April 1996

Science & Technology REVIEW

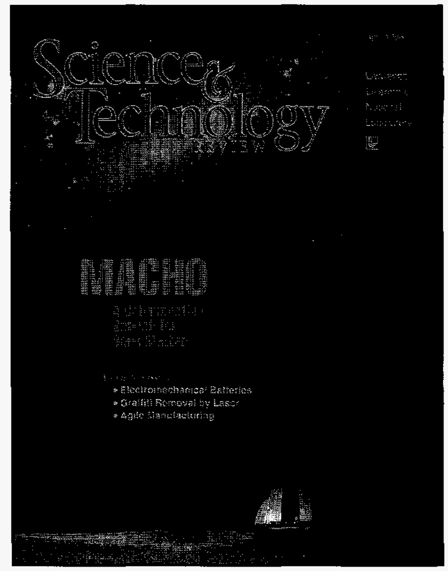
Lawrence
Livermore
National
Laboratory

MACHO

Also in this issue:

- Electromechanical Batteries
- Graffiti Removal by Laser
- Agile Manufacturing

The Mt. Stromlo Observatory's 1.27-m reflecting telescope scans the Southern Hemisphere's night sky for MACHOs in collaboration with Livermore researchers. About ten million CCD images per night from the Large Magellanic Cloud (background, magnified) are providing data to support the theory that MACHOs exist and comprise over half the dark matter in the universe.



Cover image: John Maduell

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The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. *Science and Technology Review* (formerly *Energy and Technology Review*) is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments, particularly in the Laboratory's core mission areas—global security, energy and the environment, and bioscience and biotechnology. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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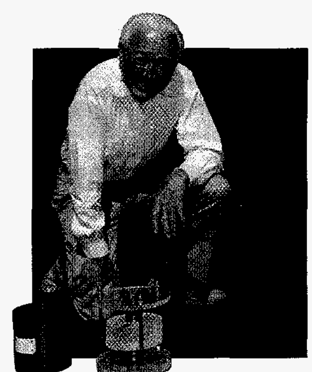

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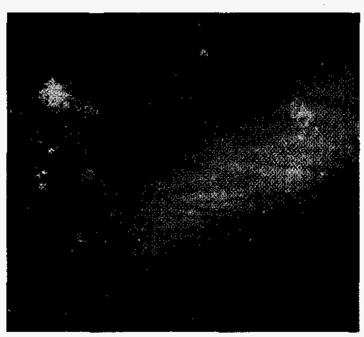

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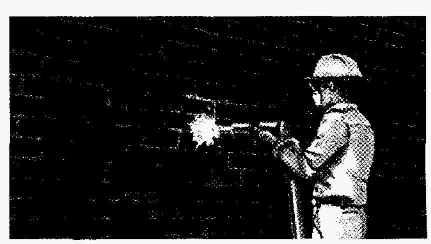

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Lab succeeds in quest to metallize fluid hydrogen

A Livermore team is reporting success in a quest that has long eluded condensed-matter physicists: the high-pressure, high-temperature metallization of hydrogen, the simplest and most abundant element in the universe. Scientists predicted early this century that hydrogen metallizes when subjected to extremely high pressures, but they have been unable to prove it. Livermore researchers achieved metallization by employing a two-stage gas gun to perform shock-compression experiments on liquid hydrogen. On the basis of electrical conductivity experiments, they found that the metallization pressure of fluid hydrogen is 1.4 million bars at nine-fold compression and 3,000 K. For comparison, pressure at sea level is 1 bar. These results suggest that the metallization pressure is temperature-dependent because predictions are 3 million bars at 0 K.

Understanding how hydrogen behaves at high pressures and temperatures is important to planetary and inertial confinement fusion scientists. The planet Jupiter is 90% hydrogen; the hydrogen in its interior is at temperatures and pressures equivalent to those measured in these experiments. Hydrogen, in the form of deuterium and tritium isotopes, is the fuel in inertial confinement fusion targets, which also reach temperatures and pressures equivalent to those measured in these experiments.

The LLNL team's findings are already creating a noticeable impact in the physics community, where metallizing hydrogen is a controversial subject. These new results have been accepted for publication in Physical Review Letters in a paper titled "Metallization of Fluid Molecular Hydrogen at 140 GPa (1.4 Mbar)" by the team of Sam Weir, Art Mitchell, and Bill Nellis.
Contact: Bill Nellis (510) 422-7200 (nellis1@llnl.gov).

Lab hosts U.S.–Russian plutonium disposition panel

In January the Laboratory hosted a three-day meeting of a U.S.–Russian committee studying options for disposal of surplus plutonium from dismantled weapons. The U.S. delegation was headed by Dr. Bruce MacDonald of the White House Office of Science and Technology. Nikolai Egorov, vice minister of the Russian Federation Ministry for Atomic Energy and head of the Russian delegation, said he thought that it was particularly relevant that the two countries were discussing the issue at Livermore.

In January 1994, U.S. President Bill Clinton and Russian President Boris Yeltsin agreed to create a joint working group of experts to study options for long-term management and disposition of fissile materials, particularly plutonium. The group is scheduled to issue its final report in early summer.
Contact: Jeff Kass at (510) 422-4831 (kass1@llnl.gov).

Construction management firm selected for NIF

Following a nationwide search, Sverdrup Facilities Inc. has been selected as construction manager for the proposed National Ignition Facility. The firm is nationally recognized for its expertise in design and construction of highly complex scientific facilities, such as the alternate Space Launch Complex at Vandenberg Air Force Base.

The stadium-sized NIF, designed to play an essential role in safeguarding the nation's nuclear stockpile, will be housed in a complex of structures. The two main buildings will be the Laser and Target Area Building and the Optical Assembly Building. Sverdrup will provide construction management services for both buildings.

Livermore is the preferred Department of Energy site for NIF, but a final decision on locating the project will not be made until later this year.
Contact: Bill Hogan at (510) 422-1344 (bill-hogan@llnl.gov).

Study offers recommendations on fuel-tank cleanups

Billions of dollars could be saved and thousands of acres of land returned to use sooner if California adopts new approaches to cleaning up its leaking underground fuel tanks. That is a finding of a Laboratory study, conducted in collaboration with other University of California scientists. The study was performed for the California State Water Resources Control Board, which regulates cleanup of leaking fuel tanks.

In most cases, said the study team, naturally occurring microbes in soil and water can clean up fuel contamination as effectively as human "pump-and-treat" efforts. Fuel contamination generally does not spread far, the researchers determined, and microbes will usually break down most pollutants before they can reach a source of drinking water.

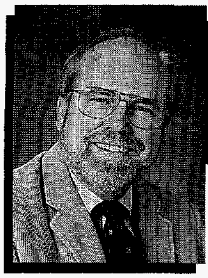
The study recommended that, in many cases, active cleanup at low-risk sites be stopped and naturally occurring microbes allowed to complete the restoration. A large proportion of the state's sites can be considered low-risk, the report concluded. Sites being remediated through natural microbial action still would be cleaned to existing state regulatory standards.
Contact: David Rice at (510) 423-5059 (rice4@llnl.gov). Copies of the study can be obtained by faxing a request to the State Water Resources Control Board's Rachel Horsley at (916) 227-4349. The study is also available on the Laboratory's World Wide Web site at http://www.llnl.gov/environment/erd/rice.

[redacted]

