Material Differences

by Alan S. Brown

Innovations in materials and materials processing could play a pivotal role in resolving three of today's most pressing concerns: energy, climate change and the environment, and national security, says Jeffrey Wadsworth.

Wadsworth's unusual background makes his thesis worth hearing. The executive vice president of global laboratory operations for Battelle Memorial Institute, the world's largest independent non-profit research organization, Wadsworth will assume the duties of president and CEO in the fall. He now oversees Oak Ridge National Laboratory (which he directed), Brookhaven, Idaho, Lawrence Livermore, and Pacific Northwest National Laboratories, as well as the National Renewable Energy Laboratory and the National Biodefense Analysis and Countermeasures Center. He also helped establish the U.S. Department of Homeland Security's science and technology operations.

He is also a noted researcher. His 2005 induction into the National Academy of Engineering noted more than 250 papers on high-temperature materials (especially intermetallics) and superplasticity. In addition, he is well known as a historian of metallurgy, specializing in the Middle East's legendary Damascus swords.

As a result, Wadsworth's résumé combines world-class research; a broad yet intimate knowledge of the nation's most important energy and defense-related research; and a historian's eye for the way events have shaped science and technology.

Moreover, he has a profoundly engineering-oriented understanding of the world. He does not minimize the challenges posed by energy, climate change, or homeland security. Yet he remains powerfully optimistic: "Necessity is the mother of invention. We've done it before, and we can do it again."

That means action. He recalls sitting on a university's review board. "The school was thinking of closing its civil engineering program because it had only a few students," he recounts. "So I asked, 'If you really believe in global warming and that ocean water levels are going to rise, why not expand your department and specialize in ways to prevent coastal flooding?'

"The people who figure this out are the ones who are going to thrive," he explains. "We produce people who can state problems elegantly, but we also need people who understand how to solve these problems."

Dr. Jeffrey Wadsworth, executive vice president of global laboratory operations for Battelle Memorial Institute, the world's largest independent non-profit research organization, holds B.S., Ph.D., and D. Met. degrees in metallurgy.

Materials have given their names to the ages of civilizations. Jeff Wadsworth believes that the next materials age will help solve problems posed by energy, climate change, and national security.

THE CHALLENGE

Wadsworth believes that materials will enable many of those solutions, just as they always have. This is why materials have given their names to the ages of human civilization. The Stone Age defined humanity's ancestors as tool users. The Ceramics Age gave people a means to store oil, wine, water, and other products for prolonged periods. Bronze and then iron gave their names to civilizations that dominated the world for five millennia. Over the past half a century, nuclear power and then silicon electronics have reshaped our world in surprising ways.

New materials have changed the balance of power, starting with the sophisticated stone and bone tools that enabled Cro-Magnons to overwhelm Neanderthals in Europe, says Wadsworth. The city-states of Asia, Mesopotamia, and Europe rose to power with copper and then bronze weapons, only to fall before civilizations that had mastered harder and more deadly iron and steel.

Materials drove the modern war machines. New grades of iron and then steel harnessed the explosive power of gunpowder in firearms and cannons. Mass production of iron and steel products delivered by steel ships and trains using iron pressure boilers formed the backbone of the modern military while transforming the global economy.

The Manhattan Project tamed uranium and plutonium for the atomic bomb. Its success showed American policy makers that science could strengthen America's security. Defense dollars funded research into molybdenum, tantalum, niobium, and tungsten, which now play key roles in ballistic missiles. Military funding helped encourage the silicon revolution, and it paid for the development of such high-power and high-temperature electronic materials as gallium arsenide, silicon carbide, and gallium nitride.

It may take a similar governmental commitment to grapple with the three overriding concerns of our time, energy, climate change and the environment, and homeland security. Yet government has dealt with these issues since the Industrial Revolution, says Wadsworth. Only the specifics have changed.

