable cost within that timetable. The second issue is that we need to deal with an increasingly out-of-control miscellaneous electric load. This is not lighting, appliances, heating and cooling or hot water. This is everything else—cell phone chargers, electric toothbrushes, hairdryers, plasma televisions, VCRs, Tivo boxes and your home office with computers, faxes, printers. This extra demand amounts to 2,500 kilowatt hours per year per household and is growing at an outrageous 3.5% per year. With today's technologies and capabilities at ORNL in development of advanced sensors and controls, we can combat this growing problem.

STILL PURSUING THE ELECTRIC CAR

A practical electric vehicle requires more than a hydrogen fuel cell.

The lead-acid-battery-powered, all-electric car of the late 20th century failed to attract consumers because of its high cost and limited range. In the future, the all-electric car may have a better chance of succeeding because of the Department of Energy's commitment to improving electrified vehicles. To enable more electric ground transportation, ORNL is developing improved materials for batteries and analyzing novel means such as hydrogen fuel cells to generate electricity on-board vehicles.

Tim Armstrong, manager of ORNL's Hydrogen, Fuel Cell and Infrastructure Program, says that the Laboratory is supporting DOE's hydrogen program primarily through research on hydrogen production, delivery, storage and fuel cells.

Hydrogen must be produced for storage on board the car and at service stations. ORNL characterizes and develops membranes for purifying hydrogen and separating it from hydrogen-containing gases.

Studies at ORNL's High Temperature Materials Laboratory are determining mechanical properties and durability of a palladium membrane being developed by Pall Corporation and partners. ORNL researchers are developing a next-generation, all-ceramic membrane based on molybdenum oxide for purifying hydrogen from coal gas and syngas, a mixture of hydrogen and carbon monoxide that can be made from biomass-derived gas.

In addressing the question of how to deliver hydrogen cost effectively to service stations, ORNL researchers are examining distributed hydrogen production hubs with 50-mile-long pipelines, like spokes of a wheel. Other approaches might be an all-hydrogen centralized pipeline network or the delivery of hydrogen through a centralized natural gas pipeline network.

ORNL is working with several universities on coating metallic pipelines to make the alloys withstand hydrogen-induced embrittlement. Various alloys are being studied to determine which are least likely to leak significant amounts of hydrogen and become brittle under pressures of approximately 1,500 pounds per square inch.

"Laying pipelines of different iron-based alloys costs $1 million a mile," says Armstrong. "One significant cost is welding. Every weld point changes the microstructure, making hydrogen leakage more likely." ORNL researchers led by Zhili Feng are examining friction stir welding as an economic alternative to in-field welding of metallic pipelines.

ORNL researchers also are developing a "smart," fiber-reinforced, polymer pipe composed of a high-density polymer core with a polymer liner and glass-fiber wrap for improved strength to slow down diffusion of hydrogen from the gas stream. "To make the pipeline smart, fiber-optic sensors would be woven in the wrap to warn of potential leaks and failure points," Armstrong says. "Current polymer technology allows the manufacture of mile-long polymer pipelines for the oil industry, reducing the number of connections and potential leaks. Using mobile factories we estimate the cost of laying pipeline would be cut 50%, to half a million dollars a mile."

One ORNL-generated model suggests that the transition to hydrogen pipelines may be accommodated by tanker trucks that carry liquefied hydrogen to storage tanks at service stations where fuel-cell car tanks would be filled with high-pressure hydrogen gas. The technology for making hydrogen transportable by truck may come from a novel hydrogen liquefaction technique developed by Allen Crabtree at ORNL's Spallation Neutron Source.

One ORNL team is examining metal hydrides, carbon nanohorns containing palladium, and activated carbon for adsorbing and storing hydrogen in tanks at the filling station and on board the fuel-cell car. Another team seeks to lower the cost of producing high-

Tim Armstrong with a model of a hydrogen fuel-cell car.

strength, aerospace-grade carbon fibers for building hydrogen tanks.