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Ger van den Engh	**Flow Cytometer** U.S. Patent 5,464,581 November 7, 1995	A method and apparatus for deflecting and sorting charged particles in a fluid stream passing between a part of oppositely charged deflection plates. Ground planes associated with each deflection plate change the electric field between the charged plates to produce very accurate focus of the charged particle. Oppositely curved electric fields with multidirectional force vectors are produced.
Thomas E. McEwan	**Two-Terminal Micropower Radar Sensor** U.S. Patent 5,465,094 November 7, 1995	A radar motion sensor with associated switch that requires only a single wire pair for connection to a power source. The sensor functions as a normally open, single-pole, single-throw switch configuration. The switch, e.g., a MOSFET, is in series with the power supply and the load, which is a warning device. The output of the radar motion sensor controls the operation of the switch. A capacitor or battery is charged when the switch is open and powers the motion sensor when the switch is closed.
Steve B. Brown Fred P. Milanovich	**High Aspect Ratio, Remote Controlled Pumping Assembly** U.S. Patent 5,466,128 November 14, 1995	A remotely controlled, miniaturized dual pump assembly capable of simultaneously supplying and withdrawing a reagent to and from a sensor of a contamination measurement system. The dual-acting pump assembly fits into a small-diameter penetrometer cone or well packer assembly.
Paul G. Carey Jesse B. Thompson Nicolas J. Colella Kenneth A. Williams	**Solar Cell Array Interconnects** U.S. Patent 5,466,302 November 14, 1995	Electrical interconnects for electronic components using a silver–silicone paste or a lead–tin, no-clean, fluxless solder cream, whereby the high breakage of thin solar cells using conventional solder interconnect is eliminated. No degradation of the interconnects develops under high-current testing while providing a very low contact resistance value.
Dennis Sasaki Ger Van den Engh Anne-Marie Buckle	**High Speed Flow Cytometric Separation of Viable Cells** U.S. Patent 5,466,572 November 14, 1995	The separation of hematopoietic cell populations to provide cell sets and subsets as viable cells with high purity and high yields, based on the number of original cells present in the mixture. High-speed flow cytometry is employed using light characteristics of the cells to separate the cells, where high flow speeds are used to reduce the sorting time.
Steven Falabella	**Magnetic-Cusp, Cathodic-Arc Source** U.S. Patent 5,468,363 November 21, 1995	An ion source using a filtered cathodic arc for the production of dense, adherent coatings wherein the filtering eliminates or reduces macro-particles normally produced by the cathodic arc. The arrangement provides high magnetic fields for good ion transport while producing a low impedance path for electrodes from cathode to anode. A pair of coils, with the cathode in the center of one, produces a plane of zero magnetic field, with a hollow annular anode at the plane.
John W. Elmer Alan T. Teruya Dennis W. O'Brien	**System for Tomographic Determination of the Power Distribution in Electron Beams** U.S. Patent 5,468,966 November 21, 1995	A technique for measuring the current density distribution in electron beams using electron-beam profile data acquired from a modified Faraday cup to create an image of the current density in high- and low-power beams. The cup has a slit across which the beam is directed in a controlled manner for producing output signals that can be used for computer tomographic reconstruction showing the power distribution of the beam.
Daniel A. Seligmann William C. Moss Theodore C. Valk Alan D. Conder	**Compact Self-Contained Electrical-to-Optical Converter/Transmitter** U.S. Patent 5,469,442 November 21, 1995	A signal-conditioning circuit with elements electrically coupled to a transducer and optically coupled to a receiver/processor. The circuit elements receive an analog signal from the transducer, generate a linear reference signal, and mix the analog and reference signals to form a calibrated output signal that is converted to an optical signal.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Thomas E. McEwan	**High-Speed Transient Sampler** U.S. Patent 5,471,162 November 28, 1995	Sampler that comprises a sample transmission line for transmitting an input signal, a strobe transmission line for transmitting a strobe signal, and a plurality of sampling gates at respective positions along the sample transmission line for sampling the input signal in response to the strobe signal. The sampling gate applies a very small load on the sample transmission line and on the strobe generator.
C. Robert Wolfe Mark R. Kozlowski John H. Campbell Michael Staggs Frank Rainer	**Permanent Laser Conditioning of Thin Film Optical Materials** U.S. Patent 5,472,748 December 5, 1995	A method for producing optical thin films with a high laser damage threshold. The laser damage threshold of the thin films is permanently increased by irradiating the thin films with a fluence below an unconditioned laser damage threshold. The film is irradiated with a laser beam in a ramp-like fashion where successive steps are applied at higher fluences.
William C. Sweatt Lynn Seppala	**Method for Changing the Cross Section of a Laser Beam** U.S. Patent 5,473,475 December 5, 1995	A method and apparatus in which a circular optical beam is converted to a beam having a polygonal profile by using an optical mirror with a reflecting surface designed in accordance with a specifically derived formula in order to make the necessary transformation, without any substantial light loss or change in the uniform intensity profile of the circular beam.
Steven Falabella	**Fabrication of Amorphous Diamond Films** U.S. Patent 5,474,816 December 12, 1995	A method for coating a substrate with an amorphous diamond film by cooling and biasing the substrate and condensing carbon ions thereon; the substrate may be cooled while carbon ions are being condensed onto the substrate. The article may be coated at or below room temperature. The resulting article has at least one surface with an amorphous diamond film coating and an intrinsic stress below 6 gigapascals.
Raymond P. Mariella, Jr. Gerrit van den Engh M. Allen Northrup	**Aqueous Carrier Waveguide in a Flow Cytometer** U.S. Patent 5,475,487 December 12, 1995	A method and apparatus that use the aqueous flow stream of a flow cytometer as an optical waveguide and measure scattered light trapped within the aqueous flow stream of a flow cytometer. The liquid acts as an optical waveguide, transmitting the light to a collector, such as an optical fiber/detector. The standard light collection technique uses a microscope objective.
Lloyd A. Hackel Mark R. Hermann C. Brent Dane Detlev H. Tiszauer	**Fourier Plane Image Amplifier** U.S. Patent 5,475,527 December 12, 1995	A system in which a small portion of a laser beam is split off and generates a Stokes seed in a low-power oscillator. Low power output passes through a mask, while most laser output is focused into a larger, stimulated, Brillouin scattering amplifier. The low-power beam is directed through the same cell in the opposite direction. Amplification takes place at the focus, the Fourier transform plane of the mask image. The small holes are amplified and imaged onto a multichip module.
Stephen Azevedo Pierre Grangeat Philippe Rizo	**Process for the Reconstruction of Three-Dimensional Images of an Area of Interest of an Object Comprising the Combination of Measurements Over the Entire Object with Measurements of an Area of Interest of Said Object, and Appropriate Installation** U.S. Patent 5,475,726 December 12, 1995	The process and apparatus to reconstitute precise images by reducing errors produced by the contribution of the complement of the object. A conical beam takes in the area of interest; subsequent measurements take in the entire object. They are combined to obtain a more accurate image.
Richard W. Pekala	**Organic Aerogels from the Sol-Gel Polymerization of Phenolic–Furfural Mixtures** U.S. Patent 5,476,878 December 19, 1995	A method of making low-density organic aerogels by mixing phenolic–furfural in an organic solvent, polymerizing in the presence of a catalyst, replacing the organic solvent with CO_2, and supercritically drying. This aerogel may be used for thermal insulation, chromatographic packing, water filtration, ion exchange, and carbon electrodes.



John Holzrichter

Manager, Laboratory Directed Research and Development

FASTER and with more flexibility than most program funding, the Laboratory Directed Research and Development (LDRD) program supports R&D in new areas of our mission interest. The LDRD is a management mechanism that Congress and the Department of Energy set up in 1984. All DOE-funded laboratories have this R&D mechanism, which is similar to ones used by the Department of Defense and commercial organizations. Since 1985, we have been using these funds to enhance Livermore's scientific and technological vitality. Current annual funding of our portfolio of scientific and technological projects totals about $52 million. The projects with the greatest successes:

- Stem from an area of Livermore expertise.
- Offer something new to an important community.
- Provide meaningful results—that is, we learn something on the way to the objective.
- Provide instrumentation, algorithms, or procedures useful to other areas of the Laboratory.
- Involve creative, motivated people, who attract other similar people to the project and to the Laboratory.

Scientifically Oriented Projects

Science investigations offer the opportunity for discovering unexpected new knowledge with dramatic consequences. At Livermore, such investigations are often associated with the need to answer puzzling questions arising from experiments on complex systems. However, many important ideas occur just because we dream about the consequences of unusual observations and imagine new ways to tackle important problems. The LDRD process encourages these creative processes, most often by offering a source of funds to fully develop the new ideas.

The MACHO project featured in this issue of *S&TR* is a case in point. The MACHO project used LDRD funds to make measurements of astronomical light sources, at rates and with accuracies never before contemplated. The resulting discoveries are changing the entire scientific community's understanding of how matter in the universe is organized.

Other LDRD science investigations include the demonstration of the EBIT (electron beam ion trap) for high-Z atomic physics studies, high-pressure research on the metallization of hydrogen, and new equations of state for uranium and plutonium. Also with the help of LDRD funds, improved understanding has evolved and new inventions have been made in the areas of high explosives, solid-state laser materials, organic aerogels, and chemical mutagenic effects on human health.

Technology Examples

One of Livermore's great talents is to assemble many types of knowledge in new and unusual ways, often as physical prototypes. These technological demonstrations are evidence of progress in our mission responsibilities. Such demonstrations are needed to meet the expectations of DOE, Congress, and the public who support our large Laboratory efforts.

The new electromechanical battery, based upon stored kinetic energy in a rotating flywheel, is an example of LLNL's expertise in complex, interdisciplinary systems. In this issue, we show how technological concepts, when put together by a gifted technologist, can lead to an important new technology. In this example, the researcher synthesized a new system based on improved glass fiber composites, new magnetic motor generator inventions, new magnetic bearing ideas, and new solid-state power-management technologies. Then a prototype was constructed with LDRD funds to demonstrate that the ensemble of ideas worked.

Other LDRD-funded technology demonstrations have had impacts on our overall capabilities. Examples include a type of biofilter for underground chemical degradation, an ultrashort laser pulse generator, isotopic separation of gadolinium, sodium guide stars using Livermore's AVLIS (atomic vapor laser isotope separation) system, and the early work of our genome sequencing program.

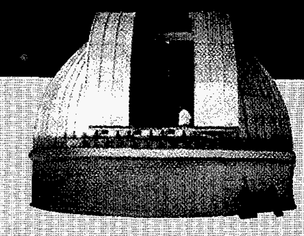
Lessons Learned

Over the past 10 years, the LDRD funding level has grown, and we have learned a great deal about how to use this resource. In the meantime, the Laboratory's missions have evolved (e.g., stockpile stewardship), the problems that the public and the R&D community want to have solved are changing, and new technologies have appeared (e.g., massively parallel computing). Today, to be successful, an LDRD project needs more time, more effort, and more communication.

Representatives from the Director's Office and the Laboratory Directorates are in the process of streamlining some of the LDRD selection procedures and the methods of eliciting new ideas. We anticipate continued successful use of these funds to further the Laboratory's responsibilities to DOE, Congress, and the nation.

Collaboration Is Key

Detecting microlensing events with novel sensors, Livermore scientists discover the contents of dark matter and anticipate future searches for extrasolar objects such as earth-mass planets and large asteroids.



FROM a series of casual conversations between peers, an informal network of colleagues, and Lawrence Livermore National Laboratory's willingness to invest in high-risk/high-payoff ventures, a project to explore the very makeup of the universe was born. Results to date: the MACHO (MAssive Compact Halo Objects) project has captured a national award, is now an international effort, and has raised exciting questions concerning basic assumptions about how our galaxy—the Milky Way—and others like it are formed (see box next page).

Birth of an Idea

As an example of how an idea, a scientific "flight of fancy," can take wing and soar to unexpected heights, the search for MACHOs began almost as an offshoot of another project. Early in 1987, Livermore astrophysicist Charles Alcock, now head of the Laboratory's Institute of Geophysics and Planetary Physics, was focusing on a search for comets.

Alcock, working with Livermore physicists Tim Axelrod and Hye-Sook Park, was exploring additional ways to apply an innovative imaging technology developed for the Strategic Defense Initiative (SDI) in its search for comets at the outer edge of our solar system.

to Success

This imaging technology is based on a new class of high-resolution, wide-angle cameras, which could locate and track a large number of fast-moving objects against a cluttered background.

The camera system[1] drew heavily from the Laboratory's competency in advanced sensors and instrumentation, and it demonstrated the Laboratory's strength in integrating complex systems. The camera used charged-coupled-device (CCD) sensors—similar to those used in household video cameras—to capture digital images. This kind of imaging system, if combined with powerful parallel processing computers, could quickly produce, process, and analyze many thousands of images. Such a system would be ideal for tracking satellites—or comets, thought Alcock—in a starry night sky.

A chance conversation between Alcock and Livermore's David Bennett, then at Princeton University, led Alcock to reread a 1986 scientific paper about MACHOs written by a Princeton astrophysicist, Bohdan Paczynski.[2] In his theoretical paper, Paczynski suggested that MACHOs might be identified through a "gravitational microlensing effect." Microlensing occurs when a massive object passes between a distant star and an observatory (Figure 1). The gravitational field of the object acts as an amplifying lens, bending the star's light rays and making the star appear brighter. These events are extremely rare. At any given time, only about one star in two million is microlensed. The microlensing event can last anywhere from a few days for objects as massive as Jupiter, to weeks or even months for more massive objects.

"Rereading Paczynski's paper at this point was a remarkable experience for me," said Alcock. "I remembered reading the paper for the first time a couple years earlier and thinking it was an interesting idea and that maybe someone would find a way to do it some day. I certainly had no thought of getting into it myself. This time, while rereading, I realized that in light of the SDI technologies Lawrence Livermore had been exploring, we could almost certainly detect these microlensing events now."

Alcock did a little checking around with people in the astronomy field and discovered most people still thought that identifying microlensing events was impossible, given the existing technologies. By now, for Alcock, the idea of a comet search began to take a back seat to the intriguing possibilities of searching for MACHOs using the CCD-based imaging technology originally developed for SDI.

