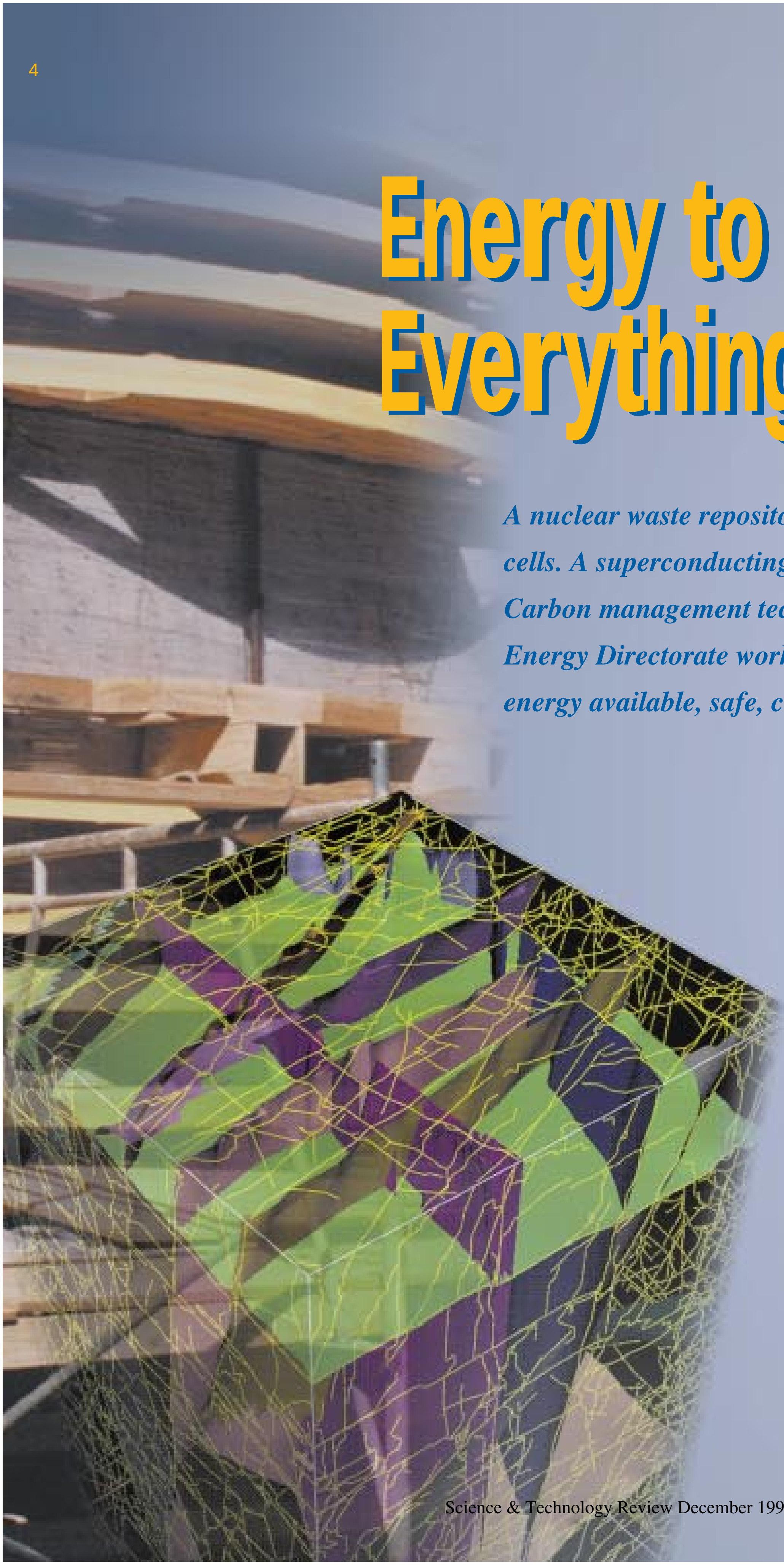

Energy to Keep Everything Running

A nuclear waste repository. Thin-film solid-oxide fuel cells. A superconducting magnet energy storage device. Carbon management technology. The Laboratory's Energy Directorate works in diverse ways to keep U.S. energy available, safe, clean, and inexpensive.

TO the unknowing eye, the energy chart produced by Livermore's Energy Directorate is just a tangle of lines, patterns, and colors (Figure 1). But to Energy staffers, it provides useful information about energy flow for a given year in the United States, from source to use.

Beyond its numbers, the chart portrays the complexities and interrelationships of the energy systems needed to support the quality of life and economic stability of the U.S. and, by inference, of any developed economy. It also points to substantial inefficiencies in converting energy into usable forms and transmitting, distributing, and using it.