Armstrong says researchers are conducting groundbreaking transmission electron microscope studies of microstructure changes to determine failure mechanisms in fuel-cell materials. Working with major fuel-cell companies in the United States and Japan, Karren More has identified different degradation mechanisms in fuel cells and assisted companies in improving their use of platinum catalysts. With the SpaciMS mass spectrometer adapted by Bill Partridge to study real-time gas distributions in fuel cells, ORNL is well positioned to help partners improve or develop fuel-cell materials and models to get the electric car out of the laboratory and on the road.—*C.K.*

NEW "ARMS" for Disabled Soldiers

Designing a better prosthetic arm for military amputees

Jesse Sullivan, a double amputee from Dayton, Tenn., has been called the world's first "bionic man" with his thought-controlled, state-of-the-art prosthetic arm. He can eat with a fork, pick up a cup, paint his house or guide a weed eater by bending his advanced appendage's elbow and rotating its forearm. But he still cannot grasp and throw a baseball, cast a fishing line, tie his shoes or type on a computer keyboard as naturally as before. That may change with the help of numerous organizations including Oak Ridge National Laboratory, some 50 miles north of Sullivan's hometown.

In 2001 while working as a utility lineman, Sullivan lost both arms after a 7000-volt shock in a power-line accident. Physicians at the Rehabilitation Institute of Chicago (RIC) reattached nerves from Sullivan's amputated arm to his chest muscles, which were connected electronically to the prosthetic arm. When he thinks "close hand," electrical signals released as his chest muscles contract are picked up by electrodes in the prosthesis. The electrodes relay the signal to a computer chip that commands his electronic hand to close. Northwestern University's Prosthetics Research Laboratory developed this thought-controlled arm.

Sullivan is now testing an even more advanced prosthetic arm that allows him to pull a credit card from his pocket and stack cups by controlling grip force. This next-generation prototype was designed and built by a team of multiple organizations through funding from the Defense Advanced Research Projects Agency (DARPA), the U.S. Department of Defense agency responsible for development of new technology for use by the military.

DARPA has been funding two programs to create a fully functional upper limb that responds directly to neural control. The motivation for this demanding research project is the growing number of American soldiers who have lost limbs while serving in Afghanistan and Iraq.

The first DARPA program, Revolutionizing Prosthetics 2007, is led by DEKA Research and Development Corp. The objective of this two-year program has been to design and fabricate an advanced prosthetic arm and hand using the best available technologies. The second program, headed by the Applied Physics Laboratory (APL) of Johns Hopkins University, is developing enabling technologies that will give the next-generation prosthetic the properties of a biological arm, so the amputee can feel and manipulate objects naturally. This aggressive, four-year program requires breakthroughs in neuroscience, robotics, electrical power, sensing and actuation technologies.

While Sullivan and others test the first DARPA prototype, two ORNL groups and dozens of other organizations are developing candidate technologies for the second prototype, which will be completed in late 2009. Art Clemons serves as the liaison between the ORNL groups and their DARPA program managers, as well as APL, the program's system integrator.

Fluid joints

Sullivan's bionic arm and DARPA's first prototype both have electric motors that provide seven degrees of freedom, or independent movements. But John Jansen and Lonnie Love in ORNL's Robotics and Energetic Systems Group are developing a new technology, mesofluidics, that could provide actuation to prosthetic finger, thumb, wrist, elbow and shoulder joints, conferring the strength and speed of a natural arm and hand. Mesofluidic technology is more compact and offers more force and speed capacity than electromagnetic actuation in today's bionic arms. Love and Jansen have demonstrated this technology on an elbow capable of 60 foot-pounds of torque. They are developing a prototype finger that has 20 pounds of pinch force.