"We never started with an actual SDI design of something," emphasized Alcock. "We started at the whiteboard, from scratch. What this SDI technology did was convince us and others that it was possible to create a system that could produce, reduce, and interpret many thousands of digital images. This was at a time when CCDs had two contrasting uses: in television cameras, where they simply produced images,

MACHOs: Why Search for an Echo of Dark Matter

Why bother searching for MACHOs? The answer is really an answer to a larger question, one that astronomers have been puzzling for years: What is the universe made of?

For several decades, astronomical evidence has suggested that an invisible, "dark" matter surrounds and permeates the disks of our own galaxy, the Milky Way, and other spiral galaxies like it. If this dark matter were made of normal stars, dust, or gas clouds, it would be readily detected. Astronomers have determined that more than 90% of the Milky Way's mass cannot be detected with available techniques, so the unseen substance is referred to as "dark matter."

There are many theories as to what this dark matter is. One thought is that it consists of hypothetical elementary particles not yet detected, such as axions, massive neutrinos, and weakly interacting massive particles (known as WIMPs). An alternative theory is that dark matter is made up of massive objects such as neutron stars or black holes or, less exotically, brown dwarf stars 10 to 80 times the mass of Jupiter. Or, perhaps it is composed of objects similar in mass to the planet Jupiter itself. In fact, MACHO has come to be the generic term astronomers use to describe all the proposed dark, massive objects in the Milky Way's galactic halo that have not been detectable by previous means.

So, why search for MACHOs? As physicist Alcock notes, there's no question that dark matter exists. The question now is: what is it? Searching for MACHOs would provide a clue as to whether MACHOs make up some or possibly all of the dark matter.

and in astronomy, where people typically took a few images per night. This notion that you could take thousands of images with large arrays of CCDs and analyze them—that was SDI's legacy to the MACHO project." (See box, p. 9.)

The core group of Alcock, Axelrod, and Park gained a fourth member: astronomer Kem Cook. Once Cook joined the discussions, the team became very specific about system design, even to the point of having preliminary selections for CCDs, and about what the project process needed to be. "At that point," said Alcock, "it became clear to us that this was a very doable project."

Birth of a Project

In fall 1989, the MACHO project was launched in earnest with funding from Livermore's Laboratory Directed Research and Development (LDRD) Program. This program provides a way for high-risk/high-payoff projects at the Laboratory to get a fast start. But funding is only a start; the LDRD cannot cover everything.

"In the process," noted Alcock, "you get quite a bit of guidance, both from the LDRD office and from one's own directorate office as to, if you're successful, just how much funding you might get. It was beginning to look as though the project was more expensive than we could manage with just the LDRD, and it was also becoming apparent that we needed more people, more collaborators."

Looking for possible collaborators outside the Laboratory, Alcock gave a seminar on the project's hypothesis and technology at the University of California's Center for Particle Astrophysics. He did not expect one talk to generate much more than a spark of interest. At the most, he figured, it would be the first in a series that might lead to some limited collaboration in the future. However, that single seminar generated not a spark, but a firestorm of interest in the project, which led to the Center's full collaboration. Key to further progress were the Center and its sponsor, the National Science Foundation, as well as full participation from Center scientists Chris Stubbs and Kim Greist.

What Alcock did not mention was the group's breadth of planning for other contingencies. Whether or not MACHOs would be found, the growing group of collaborators set up new techniques for data analysis of light curves and for getting better information about the variations in the brightness of stars in the Milky Way and the Large Magellanic Cloud—valuable information to astrophysicists worldwide. Nonetheless, MACHOs' clues to the makeup of dark matter remained the galvanizing goal.

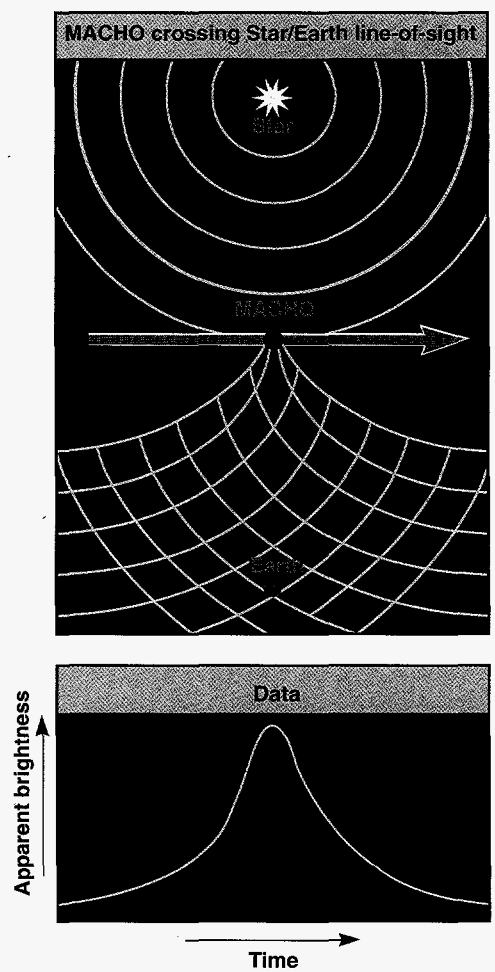


Figure 1. MACHOs passing between Earth and a star brighten the star's image to viewers on Earth by deflecting wavefronts of light coming from the star. The CCD images give information on the MACHO's relative size compared to the star.

From there, the search began for a site to build a telescope, a site that could be dedicated to the MACHO project. Included in the site requirements was the ability to view the Large Magellanic Cloud, a galaxy distant enough to exploit the gravitational microlensing effect yet close enough that individual stars could be seen using ground-based telescopes. The Magellanic Cloud, however, is only visible from the Southern Hemisphere. The site search first focused on Chile, which has the best observing conditions in the Southern Hemisphere.

What happened then is one of those miracles of serendipity, a collision of the right people in the right places at the right time. Joe Silk, a UC professor who had heard Alcock's seminar at the Center, happened to be on sabbatical at the Australian National University at the Mt. Stromlo and Siding Spring Observatories. Also at the observatories was Ken Freeman, a professor at Mt. Stromlo and Siding Spring University, who had worked with Paczynski and to whom Alcock had written about the MACHO project. Casual conversations ensued, and informal e-mail correspondence blossomed between Livermore, Mt. Stromlo, and the Center. The upshot: Mt. Stromlo and Siding Spring Observatories became a collaborator and offered to dedicate their 50-inch (1.27-m) reflecting telescope to the MACHO project for four years.

The network of collaborators has grown since those early days in 1990. Now, the project has collaborators in Munich, Germany; Oxford, England; Seattle, Washington; and San Diego, California, to mention a few. They all keep in touch and keep track of the most recent microlensing events, using the MACHO project's home page (http://www.macho.mcmaster.ca) on the World Wide Web. The Web site provides, among other things, general information about the project and "MACHO Alerts."

MACHOs Exist!

For the past two and a half years, the Great Melbourne Telescope at Mt. Stromlo has scanned the sky on clear nights, monitoring some 8.6 million stars in the Large Magellanic Cloud, searching for an echo of dark matter. The project, when viewed from its start as a "seedling" LDRD project based on SDI technology, has borne some impressive fruit.

While not directly answering the question about the composition of all dark matter, preliminary evidence indicates that MACHOs may make up over half of the dark matter. "Before we started, we expected either to find that MACHOs did not exist at all, or if they did, we expected to see about 15 events in the Large Magellanic Cloud," said Alcock. Instead, the team has observed a total of seven microlensing events in that area since they started gathering data in 1992. Even these few events prove that MACHOs exist, and that they may make up the bulk of dark matter.[3] Most people expected that most of the dark matter would be composed of one type of thing or another—almost all MACHOs or all WIMPs, for instance.

"No one really thought it might be a bit of something and bit of something else," he said. "But that is what we are finding." Results to date are consistent with about 50% of the dark matter being MACHOs, and the rest something else.

These results have also raised questions about the models used to describe the Milky Way. "The problem has become more complicated than we expected," said Alcock. "It appears that there is much more mass in some component of the inner galaxy."

One model that has received a lot of attention is that the Milky Way is not a simple disc-like structure with spiral arms, as typically pictured, but instead a "barred" spiral galaxy, where a lot of stars exist in a bar-like structure in the inner galaxy (Figure 2).

The results also uncovered some astronomically significant "special" microlensing events, including a "binary" event, a "parallax" event, and a "proper motion" event. In the binary event, two massive objects, bound to and orbiting around each other, form the lens (see its light curve in Figure 3a). "This is spectacularly different from the simple, imperfect microlensing you get from just one MACHO," said Alcock. "Given that the majority of stars in our galaxy, unlike our sun, actually come in pairs or triplets, it should not come as a surprise to us that MACHOs might behave the same way. The binary event has great significance in a possible future project: a search for Earth-like planets outside the solar system. From our point of view, a planet going around a star is just a binary, with one object being much more massive than the other."

The parallax event is the longest microlensing event seen to date: 200 days for the object to clear the face of a distant star. The length of the event led to the need for some unusual calculations. Ordinarily, the calculations do not account for parallax, the motion of the earth around the sun. But in this case, the earth completed more than half its orbit during the event, so that motion had to be taken into account.[4] (See the light curve in Figure 3b.)

Award-winning MACHO System Scans Millions of Stars a Night

In order to effectively search for MACHOs, the collaborators had to surmount some extraordinary scientific challenges. They had to obtain an enormous number of images each night through dedicated use of a telescope in the Southern Hemisphere. And how many measurements would be enough?

"We determined that 'enough' meant exceeding the total number of photometric measurements made in the history of astronomy by two orders of magnitude—tens of millions," said Alcock.

To accomplish this task, the project required an optical imaging system with an exceptionally wide field of view and a large detector to yield an imaged area about 100 times larger than that of most telescopes.[4] Along with the high-quality, large-format CCD camera, the project needed a parallel processing system that could obtain, store, and analyze massive amounts of data—a daunting task.

The MACHO camera system includes an innovative optical system designed for the 1.27-m Australian telescope, two CCD cameras, a system to acquire and process data, and data-analysis software. This system was the first astronomical system that allowed astronomers to take images simultaneously in two colors, blue and red. The two color channels help the astronomers determine if an event is a true microlensing event. A true event will show the star brightening simultaneously at different wavelengths.

The system was the first optical imaging system to fully exploit the new generation of large-format CCD imagers. For these efforts,[1] the MACHO team in 1993 won a coveted R&D 100 Award from *R&D Magazine*. Each year, *R&D Magazine* recognizes the 100 most significant new products and technological innovations.

The project's participants believe they have seen one proper motion event. Observed in only a small fraction of all events, a proper motion event occurs when the Earth, the MACHO, and the lensed star are in almost perfect alignment. Calculations for a normal event usually assume that the distant star is a point, but in this case the team had to measure the star's diameter in terms of the size of its angle as measured from Earth, about four billionths of a degree.