Reducing these inefficiencies is one of the challenges that the Department of Energy faces in ensuring that U.S. energy needs can continue to be met. Energy availability is also threatened by other factors. The emergence of developing economies puts increasing pressure on world energy supplies. U.S.

dependence on foreign oil means that political disputes can result in energy crunches. The possibility of global climate change caused by burning fossil fuel is stimulating some rethinking about energy resources and energy production. In addition, the continuing concern about nonproliferation and nuclear waste disposal may limit nuclear energy options.

Pursuing Integration

Lawrence Livermore's Energy Directorate is helping DOE address some of these large energy issues. Not only is Livermore innovating technologies for energy production, storage, and distribution, it is assessing the risks and feasibility of various alternative energy resources and investigating transitions to other forms of energy.

The Laboratory continues to develop better ways to ensure the safety and reliability of nuclear power by addressing the technical problems of the nuclear fuel cycle from supply, fuel storage, and transport issues to waste storage, safety, and security issues. Livermore nuclear specialists are working with other national laboratories, private industry, and universities to propose the development of next-generation, small-scale fission reactors that improve reactor safety, economics, waste management, and proliferation resistance.

In the meantime, magnetic fusion energy researchers are experimenting with new fusion reactor configurations—such as a spheromak—not only to meet the scientific goals and requirements for achieving fusion, but also to make fusion power economically feasible. Feasibility will largely depend on finding more compact and less complex fusion