The researchers designed and built a one-inch-high pump driven by a tiny electric motor, compact valves to control the flow of mineral oil or other fluid and actuators, such as pistons in cylinders into which the fluid is pumped at a pressure of 2,000 pounds per square inch. Powered by a rechargeable lithium-polymer battery pack, the pump compresses and displaces the fluid. As pressure builds up, the oil forces the piston to the cylinder's end, causing the elbow or finger joint to bend.

"DARPA wanted to know if we could build an artificial arm with elbow and wrist joints that could curl 60 pounds using mesofluidic technology," Jansen says. "Most humans cannot lift such a weight using elbow and wrist power."

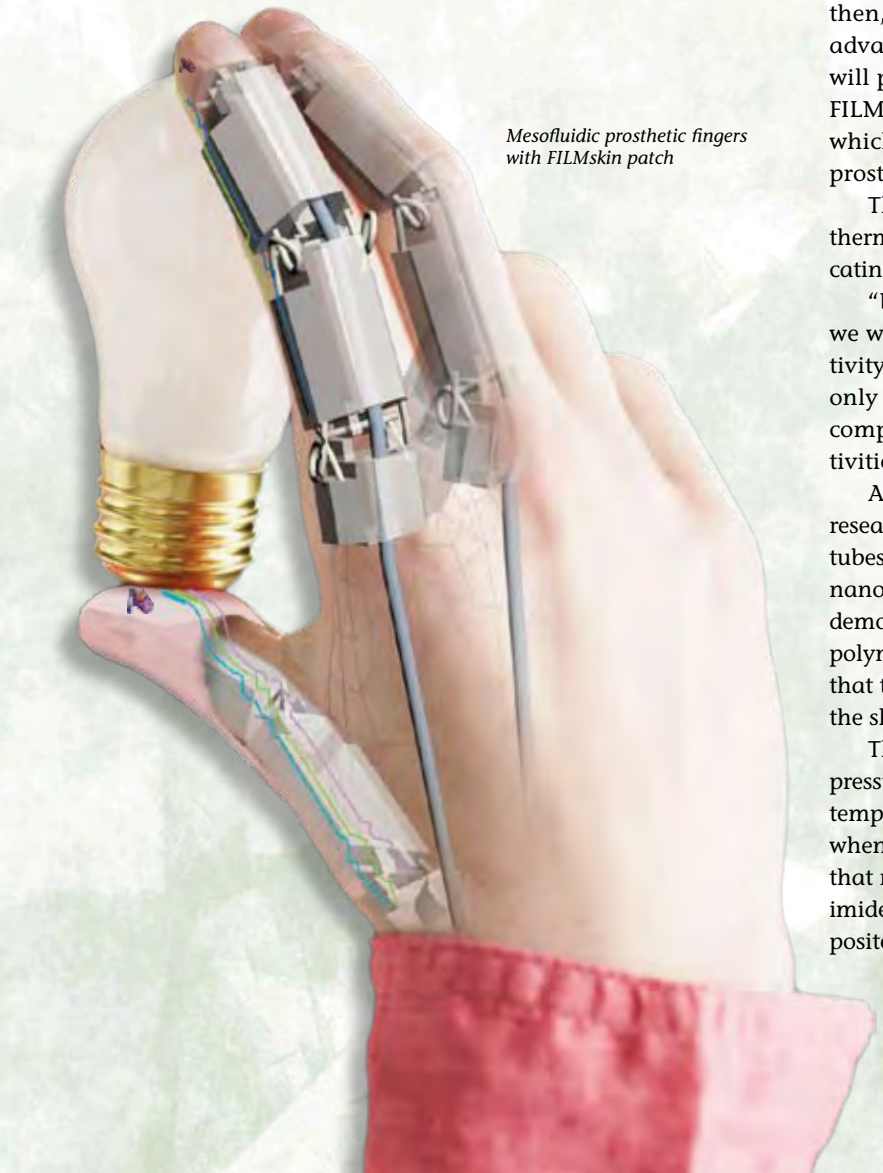
"The 60 foot-pound elbow torque milestone was a classic 'DARPA hard' objective that many researchers thought unachievable," Love says. "We met this DARPA milestone by demonstrating the power and strength attainable from mesofluidic technology."