Now that the project has matured, one of its most valuable results is the formation of a network of collaborators. These informal collaborators and other interested astronomers follow up on the MACHO events as they are discovered by the main telescope at Mt. Stromlo. To initially find MACHO events, the project needed the big survey instrument with its elaborate cameras and data processing system, like the one Livermore developed. However, once an event is found, a more conventional instrument can be pointed at that event and gather more information. Some of the observatories now involved are in Australia, New Zealand, Chile, South Africa, and Israel.

Surveying the Future

The core survey for MACHOs is slated to run through about the year 2000. The data acquired by then will increase the statistical accuracy of the survey. In the meantime, Alcock and others are interested in doing further astronomical exploration with the MACHO microlensing technology. According to Alcock, two strong possibilities are searching for extrasolar Earth-mass planets and searching for large asteroids on a collision course with Earth. In both cases, the network of collaborating observatories plays an important role.

For many of the MACHO events, the lenses are just low-mass stars, not very different from our Sun. If those stars have planetary systems around them, from time to time those planets should appear as a little brightening "blip" in the data, lasting a day or less. This short-term brightening is the planet's signature. Since the Mt. Stromlo telescope makes measurements only once a day, this small additional signal would not normally be detected. The collaborating network of observatories could focus their telescopes on the microlensed star, looking for such a planetary signature.

To do a meaningful search for Earth-mass planets, said Alcock, there needs to be substantial technology development—a new telescope, probably based in Chile, and a more aggressive survey for MACHOs. To locate Earth-mass planets, this new telescope would need to find on the order of 300 MACHO events a year, whereas the Great Melbourne Telescope now finds about 60 per year, most of which are in the Milky Way. A planet search would also require a more organized network capable of exquisitely sensitive measurements. The measurements made by the network would need to be very photometrically precise, better by a factor of ten than can now be done with existing telescopes.

The second possibility, searching for Earth-threatening asteroids, also seems to be a natural fit for the MACHO technology. Searching for these asteroids involves many of the same activities the MACHO project does now: surveying vast areas of sky using CCDs, analyzing the data very quickly, and scheduling other observatories to follow up on the objects that seem interesting.

A third, smaller project could be a return to the comet study that led Alcock to link SDI's technology and MACHOs in the first place. Instead of looking for stars that grow brighter due to microlensing, the researchers would be looking for stars "winking out" as a comet passes in front. This search would be yet another order of magnitude more difficult than either the

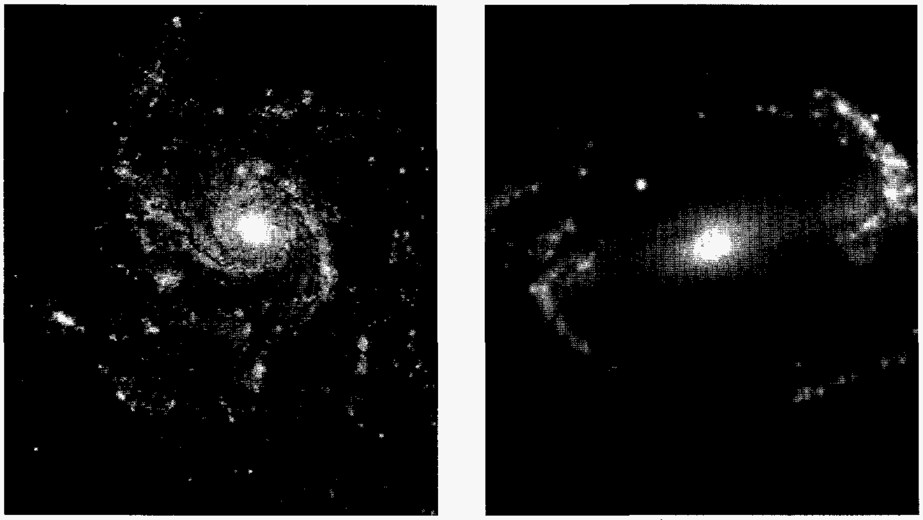


Figure 2. We usually envision the Milky Way as a spiral galaxy (left), but a spiral bar galaxy (right) may be closer to its actual configuration once the population distribution of MACHOs in the core is understood.

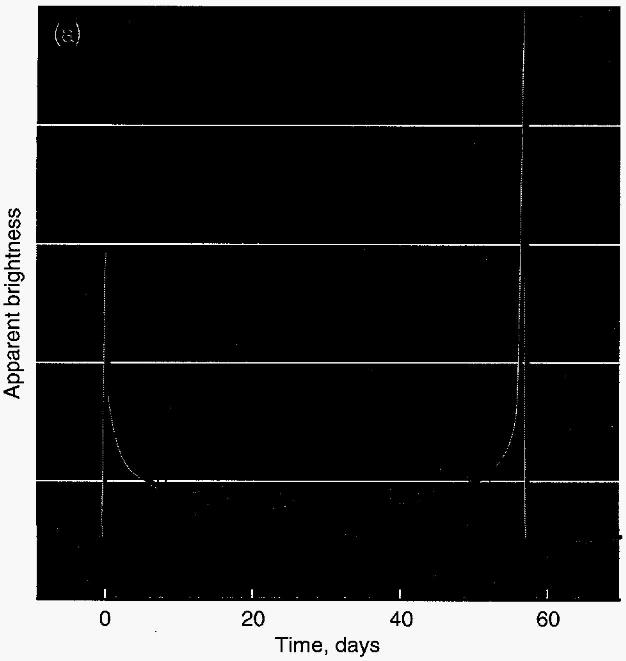
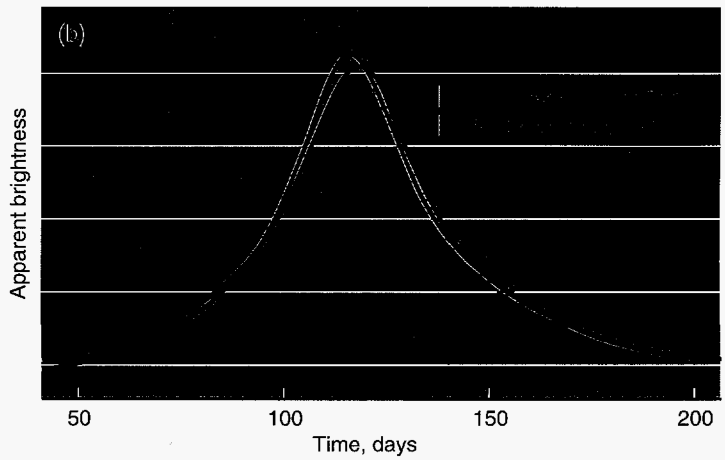


Figure 3. Light curves of (a) a binary event and (b) a parallax event. The plots show the variation in brightness of the star being lensed as a function of time. The X axes show the lengths (in days) of the observation; the Y axes show the ratio of the brightness of the star during a particular measurement to its mean brightness when it is not being lensed.



search for planets or Earth-threatening asteroids, because comet events, instead of lasting days or weeks, last only a fifth of a second. "You really have to be paying very close attention," he noted. "But it can be done. It is just a question of putting it together. And that is what the Laboratory is expert at, one of its very greatest strengths."

As Alcock pointed out, Laboratory team members did not design the computers used for the MACHO project or invent the CCDs. "We used off-the-shelf computers, and we bought state-of-the-art CCDs. What we did, better than anyone else could, was integrate them. It was the first time that those very large CCDs had been used to their full potential in an integrated system. It was for that integration that we got the R&D 100 award."

Key Words: CCD sensor, dark matter, extrasolar, light curve, MACHO, microlensing event.

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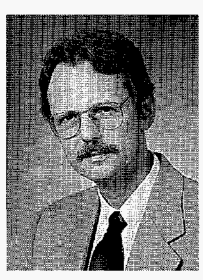
About the Scientist



CHARLES R. ALCOCK joined the Laboratory as head of its Astrophysics Center in 1986; since 1994, he has been head of the LLNL Institute of Geophysics and Planetary Physics. From 1981 to 1986, he was an Associate Professor at Massachusetts Institute of Technology, where he also received the Alfred P. Sloan Research Fellowship. From 1977 to 1981, he was a member of the Institute for Advanced Study in Princeton, New Jersey. In 1979, he held a visiting professorship at the Niels Bohr Institute in Copenhagen, Denmark, and, in 1983, was a visiting fellow at the Australian National University in Canberra, Australia. He received his Ph.D. in Astronomy and Physics in 1977 from California Institute of Technology.

Alcock's publications number about 60 in the field of astrophysics. He and fellow team members at Livermore won a prestigious R&D 100 Award in 1993 for their work on the MACHO project.

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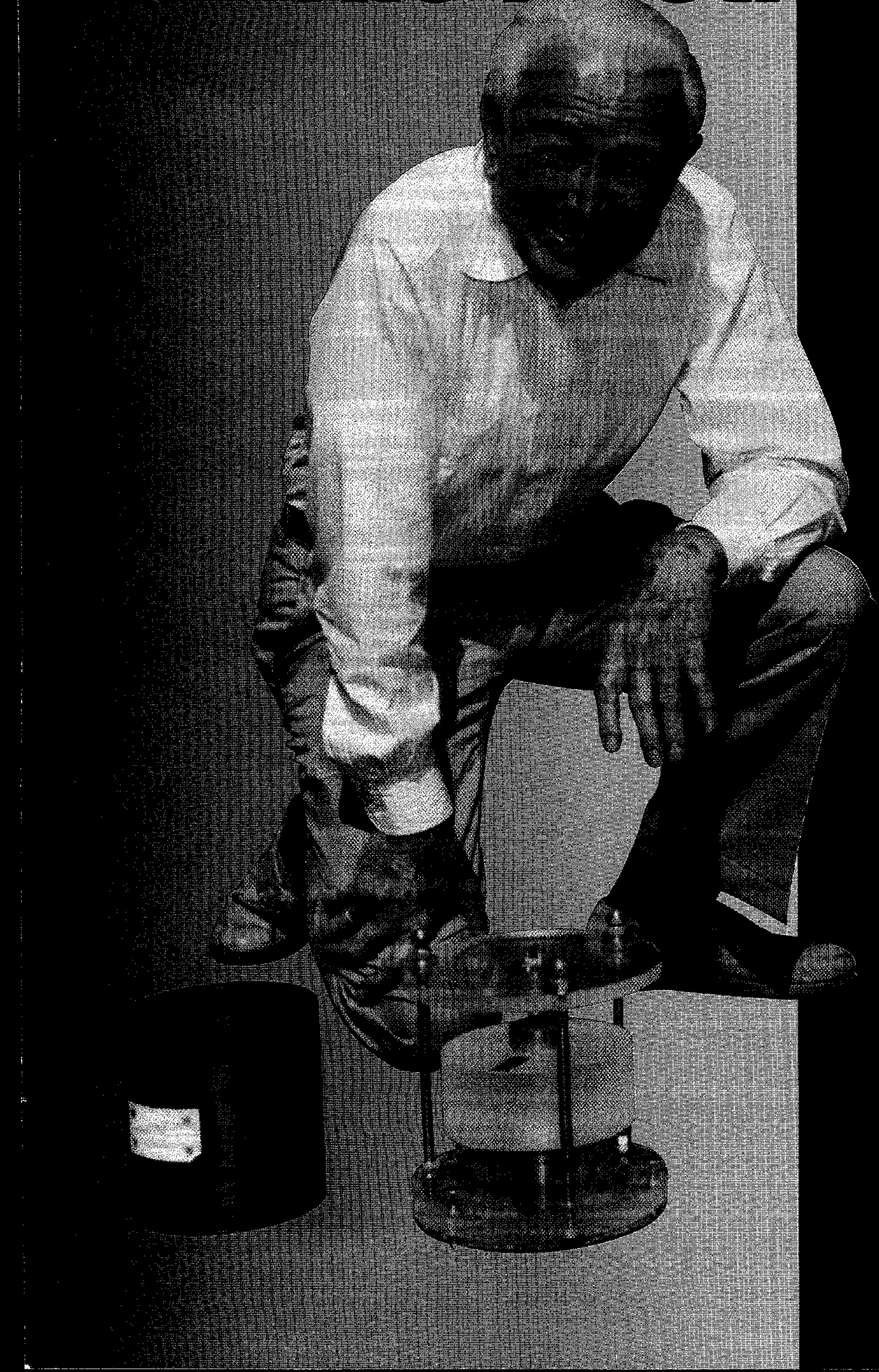