"After World War II," he explains, "security was about the Cold War and the Cuban Missile Crisis. Now it is about terrorism, nuclear nonproliferation, and cybersecurity. Environmental issues have evolved from air pollution in Pittsburgh and smog in Los Angeles, to a more sophisticated understanding of CO_2 and global warming. Energy is still about finding more oil and whether to use nuclear, but now we're also talking about whether to invest in biofuels and wind energy."

Many of these issues are interconnected. Energy generation clearly affects environmental emissions and ultimately health. Building nuclear-power plants could provide more energy, but they would produce more radioactive materials that could fall into the hands of terrorists. Energy dependency makes the nation less secure and more vulnerable to terrorism aimed at hydrocarbon sources.

ENERGY

When it comes to energy, says Wadsworth, there is no such thing as a free lunch. In 2003, oil comprised 38 percent of global energy production, followed by coal and natural gas at just under 24 percent each, and nuclear power at 6.5 percent. Hydroelectric power supplied 6.5 percent of demand, and renewables (wind, solar, geothermal) 1.4 percent.

This mix presents problems. Coal and oil, the two most polluting sources of power, make up more than three-fifths of the total. Natural gas is much cleaner, but most oil producers flare it into the atmosphere (to prevent well explosions) because they are located too far from the pipeline infrastructure needed to use it.

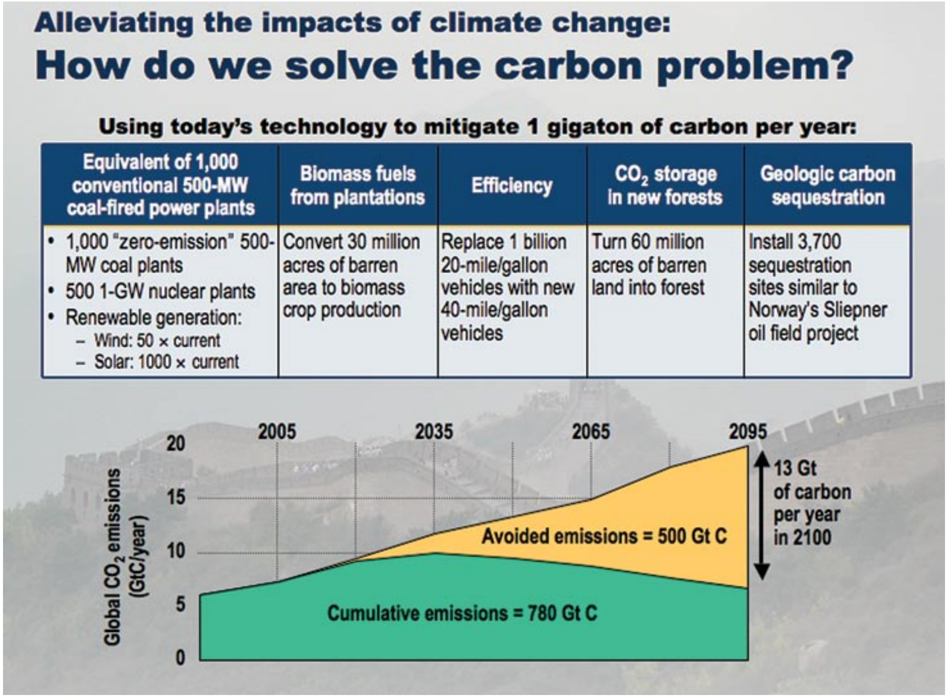
Also, energy demand is growing. A more affluent world aspires to the energy-intensive Western lifestyle. China, India, and other rapidly developing nations want cars, suburban homes, refrigerators, hot water, televisions, computers, and other energy-intensive conveniences. Wadsworth estimates that as global population rises to 9.2 billion in 2050 from 6.5 billion today, energy use will nearly double to 826 quadrillion Btus from 422 quads today.


Traffic in Beijing, 2006

The easiest route to more energy production runs through coal. China, for example, brings on roughly one new coal plant per week. Most have rudimentary if any environmental controls. The world is pumping more CO_2 into the atmosphere, and the consensus among the overwhelming majority of scientists is that this is accelerating the pace of climate change.