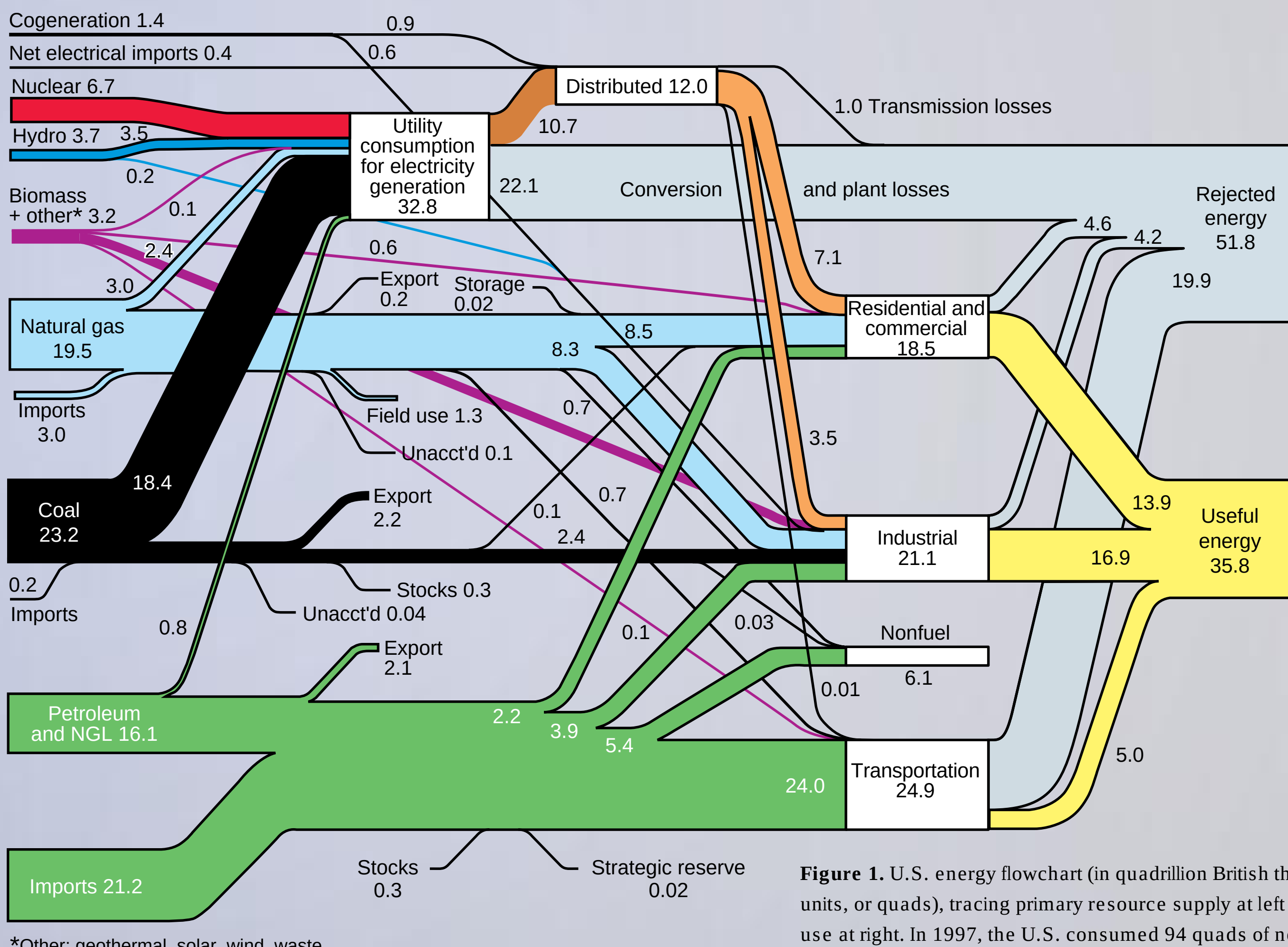

Figure 1. U.S. energy flowchart (in quadrillion British thermal units, or quads), tracing primary resource supply at left to end use at right. In 1997, the U.S. consumed 94 quads of net primary energy resources.

schemes. The spheromak generates its own magnetic fields by an internal dynamo and thus does not require as many magnets as fusion devices such as the tokamak, which in turn leads to engineering simplicity. By using a combination of theory, experiments, and advanced computational simulations, researchers are working to make the spheromak an attractive fusion reactor.

The breadth of the energy R&D landscape could lead to seemingly disparate research. However, Terry Surles, the new Associate Director for Energy, urges his scientific and technological experts to provide "big picture" thinking, which will create opportunities to solve complex national and international energy problems and do it better (see box below). He also directs effort toward developing new ways to use resident expertise to enlarge problem-solving capabilities, achieve synergies, and leverage Laboratory talent.

Because energy use is complex, research topics naturally are diverse. Surles encourages researchers to leverage their projects to reach a worthy objective: speed up the development of innovative technologies and ease their commercialization so the public can benefit from them sooner.

Livermore expertise can cut a wide swath through energy research and technology development needs, he says, "provided there is careful thinking about technology development—to identify the program areas most appropriate for Livermore—and the best integration of Livermore disciplines."

At the same time, Surles demonstrates how energy projects are less dispersed than they seem, because they can be organized into what he calls "a technology portfolio based on technology-specific 'bins' such as conversion and storage, carbon management, or the nuclear fuel cycle."

Keeping Nuclear Energy Viable

Although 20 percent of the country's electrical energy is supplied by nuclear power plants, challenges remain for this source of power. After the experience with Three Mile Island and Chernobyl, concerns continue about the safety and proper waste management of this source of relatively clean electricity.

One issue continuing to concern the public has been the disposal of hazardous nuclear waste generated by nuclear reactors. Thousands of metric tons of spent fuel from commercial nuclear power plants are being stored, temporarily, at facilities that are almost at capacity. A permanent disposal site is crucial, not only for safety and environmental reasons, but also for continuing nuclear power plant operation. Work to provide such a site has been progressing, with Lawrence Livermore involved in a key part of it.

The work on the Yucca Mountain Nuclear Waste Repository is now entering the viability assessment phase, which means that Congress will soon decide whether the Yucca Mountain site is suitable for nuclear waste disposal and whether to seek licensing by the Nuclear Regulatory Commission (NRC). Arriving at this decision point has taken over 20 years.

This considerable effort is required because the project is unique as well as important. No one has had experience in completely isolating stored nuclear waste materials for 1,000 years, which is the capability the NRC is requiring for the repository. After the 1,000-year mark, the nuclear waste releases cannot exceed more than 1 part in 100,000 of its remaining radionuclide inventory, and that rate must hold for at least 10,000 years. This means that repository scientists and engineers must predict how nuclear waste, subject to initially high temperatures as well as radiation, will behave in and interact with its engineered barrier system and the geologic environment for thousands of years.

Lawrence Livermore, one of many organizations working on Yucca Mountain, is responsible for the engineered barrier system to keep the waste contained (see *S&TR*, March 1996). The work to develop this system includes designing different waste packaging concepts to accommodate spent nuclear fuel and high-level waste, assisting in the design of the containers into which the waste packages will be placed, and studying the interactions of the waste and the waste packaging with the immediate repository environment.