Electric-motor systems are inefficient as prosthetics partly because they require extra energy for accelerating and braking the arm's movements. "The energy used by our prosthetic arm bending at the elbow is 21% of the input energy supplied by our battery-powered, miniature hydraulic pump," Jansen says. "That is the same energy efficiency as human muscle."

Another DARPA objective met at ORNL is finger pinch force, which results from pushing any finger hard against the thumb. Love and another robotics engineer, Randy Lind, designed a mesofluidic finger using aluminum pistons and cylinders connected by tiny valves.

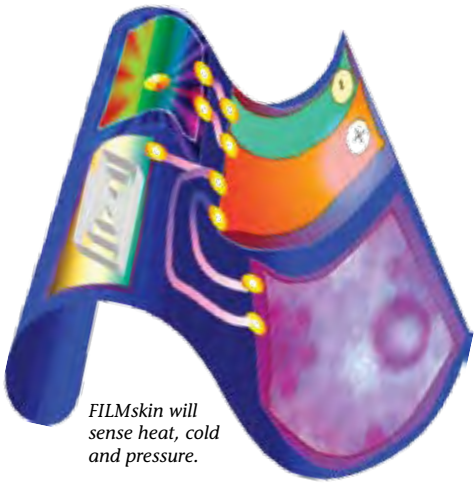
"Our next goal will be to demonstrate that a mesofluidic finger can exert 20 pounds of pinch force," Love says. "This design shows that compact, high-strength actuators and valves can fit inside the volume of a finger, an important benefit of mesofluidics."

The DARPA hand will have the human hand's dexterity and 24 degrees of freedom. "Our prosthetic fingers will be designed to move at the same speed as human fingers," Jansen says. "Other researchers are working on providing electrical feedback between the brain and finger joints, to enable military amputees to resume their normal activities, from pulling a gun trigger to typing on a computer keyboard."



Mesofluidic prosthetic fingers with FILMskin patch

FILMskin



FILMskin will sense heat, cold and pressure.

ORNL materials scientists are collaborating with National Aeronautics and Space Administration researchers to produce a flexible, integrated, lightweight, multifunctional skin, or FILMskin, for a next-generation prosthetic hand and arm. The team's challenge is to make a revolutionary skin that will outperform current prosthetic coverings in properties and functionality, allowing the prosthetic wearer to feel heat, cold and touch.

Ilia Ivanov and Dave Geohegan, both of ORNL's Nanomaterials Synthesis and Properties Group, are collaborating on the FILMskin project with Joycelyn Harrison and Cheol Park, both of the National Institute of Aerospace in NASA's Langley Research Center. The ORNL researchers' task is to develop material that matches real skin's thermal properties and, then, a temperature sensor, whereas NASA's task is to develop advanced pressure sensors. Together, the two organizations will produce a one-inch-square patch of a lightweight, durable FILMskin composite of a polymer and carbon nanotubes, which will exhibit multifunctionality not possessed by current prosthetic coverings.

The complex makeup of warm human skin is revealed in a thermal image of the hand, which displays different colors indicating different skin temperatures.

"By exploiting carbon nanotubes' ability to conduct heat, we will create nanocomposites with the thermal conductivity of muscle, fat or skin. We recently showed that, with only 8 volume percent of nanotubes, we can make a polymer composite with a thermal conductivity that far exceeds conductivities of different tissues."