Policy makers hope to put a lid on emissions, but this is easier said than done. Consider, for example, wind energy. Wind accounted for 30 percent of America's new electrical generating capacity in 2007, according to the American Wind Energy Association. The U.S. Department of Energy estimates that wind could provide 20 percent of the nation's total energy demand by 2030 if build rates triple (entirely likely) and the nation invests in transmission lines to link wind generators to the power grid.

This sounds impressive. Yet assume U.S. energy consumption grows at historical rates (roughly 0.9 percent per year since the oil shocks of 1973). By 2030, energy consumption will rise to 122 percent of today's level. If 20 percent of American energy comes from wind, that leaves 80 percent from conventional sources. This 80 percent is equivalent to 97 percent of today's output (1.22 x 0.8 = .97 with rounding), compared with 98.6 percent today. Wind would have replaced future emissions, but it would have done almost nothing to reduce existing emissions.



NO SILVER BULLET

Wadsworth poses the same question in a different way. The world currently emits 7-8 gigatons of carbon annually. Using today's technology, what would it take to mitigate 1 gigaton of annual emissions? Among the possible solutions:

- Replace 1,000 conventional 500-megawatt (MW) coal plants with 1,000 zero-emission 500-MW coal plants, or 500 1-gigawatt (GW) nuclear plants. Or increase wind turbine use by a factor of 50 or solar cell use by a factor of 1,000.
- Convert 30 million acres of barren land—equal to one-third of American corn acreage in 2007—to biomass crop production.
- Replace 1 billion 20-mile-per-gallon automobiles with new 40-mpg vehicles. There were 250 million vehicles registered in the U.S. in 2006.
- Store CO_2 in 60 million acres of new forests (two-thirds of 2007's corn acreage).
- Install 3,700 sequestration sites similar to Norway's Sliepner oil field project, which injects carbon emissions into underground rock formations.

Assuming we start doing this soon, the world could avoid 500 gigatons of cumulative carbon emissions by 2095, says Wadsworth. But during the same period, we would release 780 gigatons of carbon into the atmosphere. By 2095, emissions would have declined only to 1990 levels.

There is no silver bullet, no one thing that will solve any of these problems, says Wadsworth. Instead, energy and environmental decisions involve tradeoffs.

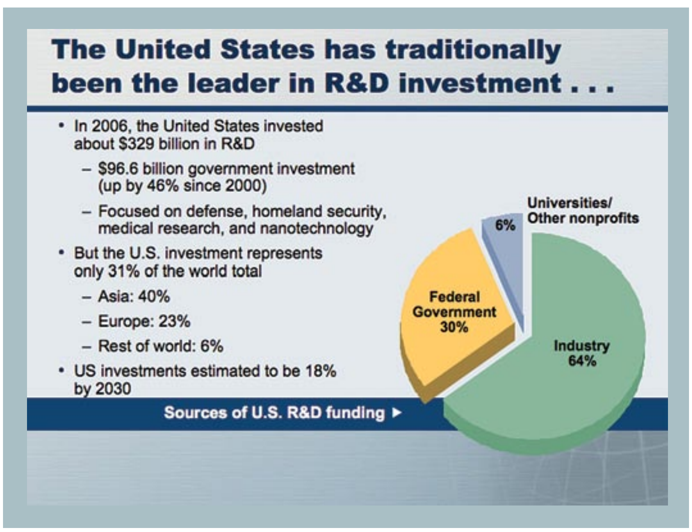
"There's nothing simple about generating energy," Wadsworth explains. "Something like wind energy looks attractive, but the towers are eyesores, and the generators are noisy. Tidal-wave energy has an impact on beaches and bird habitats."

Because every solution has costs and benefits, any combination of solutions will revolve around both technology and policy. He points to nuclear energy as an example.