Bridging Scientific Disciplines

Recent issues of *Science & Technology Review* have highlighted many Livermore energy projects, including:

- Induct95, software for simulating plasma-assisted manufacturing, October 1998
- Magnetically levitated train concept, June 1998
- Simulations of physics processes in magnetic fusion energy, May 1998
- Argus computerized security system, April 1998
- Software protection systems, March 1998
- Precision engineering, January/February 1998
- Oil-field tiltmeter, October 1997
- Nuclear power safety, July/August 1997
- Unitized regenerative fuel cell, May 1997

The goal—repository licensability—will be achieved only if high confidence in the long-term safety of the repository is demonstrated. Livermore's work toward this goal is being accomplished by a multidisciplinary team. A wide range of expertise is needed for conducting the detailed investigations of the material behavior and geologic conditions of an engineered barrier system and for developing models that will describe the system's long-term behavior and overall performance. Work performed by Livermore researchers has included a variety of tests to understand corrosion effects on candidate waste packaging materials; detailed measurements of actual blocks of Yucca Mountain rock to understand its thermal, hydrologic, and geochemical characteristics (Figure 2); and testing in the actual repository environment (carried out in onsite laboratories deep within Yucca Mountain) to determine the site's hydrologic and geochemical characteristics.

As the project moves closer to licensing application, which is slated for 2002, Bill Clarke, project leader for engineered barrier system materials, says the project is stepping up its quality assurance (QA) program and checking, certifying, and qualifying all project documentation.

"QA documentation," says Clarke, "provides the basis for scientists and engineers, the regulators, the government, and the public to engage in a process of understanding each other's point of view." The supporting facts and figures in QA documents also allow scientific assessments of repository performance to be defended in licensing hearings.

Clarke says that quality assurance will continue to be important through the long life of the repository because "future researchers without any actual experience on the project will need to understand the threads and progression of this work as they are evaluating repository performance."

One major component of the QA effort deals with the qualification of project software, specifically the large set of numerical models used to simulate repository processes to predict repository performance for tens of thousands of years into the future.

The demands on these models are unprecedented, and development has been challenging because data have been difficult to obtain. For instance, much of the information on how chemical processes affect rocks and other materials over very long times

Figure 2. (a) Rock was cut out of Yucca Mountain in Nevada and (b) tested to determine hydrologic and geochemical characteristics.

cannot be ascertained by accelerating the change processes in the laboratory. Rather, this information must be obtained from analogs—concrete in civil structures of known ages or very old relics excavated from geologic areas with characteristics relevant to Yucca Mountain geology (Figure 3).

The unique models are undergoing a highly structured qualification process that will provide documents describing the purpose, lifecycle, methodologies, and usage of the software. One important component of the documentation is the verification and validation plan, which provides for comparisons of modeling results with other codes, problems, and expert judgment.

Fusion Spinoff: Quality Power

Computer users know that surge suppressors are important for protecting sensitive electronics. Similarly, this kind of protection is even more desirable for expensive industrial equipment and electronic controls because their failure could shut down critical operations or an entire plant. When a momentary surge of power, sagging voltage, or other power-supply problem occurs and affects loads connected to a regional transmission system, a momentary supply of local "clean power" is needed.

Such a supply could come in the form of stored energy augmenting or substituting for incoming power. Energy storage technologies currently pursued by Livermore's Energy Directorate may prove useful for this purpose. These include the modern battery, flywheel, and superconducting magnetic energy storage (SMES) systems. Although batteries deliver hundreds of watts, and flywheels can store some tens of kilowatts, SMES systems can deliver multimegawatts and more.

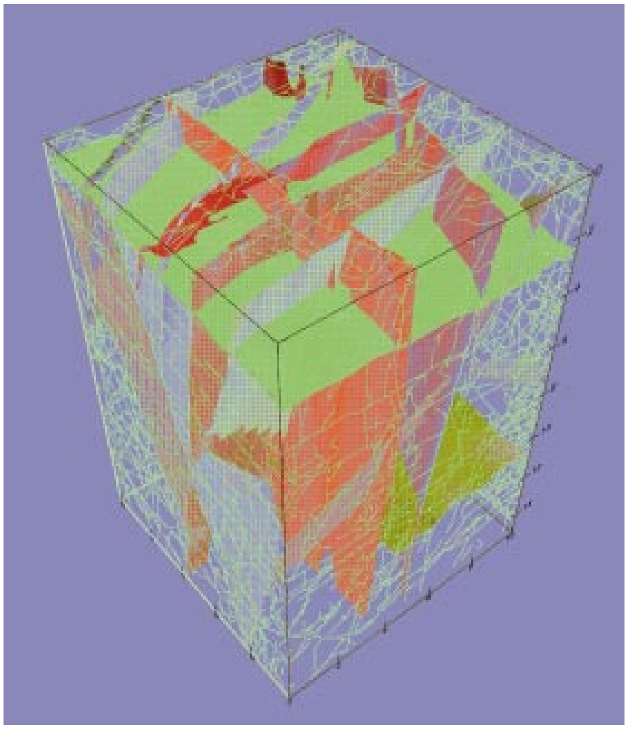

Figure 3. Chemical processes from the rock tests (see Figure 2b) and other data are being integrated into a model of the immediate environment of the proposed Yucca Mountain nuclear waste repository.