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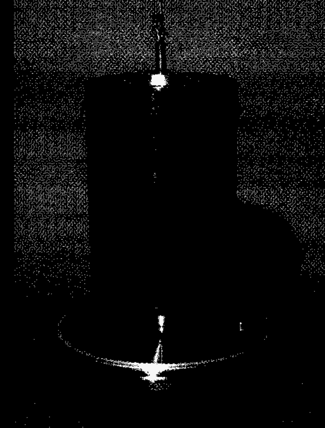

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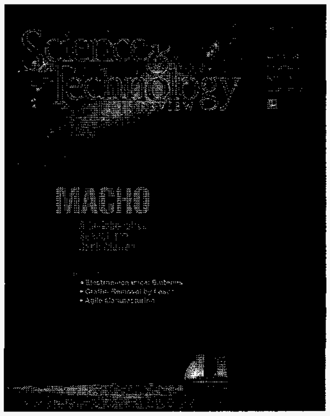

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Old Idea
Battery

SPINNING at 60,000 revolutions per minute, a cylinder about the size of a large coffee can may hold the key to the long-awaited realization of practical electric cars and trucks. The graphite, fiber-composite cylinder belongs to a new breed of LLNL-developed, flywheel-based, energy storage systems with new materials, new technologies, and new thinking about the most efficient ways to store energy.

Called an electromechanical battery (EMB) by its Laboratory creators, the modular device contains a modern flywheel stabilized by nearly frictionless magnetic bearings, integrated with a special ironless generator motor, and housed in a sealed vacuum enclosure. The EMB is "charged" by spinning its rotor to maximum speed with an integral generator/motor in its "motor mode." It is "discharged" by slowing the rotor of the same generator/motor to draw out the kinetically stored energy in "generator mode." The ... features a special array of ... magnets (called a Halbach ...) generator-motor to perform ... charging and discharging ... efficiently.

The EMB offers significant advantages over other kinds of ... storage systems ... For example, the efficiency ... recovery (kilowatt-hours ... kilowatt-hours in) is projected ... 95%, considerably better than ... electrochemical battery ...

Figure 1. ...

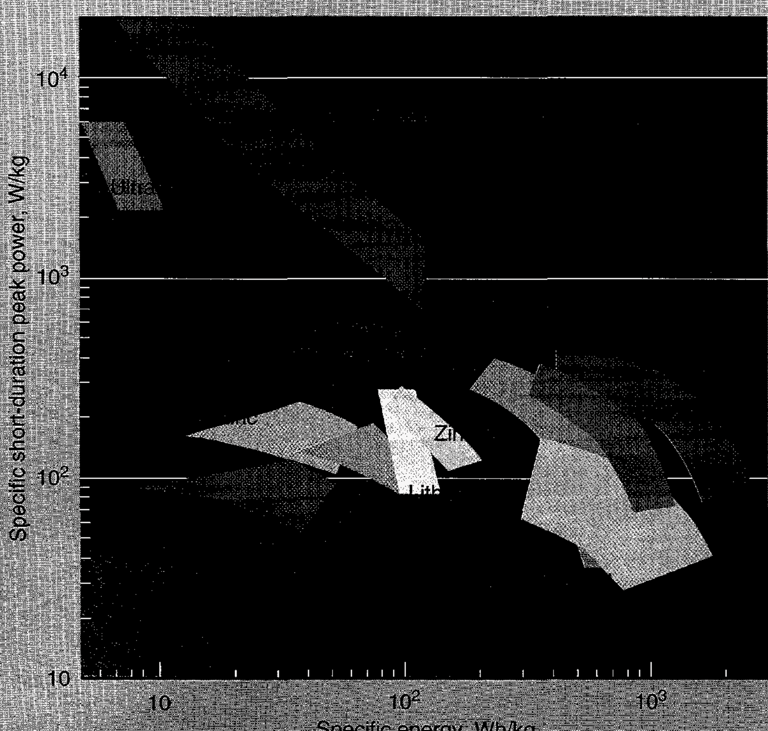
Storing Energy

Since the introduction of electricity into society, stored electrical energy has played a critical role in the development of electrical devices. Before the turn of the century electrochemical storage cells were used to power the telegraph and the telephone. Some of the earliest automobiles were powered, not by an internal combustion engine, but by an electrical motor that drew energy from lead–acid storage batteries. Before the 1920s, electric cars were as common as gasoline-powered ones.

Today, concern for the air pollution from the gasoline-powered automobile has intensified the development of electric-powered cars and power to run them. However, along with the concern for less pollution come the plaguing shortfalls of current electric autos: sluggish acceleration, limited driving range, and too-short battery service lifetime. The figure below illustrates the vast differences in present power storage strategies. Today the push is on to develop a vehicular "super battery" to overcome these limitations.

The electric car is only one example of the need to store energy. Others include "load leveling" for electrical utilities, which must make more efficient use of their transmission lines and base-load generating plants. Also, wind and solar-electric power systems, owing to the intermittent nature of their power outputs, urgently need energy storage systems that can deliver power when it is needed, not just when it is generated.

Thus far, virtually the entire effort to develop improved batteries for storage has centered on hoped-for extensions of the electrochemical art. The Laboratory's electromechanical battery (EMB), however, may be a better way to go or, at the very least, be an important piece in the evolving energy storage infrastructure.



Various energy storage devices are compared for peak power and specific energy. Batteries and fuels produce roughly the same range of peak power, about one order of magnitude below advanced flywheels.

solving challenging problems in motor/generator design, composite rotors, magnetic bearings, containment, and integrated system design.

Old Invention, New Use

Despite its current high-tech appearance, the flywheel is one of society's oldest inventions. (Its kin, the potter's wheel, is mentioned in *The Bible*.) Even the "modern" idea of coupling a flywheel to a generator/motor to emulate a battery for use in electric vehicles is at least four decades old. It dates to the Swiss "Gyrobus," an urban bus that used a steel flywheel to power a generator/motor and drive it between stops, where a charging trolley was engaged. Too cumbersome, too expensive, and too limited by 1950s-era power electronics, the Gyrobus never caught on, but a few researchers have not let the concept die.

Livermore has been involved in developing flywheels made of composite materials since a new way of thinking about such flywheels was published in a 1973 seminal article in *Scientific American*. It was written by Richard Post, Livermore fusion scientist and current EMB program leader, and his son Stephen. An LLNL program from 1978 to 1983 validated various flywheel design concepts using rotors made of composites and yielded valuable data on rotor failures (called bursts) and life spans.

"In the intervening years, several critical technologies emerged, and new design principles were established that made it worthwhile to re-examine the basic idea," says Post. Out of this effort emerged the Livermore concept for the EMB, with far more economic promise and wider applications than the older prototypes (see box next page).

The current Livermore program began in 1992 under Laboratory Directed Research and Development funding. The program drew considerable interest from the private sector and eventually direct sponsorship of development work by three companies. Trinity Flywheel Batteries Inc. and Westinghouse Electric Corp. continued to develop EMBs to smooth out the flow of electricity for factories, computer centers, and other facilities; General Motors Corp. has evaluated EMBs as part of a future automobile propulsion system.

"This unusual technology transfer arrangement offers several advantages. It places significant emphasis on the end use of EMBs and addresses the flywheel system as an interdependent whole, rather than as a collection of subsystems," Post says. Indeed, the primary thrust of the present program is to test complete prototype EMB systems. Operation at over 100 kW of power and storage of more than 1 kWh of energy have been demonstrated using compact rotors and integrated containment structures. Prototype rotors have been tested at 60,000 rpm and have exceeded specific power of 8 kW/kg with a measured energy recovery efficiency of more than 92%.

Module Conserves Energy

The basic Livermore module consists of a high-speed rotor integrated with a generator motor, suspended by magnetic bearings, and housed in a sealed, evacuated chamber. An artist's concept of such a module, a small one storing about 1 kWh of energy and "about the size of a bread box," is shown in the cutaway drawing in Figure 2.

Table 1 lists some of the attributes of the basic module. Also listed for comparison are typical values for the common lead–acid battery. One can see a substantial advantage of the EMB over its lead–acid counterpart.

EMB Applications for Vehicles

Except that their output is alternating current rather than direct current, EMB modules would power an electric car in the same way as a bank of electrochemical batteries. If each module stored about 1 kWh, as is currently projected, some 20 to 30 modules might be needed to provide the 200-mile-plus range for a vehicle required by the public. At the same time, the fast charge (5 to 10 minutes) that could be designed into such a car would answer the challenge of long-range trips, provided there was a "charging station" infrastructure, (which could also use EMB modules for peak power demand).

Although these possibilities are intriguing for long-range planning purposes, they may not be very realistic in the short term. Fortunately, there is another possibility: a "hybrid" internal combustion–electric car. One kind of hybrid would feature a small, constant-speed internal combustion engine (piston or a gas turbine) to provide average-power requirements, with one or two EMB modules providing peak power-handling capabilities and recouping energy otherwise lost through braking or descending a hill. Such a hybrid would fit well with the present vehicle infrastructure while also significantly reducing air pollution and fuel consumption.