"In 1974, the U.S. led the world in nuclear engineering and had more operating reactors than any other country in the world," he explains. "Due to policy decisions, the United States stopped building nuclear reactors. France continued to build them, and nuclear reactors now supply 80 percent of its electrical energy.

"This has big implications. If you look at CO_2 emissions from energy use, most countries fall on straight line. Those that use more energy produce more CO_2. The only exceptions are Brazil, because it uses sugar cane ethanol for cars, and France, because of nuclear energy."

Energy and climate change are linked in obvious ways. Yet homeland security is part of the same mix, says Wadsworth. America's enormous appetite for oil puts the nation at risk. We send much of our wealth overseas to buy oil from nations that do not embrace democracy or cultural tolerance.



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As we have learned in the Middle East, the threat may not come from nations, but from individuals who master or steal technology. In the past, they hijacked airplanes. In the future, they might build *dirty* radioactive bombs, wage cyberwarfare, or unleash such diseases as anthrax or plague. Because technology is so widely available and portable, terrorists might one day steal or build a nuclear bomb or *engineer* a killer virus.

For the past seven years, the Department of Homeland Security has funded the development of sensor materials that can detect nuclear materials or bioterrorism. In fact, the same sensors used to prevent bioterrorism are also the first line of defense in guarding against global pandemics. "The pandemic flu of 1918 killed more Americans than we lost in World War I, World War II, Korea, and Vietnam together," says Wadsworth. "With people flying all over the world, this is a security concern." The question is whether we can make surveillance technology powerful enough to catch an unexpected threat from an unseen enemy coming from an unknown direction.

CONCERNS

America's ability to answer these challenges will depend on research investment, science and technology education, and global competition, says Wadsworth.

Since the end of World War II, the United States has led the world in R&D investment. Today, it accounts for 31 percent of global R&D investment. The continents of Asia (40 percent) and Europe (21 percent) also are leaders. Yet U.S. R&D spending is growing more slowly than that of its competitors. Wadsworth expects America's share of global R&D spending to fall to 17 percent by 2030.

Wadsworth sees disturbing underlying trends. In 2006, the United States spent $329 billion on R&D. Business accounted for 64 percent of the total, primarily technology development and integration. Federal spending, roughly 30 percent or $97 billion, went primarily for defense, homeland security, medical, and nanotechnology research. In fact, governmental investment in R&D has risen 46 percent since 2000.

Yet federal spending for fundamental science has flattened or declined. This is critical, says Wadsworth, because early governmental funding of fundamental work has made the nation a leader in nanotechnology, genomics, medicine, and large-scale supercomputing.

The Spallation Neutron Souce, Oak Ridge, TN

For several years, Wadsworth has fought for more money for basic sciences. "There's been a huge effort to double the budgets of the National Institute of Standards & Technology [NIST], National Science Foundation [NSF], and the Department of Energy's office of science. Money has been placed in the budget, then zeroed out.

"If you look at basic science investment in the physical science, a lot of it is consumed in big, specialized facilities like the $1.4 billion spallation neutron source at Oak Ridge. That's good, but it decreases the amount of money available for research. We've also pulled back from some international projects, like ITER [a $9.3 billion fusion reactor being developed by nine countries]. We're looking like we're not a reliable international partner in science."

Science and technology education is also a concern. "U.S. students have not fared well on international science and math tests, and that can't be good," says Wadsworth. This has been a concern for a long time, but in the past the United States filled the gap by drawing the best researchers from all over the world to work here.

Wadsworth was one of them. "When I was going for my Ph.D. in England, every major work I referenced was written in the United States," he recalls. If he wanted to work with the best in his field, he needed to come to America.

That is no longer the case, especially in fields like nanoscience, computers, and biology. "The price of entry in these fields is quite low, maybe $100 million for a world-class facility. That's not much for a nation state," he says.

A visit to Tsinghua University in Beijing underscores his point. "They have a wonderful nanoscience center," says Wadsworth. "They have equipment that's the best in the world. When you walk into the entrance, the only illustrations on the walls are papers from the world's top journals, *Science* and *Nature*. There are facilities just like it in Singapore, Bangalore, and other fast-developing nations."