Superconducting magnets of the specific type useful for a SMES system have been in continuous development in magnetic fusion energy programs throughout the world. Specifically, the conductor for these magnets, consisting of superconducting cable inside a conduit with liquid helium flowing under high pressure, is a major development. This kind of conductor must exhibit little loss when stored energy is extracted from the magnet.

Livermore's superconducting magnet experts have been collaborating in a national effort to build a model superconducting coil for the International Thermonuclear Experimental Reactor. In addition, Livermore has a high-field, high-current magnet test facility—one of only a few similar testing facilities in the world. The combination of expertise and facility proved attractive to the International Superconductivity Technology Center of Japan and led to a contract to test the Toshiba Corporation's SMES developmental coil, which is part of a Japanese national project.

At the Laboratory, the 3.5-meter-diameter Toshiba SMES coil has been installed in a 4-meter-diameter vacuum vessel (Figure 4). A crew of mechanical and electrical engineers and technicians has been busily getting the superconducting magnet testing facility online after it had been mothballed for three years.

In the facility's control room, engineers Jon Zbasnik and Nicolai Martovetsky have been planning the tests and performing system checkouts with several Toshiba engineers. Tests will provide information such as how well the coils' superconducting material performs, how well the coils can cycle without excessive energy loss, and how many cycles can be run before maintenance is needed.

Toshiba envisions a pilot SMES plant using a toroidal magnet system to store up to 480 megajoules. Ray Smith, engineering group leader for Energy, says that SMES devices, when fully developed, will have several uses. For example, in addition to providing emergency power in critical facilities where electrical power loss could cause big problems, SMES devices may be used to create an immense network of distributed storage systems that could radically alter the energy infrastructure in a deregulated system.

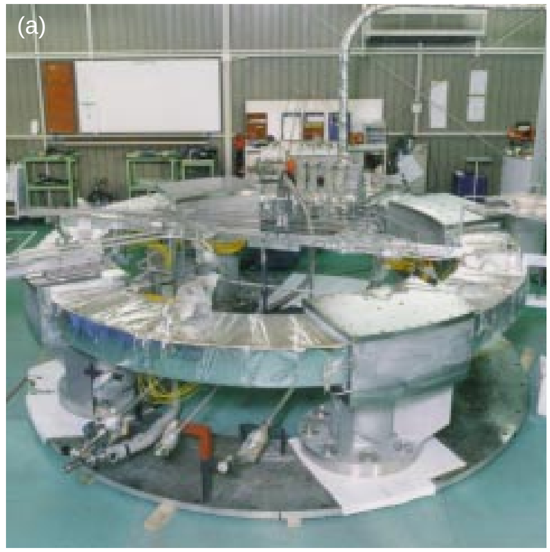

Figure 4. The Laboratory is testing (a) Toshiba Corporation's developmental superconducting coils at (b) Livermore's Superconducting Magnet Test Facility. Such magnet coils would be used as energy storage devices for emergency power.

Improving Generating Efficiency

Most combustion processes that generate electricity use fossil fuel and create pollution. A fuel cell, which converts the chemical energy in fuels directly into usable electricity without combustion, is highly efficient and far less polluting. Lawrence Livermore scientists have studied a variety of fuel cells—zinc–air, proton exchange membranes, and solid-oxide—for transportation and stationary power applications.

Solid-oxide fuel cells (SOFCs) have emerged as the Livermore fuel cell technology with the greatest potential. Livermore's materials-science expertise has led to new concepts in thin-film deposition and multilayer technologies that are being used to improve the cells' power density, reduce their operating temperatures, and lower their fabrication costs.

SOFCs consume fuel and an oxidant that are combined at elevated temperatures to produce electrical current. A fuel cell consists of three electrochemical components: a cathode that electrochemically reduces oxygen from air, an electrolyte that ensures the transport of oxygen ions, and an anode where fuel (hydrogen or another combustible gas) is oxidized by combining with the oxygen ions transported through the electrolyte. A single fuel cell generates a low voltage (about 1volt), so many fuel cells must be connected in series (a fuel cell stack) to obtain higher voltage. An electrical interconnect provides contact between cells (Figure 5).

A fuel cell can be made more efficient when its electrolyte layer is made thinner, thus reducing its resistance losses. Livermore has developed fuel cells that use thin films of yttria-stabilized zirconia to reduce electrolyte thicknesses as well as fuel-cell operating temperatures by at least 200°C (Figure 6).