Another type of EMB hybrid would use electrochemical batteries, with EMB units again providing peak power demands. (See the article on zinc–air batteries in *Science & Technology Review*, October 1995.) Besides providing snappier performance, the EMB would reduce wear and tear on conventional batteries and improve the efficiency of a regenerative braking system.

Compared to stationary EMB applications such as with wind turbines, vehicular applications pose two special problems: gyroscopic forces and containment in the case of failure. Solving both problems is made much simpler by the choice of small modules.

Gyroscopic forces come into play whenever a vehicle departs from a straight-line course, as in turning or in pitching upward or downward from road grades or bumps. The effects can be minimized by vertically orienting the axis of rotation (as in Figure 2, p. 16), which is also a desirable orientation for the magnetic bearing system. The designer can also mount the module vacuum chamber in limited-excursion gimbals or provide restoring forces in the magnetic bearing system (or in a mechanical backup bearing) to resist the torque from the vehicle's movements. By operating the EMB modules in pairs—one spinning clockwise, the other counterclockwise—the net gyroscopic effect on the car would be nearly zero.

The other special problem associated with EMBs for vehicles is failure containment. The limited understanding of rotor burst and containment is presently the single most significant obstacle to implementing flywheel energy storage in vehicles. To acquire further understanding, the Livermore team is performing a series of rotor burst tests using both integrated flywheel systems and isolated parts. In addition, the team fires projectiles composed of rotor material at various containment structures at speeds exceeding 1,000 meters per second. The tests show that a well-designed rotor made of graphite fibers that is made to fail turns into an amorphous mass of broken fibers. This failure mode is far more benign than that of metal flywheels, which typically break into shrapnel-like pieces that are difficult to contain. The team is working toward the design of lightweight structures (made in large part of low-cost fiber composite) to completely contain rotors that fail for any reason.

An array of small EMB modules, each with its own reinforced vacuum housing and an outer protective housing (Figure 2), offers a major advantage over the problems posed by a few large units. Not only is the energy that can be released by each unit reduced, but the twisting torque in the containment structure that might result from a failed rotor is very small compared to that of rotors just two or three times larger.

The only difference between the Livermore EMB, viewed as a "black box" to store electrical energy, and an electrochemical cell is that, instead of low-voltage direct current, the EMB "cell" accepts and delivers variable-frequency alternating current at an operating voltage level chosen by the designer. When coupled to a power converter, the EMB delivers its electrical energy at higher power levels per kilogram of mass than any known battery.

Furthermore, like other electromechanical equipment operating in a sealed environment (the household refrigerator motor and compressor, for example), the EMB is expected to have a useful service life measured in decades. This longevity should be attainable even under repeated "deep-discharge" cycling, an attribute not possessed by any known electrochemical cell.

A typical gasoline-powered automobile in urban driving converts only about 12% of the heat energy of gasoline to useful drive power. In addition, gas-powered vehicles have no way to recover the energy that is wasted upon slowing down, braking to a stop, or descending a hill. EMB vehicles offer a simple way to efficiently recoup this energy through "regenerative braking." In this mode, the electric drive motors are operated as generators to put energy back into the battery pack whenever the vehicle slows down, is braked, or descends a hill.

One way to express the resulting energy savings is through an energy conservation factor (ECF). This is the ratio of energy required to drive a vehicle powered by a gasoline engine over a given urban cycle compared to the energy that would be required to drive a vehicle with the same weight and drag coefficients equipped with an electric drive system. (Of course, the ECF for an electric vehicle must include the efficiency with which the electric utility generates and delivers electricity to charge the batteries.)

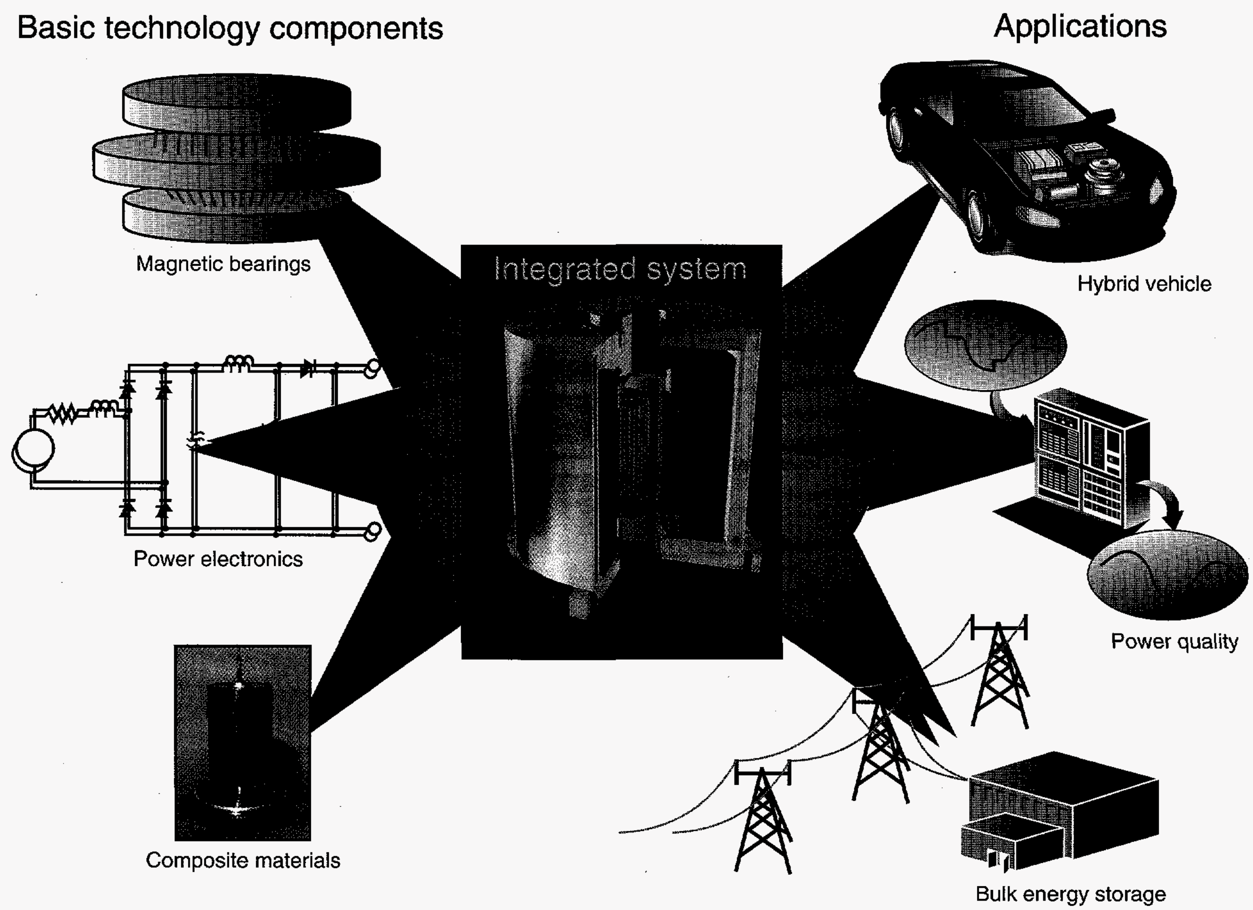


Figure 2. Concept of the flywheel battery system and its applications.

Calculations reveal that a representative automobile powered by electricity using EMBs for storage instead of an internal combustion engine would have an ECF of 4.0. That is, four barrels of oil delivered to a refinery would yield the same number of urban driving miles in a gas-powered vehicle as one barrel of oil (or its energy equivalent) delivered to a power plant for a car powered by electricity stored in EMBs. "The impact of such a major increase in the efficiency of the transportation sector would be phenomenal in terms of reducing our need for petroleum and also in terms of air pollution," says Post.

When the same calculations are done for a lead–acid electrochemical battery, the ECF drops to about 2.5, owing to its lower energy recovery efficiency (60 to 70%). Post says that if for no other reason than superior efficiency, special attention should be paid to exploiting the EMB for designing "real-world" electric vehicles.

Fiber Is Key

The Livermore effort to design and build an EMB takes advantage of recent advances in materials such as high-strength fiber composites, particularly graphite. The strength of graphite fibers, now used in everything from tennis racquets to sailboat masts, has increased by a factor of 5 over the last two decades.

These fibers play a central role in flywheel energy storage. The reason lies in the laws dictating how much kinetic energy can be stored in a rotating body (Figure 3). Any spinning rotor has an upper speed limit determined by the tensile strength of the material from which it is made. On the other hand, at a given rotation speed, the amount of kinetic energy stored is determined by the mass of the flywheel.

This observation originally led to the intuitive notion that high-density materials, namely metals, are the materials of choice in flywheel rotors for energy storage. A metal flywheel does indeed store more energy than an equivalent-size flywheel made of low-density material and rotating at the same speed. However, a low-density wheel can be spun up to a higher speed until it reaches the same internal tensile stresses as the metal one, where it stores the same amount of kinetic energy at a much lower weight. For example, lightweight graphite fiber is more than ten times more effective per unit mass for kinetic energy storage than steel.

Which modern fiber is optimum for an EMB depends on whether the designer wants maximum energy storage per unit mass (as in vehicular applications) or, for economic reasons, the designer requires the maximum

Table 1. Comparison of attributes for battery modules.

	EMB	Lead–acid battery
Specific power	5–10 kW/kg	0.1–0.5 kW
Energy recovery	90–95%	60–70%
Specific energy	100 Wh/kg	30–35 Wh/kg
Service lifetime	>10 years	3–5 years
Self-discharge time	Weeks to months	Many variables (temperature, usage, etc.)
Hazardous chemicals	None	Lead, sulfuric acid

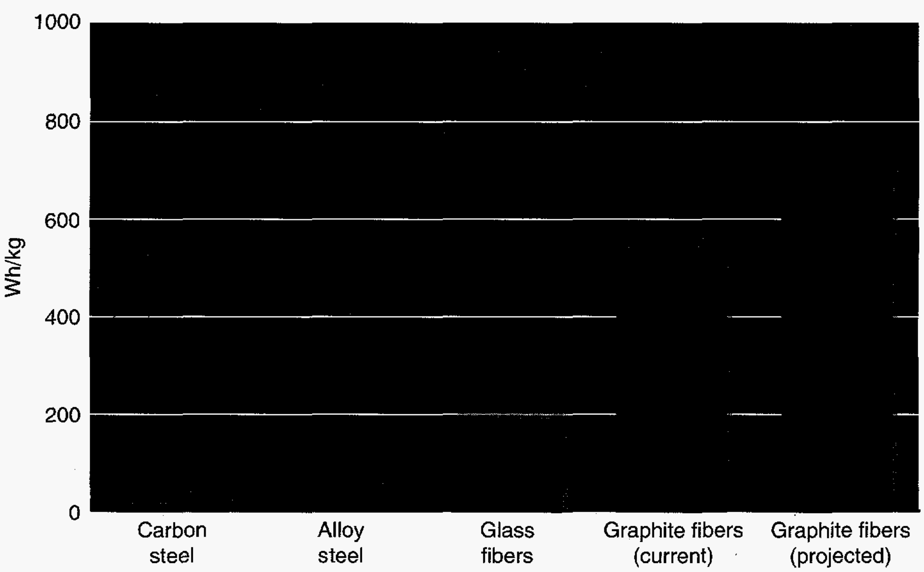


Figure 3. Steel was originally used in flywheels; but graphite, which is lighter, stores kinetic energy better.