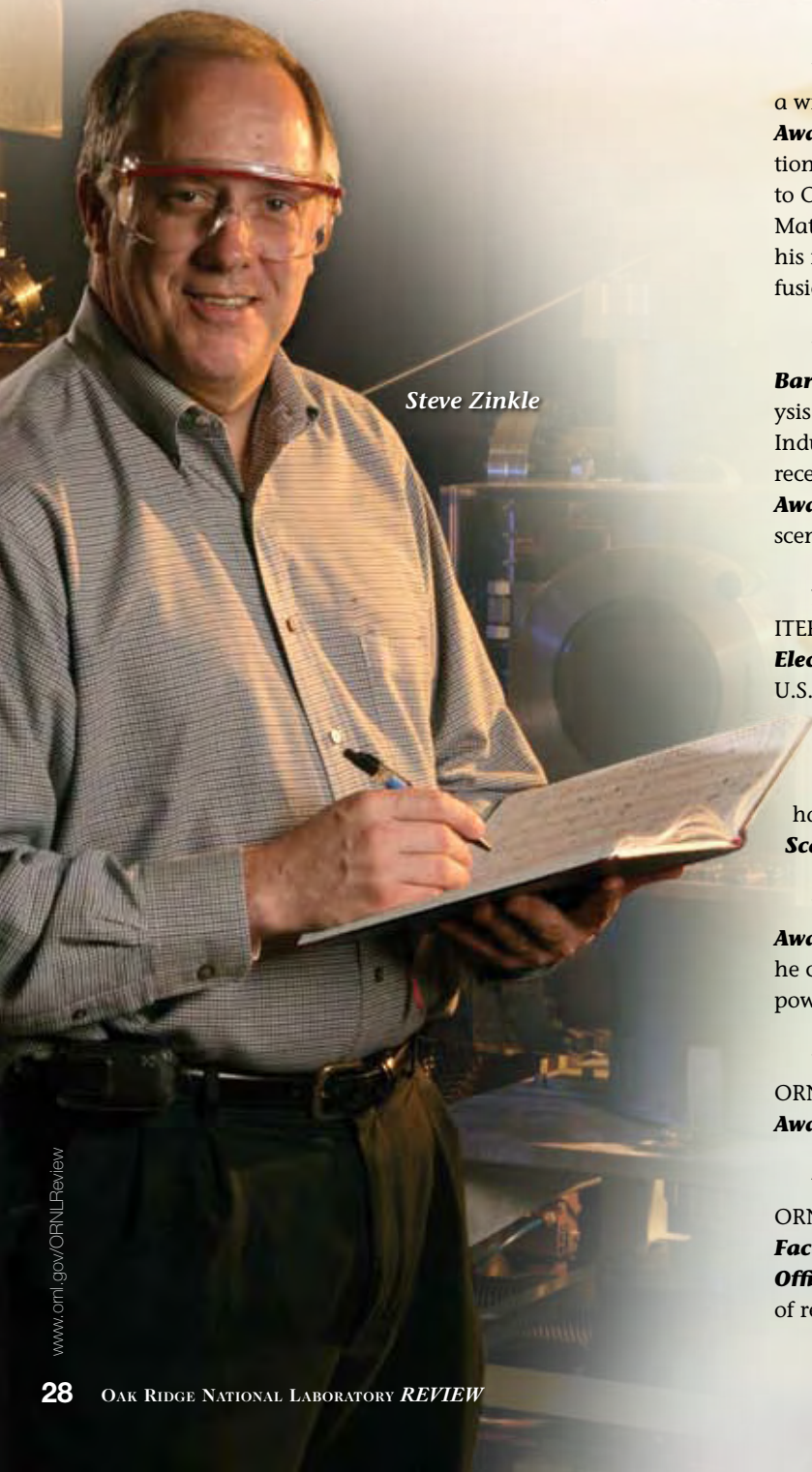
After creating thermally conductive polymer patches, the researchers will incorporate an array of vertically aligned nanotubes (VANTAs) to conduct heat quickly in the direction of the nanotube alignment to temperature sensors. Ivanov recently demonstrated that a heat pulse travels 20 times faster in a polymer containing VANTAs than in a pure polymer, indicating that the time response of temperature sensors positioned under the skin can be greatly improved.