As a result, foreign nationals no longer have to come to the United States to study. Those that do study here no longer have to stay to do groundbreaking work. Today, says Wadsworth, more of them are returning home.

INVENTION

It is easy to feel overwhelmed. Yet Wadsworth believes human ingenuity and technology can help unknot these issues.

"In the early days of the industrial revolution," he says, "England had stripped all its forests to burn wood to smelt iron, and that led to an energy crisis. So they dug mines to get coal for coke smelting. When the mines flooded, they needed to pump out the water. That led to the invention of the steam pump, which gave us railroads, steamships, and more powerful industrial machinery.

"I believe the current energy crisis will result in many innovations. Everyone has begun tackling it. The question is, 'Who is going to get there first?'" says Wadsworth.

The U.S. Department of Energy, for example, has a strategic plan to reduce America's dependence on foreign

American Superconductor

The world's first high-temperature-superconductor power transmission cable system (above) was energized in Long Island Power Authority's grid in April 2008. This system, which consists of three cables running in parallel in a four-foot-wide right of way, is capable of carrying 574 megawatts of power. The three cables shown entering the ground can carry as much power as all of the overhead lines on the far left.

oil that covers power generation, energy transmission, and energy consumption. Its power programs range from high-yield biofuels and oil-shale extraction to nanomaterial-enabled solar cells and fusion. It seeks to reduce consumption through net-zero-energy homes, more efficient vehicles and engines, and smart electrical grids.

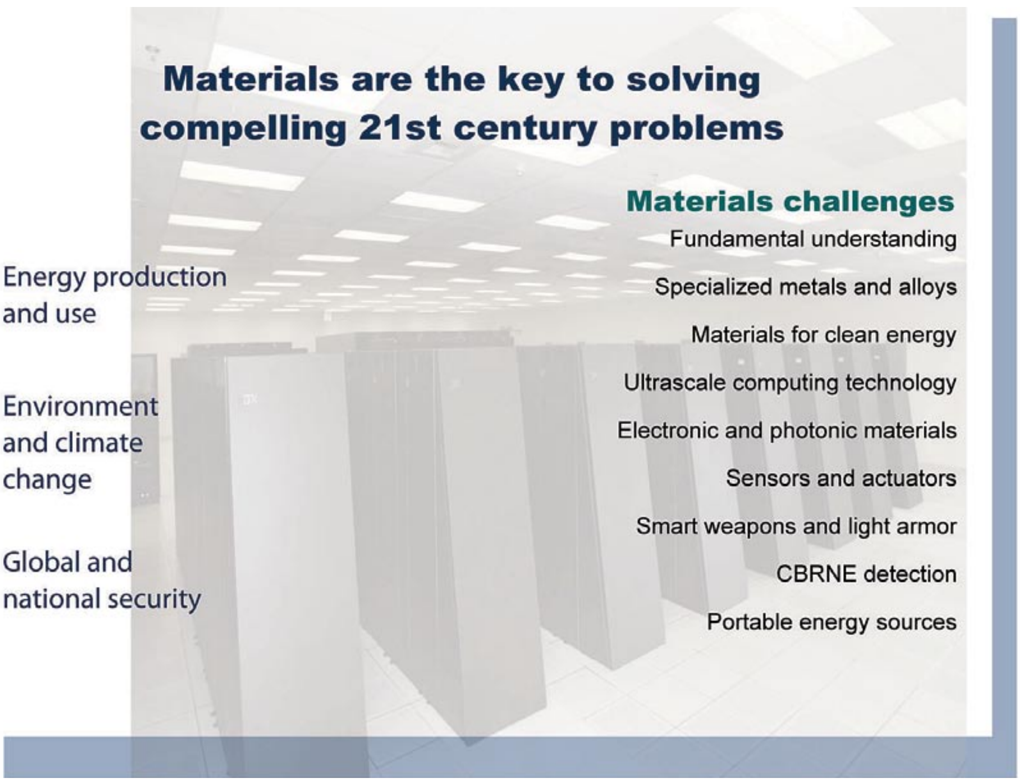
Materials play a role in all of this. Wind turbines and lightweight vehicles rely on glass and carbon-reinforced composites. Advanced solar cells use electronic thin films and nanomaterial coatings. More efficient engines require higher temperature materials.