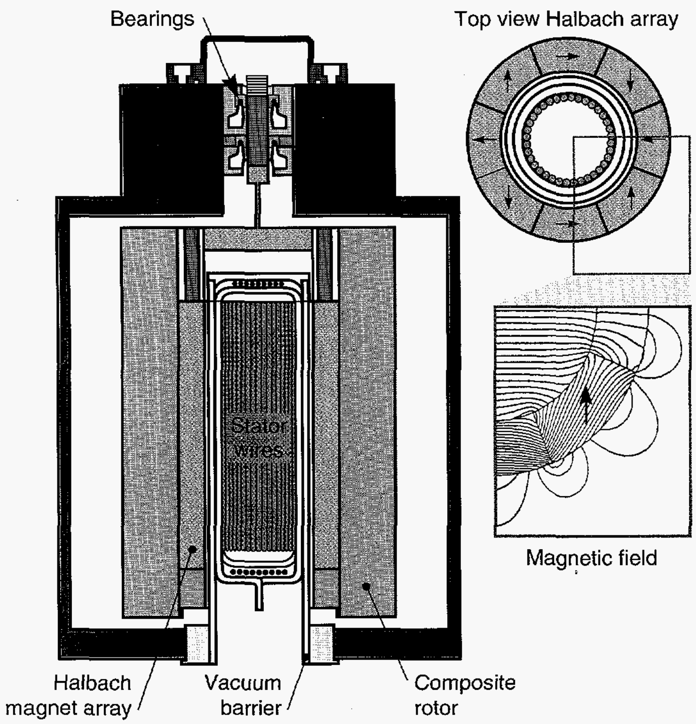


Figure 4. The Halbach permanent magnet array is an integral part of our electromechanical battery.

energy storage per unit cost (as in most stationary applications, such as load leveling for electric utilities). Vehicular uses call for graphite fibers, even though these are more than ten times as expensive as the most cost-effective fiber for EMB stationary applications.

Post emphasizes that using composite fibers has required the team to rethink the entire flywheel concept, which was based on metal flywheels. Because steel is an isotropic material, its strength against rupture is the same in every direction. Composites are typically anisotropic materials; i.e., they are strong in the direction of their fibers but up to 100 times weaker in the other direction.

Laboratory flywheel designs use a basic geometry of a cylinder, with the fiber orientation that of a tight-wound spring, i.e., essentially perpendicular to the axis of the cylinder. In this way they achieve maximal strength in the outward centrifugal direction. The rotor's highest tip speeds attained using the strongest available composite fibers range from 1,400 to 2,000 meters per second. The Livermore approach is to achieve lowest cost and tolerate modest penalties in energy density. As a result, the team uses rotors made of material costing $26 per kilogram ($12 a pound) that operate with tip speeds on the order of 800 to 1,000 meters per second, as opposed to top-performing fibers costing $130 per kilogram ($60 a pound).

Designing for Tomorrow

With rotor design and materials problems largely solved, the most important challenges facing EMB designers are the two issues of bearings and rotor dynamics. In current tests, Laboratory researchers have been using mechanical bearings. In future tests, they plan to incorporate a virtually frictionless, magnetic bearing system in which the rotor is suspended by magnetic forces derived from permanent magnets.

Although the concept of levitating magnetic bearings dates to the 1940s, every designer of such bearings must contend with Earnshaw's Theorem, derived early in the nineteenth century. This theorem asserts the impossibility of stably levitating a charged body by using electrostatic forces arising from other fixed, electrically charged bodies. By extension, the theorem also applies to magnets and magnetic bearings. Commercial magnetic bearings, now in use in specialty applications, must employ complex and expensive electronic servo systems to overcome this constraint.

The Livermore team is working to achieve levitation by using a magnetic bearing energized by permanent magnets to support the spinning mass of the flywheel against gravity, at present supplemented by a conventional bearing to stabilize the system. For the longer term, the team is aiming its main effort on rotor dynamics effects to achieve stable levitation with so-called "passive" magnetic bearings, in which no servo system is required. The team's novel approach to passive magnetic bearings, unique in the magnetic bearing community, takes advantage of the expertise within Livermore's magnetic fusion program staff.

An integral part of the rotor is the generator motor, composed only of a rotating array of permanent magnet bars that produce a rotating magnetic field. This field couples through a vacuum-tight, glass–ceramic cylinder to three-phase copper-wire windings located inside this cylinder (and thus outside the evacuated region). This ironless design minimizes hysteretic losses from fluctuations in the magnetic field, which would limit the rundown times and generate heat.

This generator motor is the first battery application of what is called a Halbach magnetic array. These uniquely arranged magnet designs were pioneered in the 1980s by Klaus Halbach[1] of Lawrence Berkeley National Laboratory. Although Halbach's work related to magnet arrays for particle accelerators, the

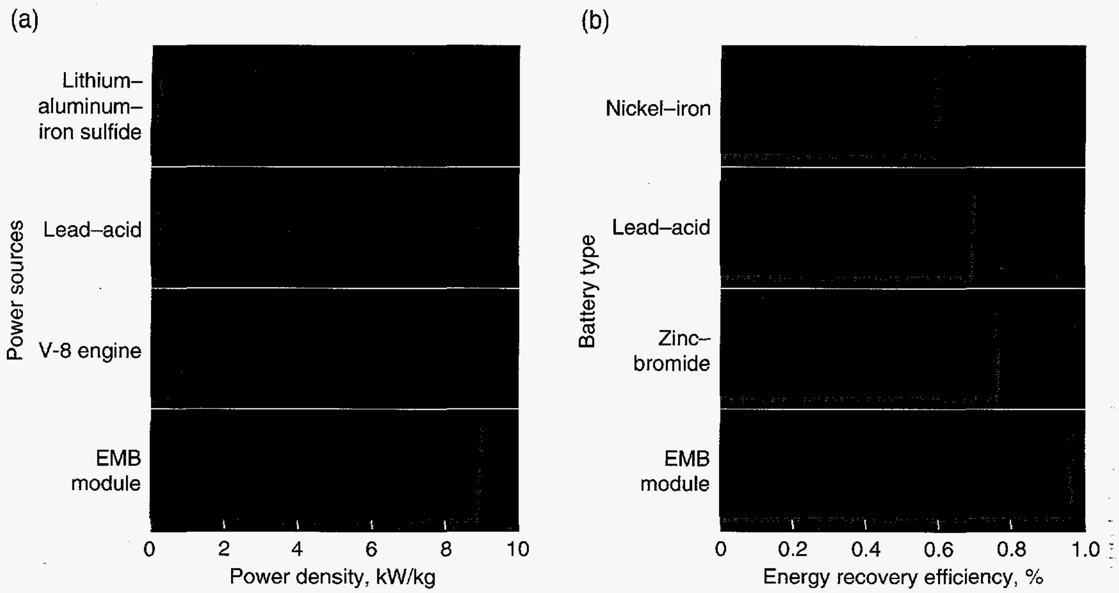


Figure 5. Various energy storage devices are compared for (a) power density and (b) energy recovery.

Laboratory team has adapted them for use in EMBs. Figure 4 shows an end view of the array.

Noncontacting magnetic bearings eliminate wear and minimize rotational drag losses, and ironless generator motor designs eliminate hysteretic losses. If there were no losses from aerodynamic drag, the rundown, or self-discharge lifetime, of the module supported by optimized magnetic bearings would be very long. Rundown times in excess of two years for magnetically levitated high-speed rotors operated in vacuo were demonstrated 40 years ago.

As in those early tests, Livermore researchers put the rotor in an evacuated enclosure to minimize the losses from aerodynamic friction. Fortunately, the degree of vacuum required to satisfy even the most demanding vehicular needs is well within commercial practice. Computer models show aerodynamic rundown times of several months and corresponding losses from aerodynamic drag of a fraction of a watt.

Together, the ironless design, the Halbach array, and the very high rotation in a sealed, evacuated enclosure give extremely high efficiency and specific power. As noted, efficiencies exceed 95%, while specific power climbs to 10 kW/kg. Figure 5 illustrates these values for a modern V-8 gasoline engine and a small EMB module.

Post says that the Laboratory's EMB development program can make a major contribution toward solving a critical societal problem—finding less expensive and more efficient ways to store electrical energy. This need, he says, appears in many aspects of the nation's use of electricity, from homes and factories to the needs of electric utilities and wind-electric and solar-electric power generators. It is felt most keenly, however, in the transportation sector, where the development of practical electric cars (or hybrid internal combustion engine/electric-drive cars) is being delayed by the lack of a satisfactory energy storage system.

Key Words: electromechanical battery (EMB), energy efficiency, flywheel, storage cells.

Reference

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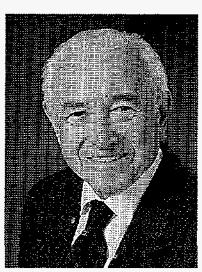
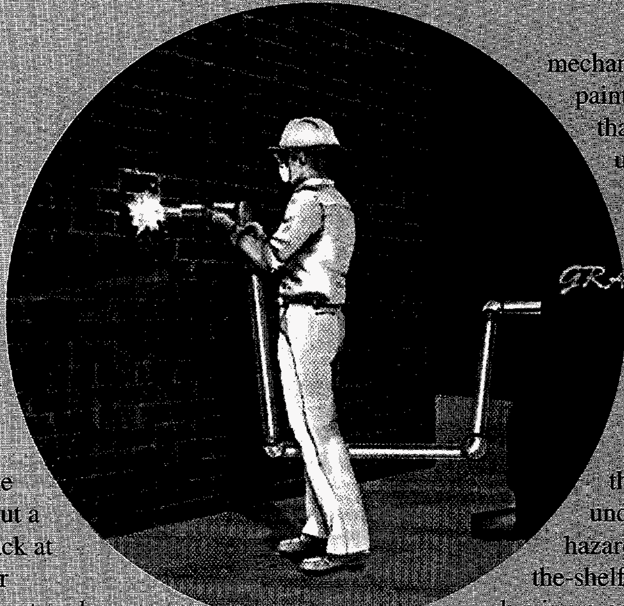


In 1951, **RICHARD F. POST** received his Ph.D. in Physics from Stanford University, Stanford, California. In 1940, he received his B.S. from Pomona College, Claremont, California. A specialist in fusion research, plasma physics, and energy storage, Post has been at Livermore since 1951. Currently he is a senior scientist in Energy, Manufacturing, and Transportation Technologies within LLNL's Energy Program. Since 1963, he also has been affiliated with the University of California, Davis, where he now is a Professor Emeritus. Recent publications by Post include book chapters, journal articles, and conference proceedings on topics such as magnetic mirror fusion research and the electromechanical battery.