The world leader in developing SOFCs, Westinghouse, uses a tubular geometry for the anode-electrolyte-cathode trilayer. Commercializing the SOFC, however, has been slow partly because the method for depositing the thin-film electrolyte in this configuration proved to be a delicate, time-intensive, and expensive operation. Livermore has been performing work to get around this problem.

In a Laboratory Directed Research and Development project to improve the thin-film technology used for SOFC manufacturing and to increase power density, materials scientist Quoc Pham is leading a team to develop a new thin-film deposition technique that may pave the way to commercializing SOFCs. The technique is based on colloidal processing, in which a substrate is repeatedly dipped in a colloidal solution. Pham's team modified this well-known process to a single coating that ranges from 1 to 80 micrometers thick. The new technique can be applied to a variety of substrate geometries. Prototype planar fuel cells fabricated with this deposition technology were tested and found to produce very promising power densities. Pham and the team are now modifying the technique for tubular substrates.

The team is also experimenting with a compositionally graded fuel-cell structure, which starts out at one edge as a pure material (the anode), progressively changes to another material (zirconia, the electrolyte), and finally transitions into the pure cathode material. The graded structure serves two purposes. It alleviates problems with chemical incompatibility between materials, and it alleviates the stress that arises from differences in thermal expansion coefficients that often exist between two pure materials. Stress usually leads to cracking at the interface during thermal cycling.

In separately funded work, the team's thin-film processing technique will be spun off to develop high-temperature steam electrolyzers that can produce hydrogen from water electrolysis. Hydrogen is an important reactant in the chemical processing industry and potentially an important, nonpolluting transportation fuel. Water electrolysis is a simple technology for producing hydrogen, simpler than more commonly used methods such as steam reforming of natural gas or coal gasification. However, water electrolysis has not been cost effective because it consumes large amounts of electricity. The Livermore technology can be used to fabricate steam electrolyzers that are cost competitive and ideal for small-scale use as well as large industrial applications.

The novel chemical and thin-film deposition processes will spin off in numerous other ways, according to Bob Glass, program leader for Energy Storage and Conversion Systems. They will be particularly useful for applications where a robust coating of oxide materials is needed or where planar as well as complex substrates must be coated. As the team is developing next-generation fuel cells, it is also helping private industry lower manufacturing costs and thus hasten commercialization of current SOFC designs.

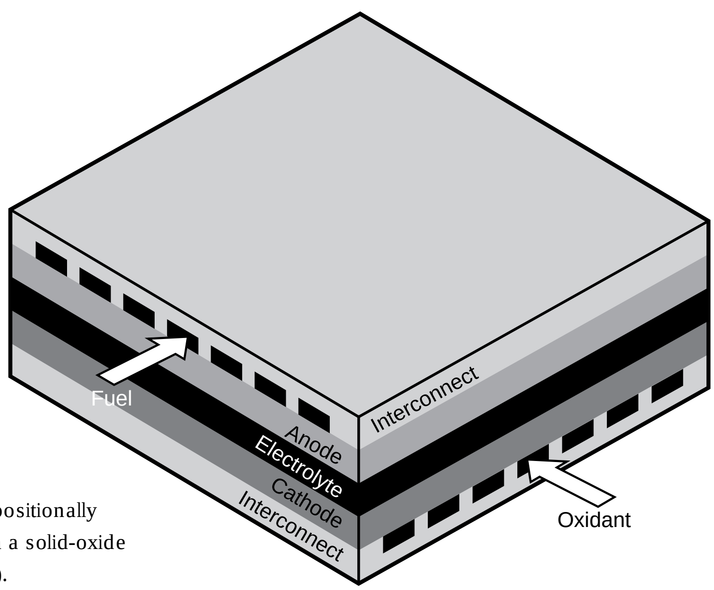

Figure 5. Compositionally graded layers in a solid-oxide fuel cell (SOFC).

Ahead: Sequestering Carbon

One important goal of Livermore's energy research is to find ways of mitigating the potentially adverse environmental effects of burning fossil fuels. Of major concern are the greenhouse gases (primarily carbon dioxide) that are emitted to the atmosphere from burning fossil fuels and that may be contributing to global climate change.

Carbon management is the umbrella term for three mitigation approaches: (1) reduction of carbon emissions through increasing various efficiencies (fossil-fuel-fired power plants and manufacturing process technologies); (2) decarbonization of the energy mix by using energy resources that involve no carbon (fission, fusion, or hydrogen and renewable energy resources) or less carbon (natural gas combined-cycle power plants); and (3) carbon sequestration, the capture and destruction or storage of carbon for geologic time periods.