Wadsworth points to several Oak Ridge materials innovations that will support these technologies. Some have already made it into the marketplace. He points to a new stainless steel with exceptional creep properties for turbo exhaust filters. It handles the high temperatures without deforming and letting hot particles sneak through.

Titanium-aluminide intermetallics developed at Oak Ridge withstand even higher temperatures. They roll hot steel plates in and out of furnaces. They not only improve furnace efficiency by 35 percent, but they survive much longer than the alloy rollers that they replace.

Oak Ridge is also deeply involved in synthesizing new materials. It is working with an industrial partner to commercialize ceramic superconductors by depositing thin films on moving metal ribbons. Superconducting wires could deliver power over vast distances with almost no electrical losses. This might make it possible for a wind farm in Kansas or solar facility in Arizona to power Atlanta or Seattle economically.

The laboratory is working on a new generation of superconductors based on fluorine-doped lanthanum-iron-arsenic. "They were discovered through computer simulations and may be able to operate at room temperatures," says Wadsworth. That would eliminate the need for the complicated cryocooling systems needed to chill superconducting cables below liquid nitrogen temperatures.



Other advances involve high-temperature materials. Becaue combustion efficiency rises as temperatures increase, they could improve the economy of a broad range of industrial processes. Researchers want to use high-temperature ceramics in these applications, but they are brittle. That may be ready to change.

Wadsworth points to silicon nitride as an example. Scientists have known that small additions of lanthanum toughen silicon nitride, but no one knew why. “Using an electron transmission microscope to look for the lanthanum was like looking for a needle in a haystack,” says Wadsworth.

“At Oak Ridge, we used 3D computer models to predict their location and explain their role in fracture mechanics,” he says. Researchers are now using the model to look for ways to improve ceramic toughness. Other researchers are using other complex models to learn how radiation weakens structural materials in order to build safer nuclear reactors.

The laboratory is also synthesizing single crystals of nanoscale molybdenum fibers. “We want to study fundamental behaviors, like why fractures occur where they do and how can we strengthen the fibers,” says Wadsworth. Among the tools used in the laboratory are diamond-tipped nanoindenters that make direct measurements of stress and strain.

Many of these advances have grown out of powerful new instruments and computational models.

Wadsworth is quick to point to Oak Ridge’s spallation neutron source, a $1.4 billion instrument designed and funded by a partnership of six national laboratories. It sets the global standard for neutron scattering research, a powerful tool that probes the inner workings of materials at subnanoscale levels.

Yet it is only one of five new facilities built at national laboratories expressly to study structures at the nanoscale level. They promise to provide a wealth of new data. Some of that data is likely to wind up in the second major advance in materials science: supercomputer-driven mathematical models of materials systems.

“Models do a lot more than explain or predict where atoms are in a structure,” says Wadsworth. “They enable us to explain fundamental behavior and redesign materials at the atomic level to improve their properties. Models have become a third leg of science, along with hypothesis and experiment.”

In fact, he states, the new material science of the Twenty-First Century is not just about materials, but about integrating materials sciences with other computing, nanotechnology, and even biology.

Biology offers an entirely new way of working with materials. It provides a set of tools that produces exact copies of materials like proteins and then controls their assembly into larger and more robust structures like cells, organs, bones, or complete individuals. Materials scientists have only begun to dream of taming its combination of precision and complexity.

And dream they will. If Wadsworth is right, necessity will push humanity forward. And new materials—and new ways of thinking about them and using them—will help us stand up to those new challenges.

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