The next step is to design sensors that detect temperature and pressure differences in FILMskin. Nanotubes could be used for temperature sensing because their electrical resistance changes when exposed to temperature changes. NASA's Park has shown that nanotubes can be dispersed in a novel biocompatible polyimide material and is now working on making the nanocomposite more responsive to pressure.

The researchers know about pressure. Says Ivanov: "DARPA wants to move really fast from basic research results to implementation of the concepts it selects."—*C. K.*

...and the WINNERS are...

Accomplishments of Distinction at Oak Ridge National Laboratory



Steve Zinkle

UT-Battelle Corporate Fellow **Steven J. Zinkle** has been named a winner of the Department of Energy's ***Ernest Orlando Lawrence Award***, which honors mid-career scientists and engineers for exceptional contributions in research and development. Zinkle, who came to ORNL as a Eugene P. Wigner Fellow and is now director of the Materials Science and Technology Division, was honored largely for his research on radiation's effects on ceramics and metallic alloys for fusion, fission and space reactor systems.

UT-Battelle Corporate Fellow **David Greene** received the 2007 ***Barry D. McNutt Award*** "for excellence in automotive policy analysis" during the recent Society of Automotive Engineers Government-Industry meeting in Washington, D.C. **Greene** and **Paul Leiby** received the ***2007 Department of Energy Hydrogen Program R&D Award***, "in recognition of outstanding contributions to hydrogen scenario analysis."

Ned Sauthoff, who is leading the U.S. role in the international ITER fusion project, has been named a ***fellow*** of the ***Institute for Electrical and Electronics Engineers***. Sauthoff, who heads the U.S. ITER Project Office at ORNL, was honored for his work in plasma physics and fusion energy at Princeton Plasma Physics Laboratory.

UT-Battelle Senior Corporate Fellow **Herbert A. Mook Jr.**, has been elected to the ***inaugural group of fellows*** of the ***Neutron Scattering Society of America***.

Masanori Murakami received the inaugural ***Nuclear Fusion Award*** from the ***International Atomic Energy Agency*** for a paper he coauthored on making fusion reactors efficient enough to produce power in this century.

Elissa Chesler, leader of the Mouse Systems Genetics Group in ORNL's Biosciences Division, received the annual ***Young Scientist Award*** of the International Behavioural and Neural Genetics Society.

Thomas Papenbrock, who holds a University of Tennessee–ORNL Joint Faculty Appointment, received an ***Outstanding Junior Faculty award*** from the ***Department of Energy's Office of Science, Office of Nuclear Physics***. This program supports the development of research programs of outstanding scientists early in their careers.

cheers to

Jeff Wadsworth

Laboratory Director
2003–2007

online extras

www.ornl.gov/ORNLReview

on the web

Watch:

- A video highlighting ORNL's cutting-edge buildings research

Download:

- Guides for energy-efficient construction and renovation

Read:

- About ways ORNL is helping industry become more energy efficient
- Steps you can take to make your home more energy efficient today

Reference desk:

- Technical and other publications detailing research outlined in this issue of the *Review*

next issue

Climate Research

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

ORNL *Review*

Editor and writer—Carolyn Krause
Writer—Larisa Brass
Designer— LeJean Hardin
Illustrator—Andy Sproles
Photographers—Charles Brooks, Larry Hamill and Wade Payne
Web developer—Dennis Hovey

Editorial office telephone: (865) 574-7183
Editorial office FAX: (865) 574-9958
Electronic mail: krausech@ornl.gov
Web addresses: www.ornl.gov
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 the Department of Energy's largest science and energy laboratory, with research competencies in neutron science, energy, biological systems, advanced materials, national security and high-performance computing.

UT-BATTELLE
Oak Ridge National Laboratory

OAK RIDGE
National Laboratory

OFFICE OF SCIENCE
U.S. DEPARTMENT of ENERGY