Research in carbon sequestration technology is a natural extension of climate research work being carried out in the Laboratory's Earth and Environmental Sciences Directorate. A large component of that work is devoted to understanding the carbon cycle in nature (see *S&TR*, March 1998, pp. 14–20). When technologists began looking at the option of injecting CO_2 into the ocean for storage, Livermore's carbon cycle modeling experts found they could contribute their expertise to evaluate the feasibility, costs, and risks of this idea.

CO_2 is absorbed into the ocean by a number of ongoing but very slow natural processes. The ocean's capacity for CO_2 is quite large. However, important questions must be answered before CO_2 sequestration in the ocean can be deemed viable. For example, given the natural cycling of carbon, how long would the CO_2 stay put in the ocean?

Ocean modeler Ken Caldeira attempted to answer this question by simulating the injection of CO_2 into the ocean off Cape Hatteras, North Carolina. The simulations revealed that most of the injected CO_2 slowly returned to the atmosphere, but the length of time it remained in the ocean depended on how deeply it had been injected. Simulations of injections to 410 meters showed the carbon remained in the ocean for over 100 years, and injections to 1,720 meters remained for over 450 years.

Although the modeling results look promising for ocean injection and storage of CO_2, the fact that storage is not permanent led Caldeira and colleague Greg Rau to look at other ocean processes controlling the carbon cycle, including some that occur over thousands to hundreds of thousands of years. Among the most important of these natural processes is one in which the CO_2 in seawater forms carbonic acid and dissolves carbonate sediments, typically the shells of ancient organisms. This "rock weathering" phenomenon is commonly observed by geologists; it is one of nature's ways of depleting CO_2.

Recently, Rau and Caldeira came up with a new concept to mimic this weathering chemical process in reaction vessels and use it for human control of CO_2. The approach converts aqueous carbon dioxide—one of the products of dissolving CO_2 in water and the form that eventually cycles back to the atmosphere—into a bicarbonate, which does not interact with the atmosphere and therefore fixes carbon in the ocean.

The reaction vessel Rau and Caldeira designed for the process holds inside it a bed, pile, slurry, suspension, or aerosol of metal carbonate mineral (Figure 7) such as that found in limestone. Carbon dioxide, which may come from the waste stream of a power plant, enters from one side, comes into contact with water, and becomes hydrated to form carbonic acid, a chemical that can dissolve limestone and other carbonate minerals. When the carbonic acid dissolves the metal carbonate inside the vessel, it reacts the CO_2 to form bicarbonates in solution, effectively sequestering the CO_2 from the atmosphere. Waste streams exiting the reaction vessel comprise a gas stream depleted of CO_2 and an aqueous

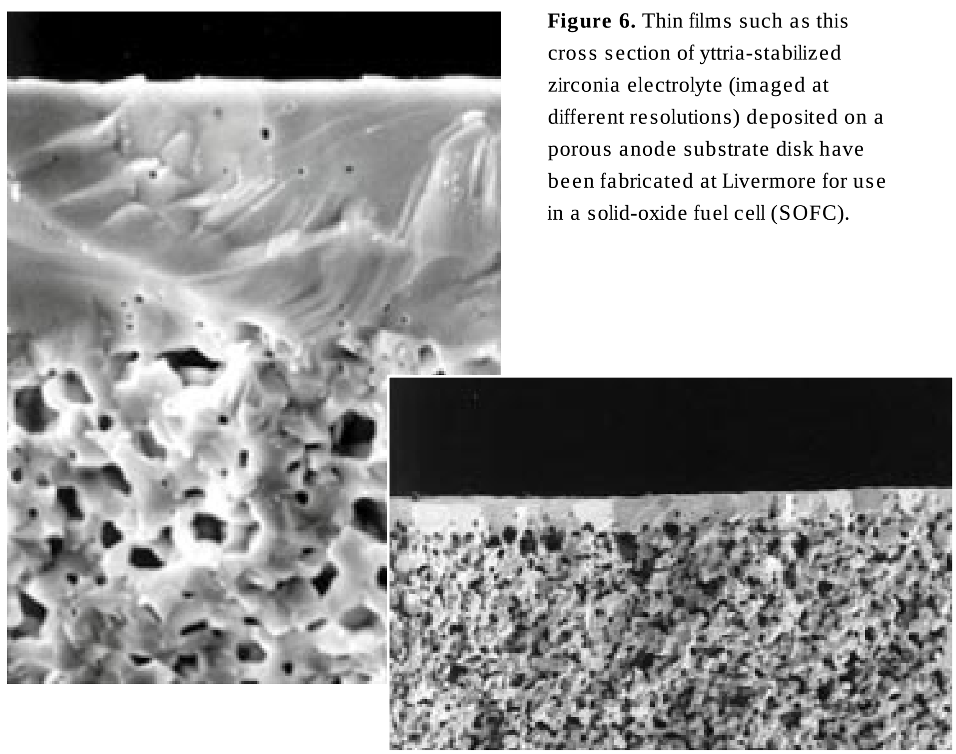

Figure 6. Thin films such as this cross section of yttria-stabilized zirconia electrolyte (imaged at different resolutions) deposited on a porous anode substrate disk have been fabricated at Livermore for use in a solid-oxide fuel cell (SOFC).

solution of metal ions and bicarbonate that can then be injected into the ocean.

Rau and Caldeira are the first to propose accelerating natural carbon mineral weathering reactions to sequester carbon dioxide in the ocean in the form of bicarbonate. Their reaction vessel is still in the design stage but is envisioned for use wherever there is waste gas containing CO_2. Many processes produce such waste streams: the combustion or processing of coal, petroleum, natural gas, or other fossil fuel; the combustion, processing, or metabolism of wood, peat, plant products, or organic compounds derived from them; and the decarbonation of limestone in the production of lime, cement, and gypsum. Caldeira says, “This device may be a cheap and easy first fix to control carbon dioxide, if the global warming issue comes to be taken seriously.”

Contributing Pieces to a Portfolio

A wide spectrum of energy technologies will be needed to meet the long-term energy needs of the U.S. and the world. Lawrence Livermore is doing its part to assure a viable energy portfolio for the future, and the Energy Directorate is charting a course to make sure the Laboratory’s contribution to that portfolio provides an integrated perspective.

— Gloria Wilt

Key Words: carbon sequestration, energy, fuel cell, global warming, nuclear waste repository, ocean model, quality assurance (QA), solid-oxide fuel cell (SOFC), superconducting magnetic energy storage (SMES), thin films, Yucca Mountain.

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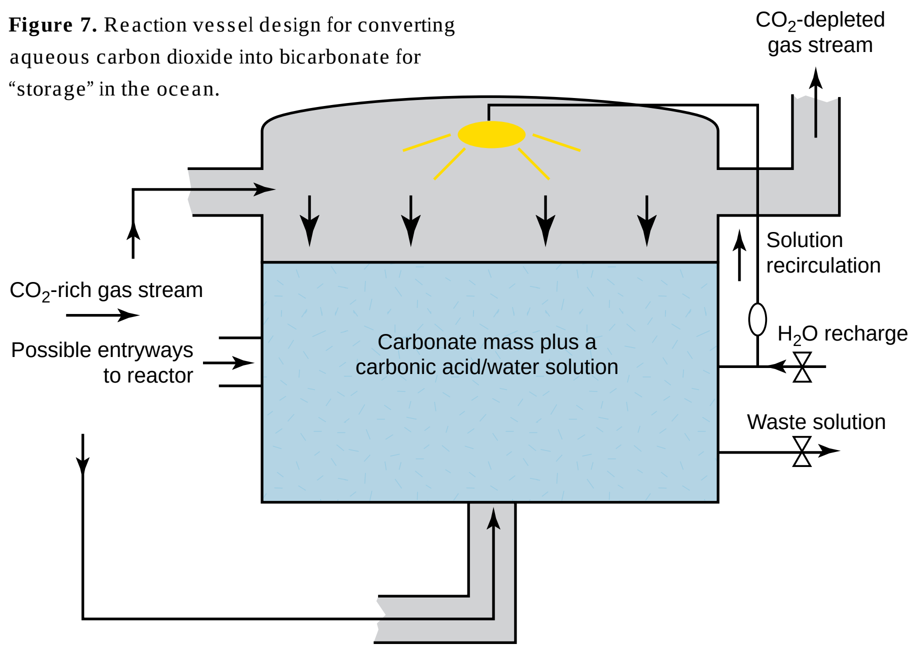

Figure 7. Reaction vessel design for converting aqueous carbon dioxide into bicarbonate for “storage” in the ocean.

About the Engineer

MARK STRAUCH came to Lawrence Livermore from the University of Michigan, where he received his B.S. and M.S. in electrical engineering in 1976 and 1978. An electrical engineer, he joined the Electronics Engineering Department to work on the Magnetic Fusion Energy Program. Since then, he has also supported the weapons program and O Division and was a group leader and division leader in the Engineering Directorate. He became deputy program leader of the Fission Energy and Systems Safety Program and assistant deputy associate director in the Energy Directorate five years ago. Strauch is an active member of the Institute of Electrical and Electronics Engineers.