Graffiti Removal by Laser



DOES removing painted scribblings with a high-average-power laser make sense? Dennis Matthews asked himself this question when unsolicited "street art" suddenly appeared near his home in Half Moon Bay, a small town about a half hour south of San Francisco. Back at work at Lawrence Livermore's Laser Programs, Matthews first used a laboratory laser to test the idea and was astounded by the result. Now development of this laser spinoff application is on its way, thanks to the expertise from the Laser Programs' high-average-power group, led by Lloyd Hackel. Once the technology is further developed, stripping hazardous and nonhazardous surface layers from a number of surfaces will also be possible.

The concept of using a laser to remove type from paper was demonstrated many years ago. A more serious problem in terms of taxpayer expense and potential environmental hazards is removing paint, such as graffiti and lead-based paint, from structural surfaces. The San Francisco Bay Area annually spends roughly $10 million to fight graffiti, and New York City spends five times as much; but both are losing the battle.

All of the methods now used against graffiti have shortcomings. Workers painting over surfaces cannot keep up with the vandalism. Sandblasting paint gives rise to airborne sand and paint particles. Chemical methods, such as soda (sodium bicarbonate) blasting, generate large volumes of liquid waste requiring extensive containment and disposal systems. Abrasives scar surfaces under the paint, and more benign methods can be so inefficient that they necessitate multiple treatments.

The basic principle behind a laser paint-stripping system is debonding of the paint by means of photoacoustic stress waves. When a laser, adjusted to the optimal power and pulse length, hits a surface layer of paint, the energy is converted into heat and sound waves. Sound waves travel through the paint layer, strike the underlying hard surface, and rebound. The reflected sound waves collide (constructively interfere) with incoming waves at the paint layer and explode the paint into powder, as shown in the illustrations. The physics mechanism—tensile failure—pulverizes paint and other types of coatings rather than chemically burning them. The underlying material remains undamaged so that no structural repair is needed.

Some lasers that have been used for paint stripping—such as the CO_2 laser used in aircraft paint-stripping applications—operate at relatively long pulse lengths and do not flake or pulverize the paint layer. Rather, they burn paint off surfaces, an undesirable feature because of the hazardous vapor that is produced. Off-the-shelf solid-state, neodymium–yttrium–aluminum-garnet (Nd:YAG) lasers operating at an output power of 10 W are not powerful enough for graffiti removal.

A high-average-power, solid-state, neodymium-doped glass laser or a Nd:YAG laser is much more suitable for cleaning surfaces and is much faster than other methods. The high-average-power group at Livermore had been developing such compact, powerful lasers for several years for applications such as generating x rays for printing advanced electronic circuits and active imaging of objects in space. They already knew that laser wavelength determines the penetration depth of the beam and the depth to which the surface layer is heated. In developing this laser for removing graffiti, the group found that the ideal laser operates at a wavelength of about 1 micrometer, with an output of about 1 joule per pulse, and a short pulse length of 5 to 10 nanoseconds. High pulse-repetition frequencies on the order of several hundred to a thousand hertz (the faster, the better) achieve the best removal rates for large areas. LLNL has built unique lasers approaching these specifications, with up to 100 W of output power. Only a little more development is needed to achieve the target paint-removal rate of about 280 m^2 per hour (about 600 linear feet of freeway soundwall in a 5-foot swath).

To better understand the principles behind cleanup applications, we tested the method with a Nd:YAG laser. This work showed that paint can be rapidly removed from smooth surfaces including polished granite or marble (as in monuments and works of art), window glass, and plastic, and from porous surfaces including brick, cinder block, and wood. The process leaves only a powdery paint residue that can be vacuumed up as part of the removal process. An unexpected bonus of the method is that it provides an acoustic indication when the work is done. The loud, snapping sound emitted during spallation ceases when the paint layer is gone, so paint can be removed efficiently even in areas hidden from an operator's view.

Livermore researchers Stan Mrowka (left) and Peter Celliers do early laser experiments to remove graffiti.

The next step will be to engineer a self-contained delivery and cleanup system that could operate from a truck or van. The portable system we envision would remove paint at least 30 times faster than the current best technology. Actual rates will depend on the coating thickness and porosity of the substrate. As shown in the illustration, left, laser light would be delivered from a telescoping, articulating light tube with a mirror relay. The articulating arm is similar to those perfected for medical use. A telescoping arm solves the challenge of reaching less accessible places, such as ceilings and surfaces above ground level. A vacuum hose within the arm's "sleeve" would retrieve all residue.

Safety, especially the prevention of eye injury, is a major consideration in development. A lens will be used to rapidly disperse the beam, thus reducing its intensity to a safe level. The beam will be focused a few centimeters from the end of the wand but will rapidly diverge at greater distances. The delivery tip will have a protective shroud made of absorbing glass, and operators will wear goggles and a helmet. A digital access code will prevent unauthorized use, and a proximity switch will disable the device if directed away from a surface.

Beyond graffiti removal, another potential large-scale use for this technology is the safe stripping of hazardous surface coatings, such as lead paint, from public and private structures. In the U.S., for example, 90,000 bridges are currently painted with toxic lead-based paint, as are about half the interiors of residences across the country. The removal methods presently used are costly, and for some structures such as the George Washington Bridge, there is no practical way to guarantee lead containment. Bridge stripping in New York City was halted when lead residue from paint was found in downwind playgrounds.

By the year 2000, a dozen U.S. commercial nuclear reactors are scheduled to be decommissioned. Laser stripping could make the metals in these facilities suitable for reuse. About 82,000 metric tons of steel and several thousand metric tons of stainless steel and copper could be recovered from these facilities and reused if the thin layer of radionuclide contamination were removed from the metal surfaces. Moreover, decontamination would aid in the recycling process of other DOE metal stockpiles: 1.3 million metric tons of radioactive stainless steel, 38,000 metric tons of radioactive copper, and scrap nickel valued at more than $1 billion.

Hackel's group estimates that they can build and deliver a prototype graffiti-removal system in one year for about $2 million. The Laboratory recently formed one alliance with an industrial partner who is interested in a commercial prototype system; additional investors or a consortium of municipalities is being sought to match development funds. Commercial units could be made for about $250,000, a price that compares favorably with that for current soda sprayers, considering the greatly enhanced capabilities of the laser method. Once portable systems are manufactured, municipalities across the country would be able to purchase them to quickly eliminate the eyesores, social statements, and unwelcome property damage caused by graffiti. More development is needed to address the problems associated with removing and handling hazardous coating materials.

Key Words: graffiti removal, high-average-power laser.

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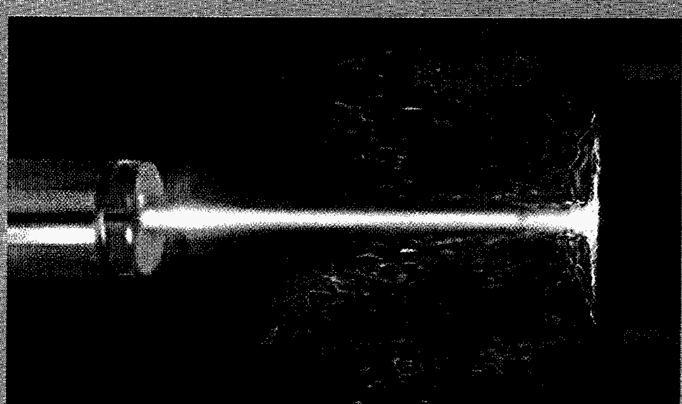

Graffiti will soon be removed by laser. With an ND:YAG laser, paint will be debonded from porous brick substrates and other surfaces.

Adding Agility to Manufacturing

INDUSTRIES depend on machine tools and robots to cut and shape parts into virtually every conceivable product, from pencils and desks to cars and airplanes. Machine tools are operated by devices called controllers, which are dedicated pieces of hardware that typically cannot be changed. Machine tools can last 50 years, but the controllers running them are often obsolete in 5 years or less, especially when product requirements change.

Recently, the U.S. dropped out of the list of the top five countries in machine tool production, and a single Japanese company now sells 80% of the world's controllers. Adding to U.S. manufacturers' woes is the fact that today's consumers are demanding greater choice in the products they buy. To keep up with demand, manufacturers need far more control over the manufacturing process. They need a process that can make a different or unique part quickly and make it right the first time at a predictable cost.

The DOE also must respond quickly to meet the demands for new, lower-cost, higher-quality components. The components at issue are critical in ensuring the safety, security, and reliability of a broad range of tasks the DOE oversees, including weapons manufacturing and disassembly. Thus, both American industry and the DOE are facing many pressures as they seek manufacturing solutions in an era of reduced budgets and dynamic change.

The solution is agile manufacturing, which offers the ability to respond to unanticipated change rather than being driven by a preconceived product made in a fixed sequence of steps.

Lawrence Livermore National Laboratory is part of a program called Technologies Enabling Agile Manufacturing, which has about 40 participants and funding of $15 million per year starting in 1994. The program's technical lead, Bob Burleson, resides at Livermore. This program brings the DOE's resources, including those at Livermore, into an alliance with private industries and other federal agencies. The goal is to speed the development of agile manufacturing technologies and deliver flexible and modular tools that will form the basis for agile manufacturing. The tools will support modeling and simulation, shop-floor control, a feature catalog, and many other functions to streamline product development.

The central idea is to develop an "intelligent" controller (see the illustration) that can be adapted to various types of machine tools. Such a controller can allow machine tools to be quickly reconfigured so they can produce different parts on demand. This new controller is the main focus of a separate $52.6-million Cooperative Research and Development Agreement (CRADA), which brings together a team of LLNL researchers (also led by Bob Burleson), researchers at Los Alamos National Laboratory, and a Louisiana-based company, ICON Industrial Controls Corp. This CRADA will spur development of software for personal computers used to control machine tools.

A software-based (intelligent) controller running on a personal computer can replace the controllers already installed in existing machine tools, and the new controllers can be built into future machines. With this type of controller, a machine tool can be reconfigured in days or even hours rather than months or years.

But the advantages of agile manufacturing do not stop there. An intelligent controller allows a two-way exchange of information, a feature that is not possible with hardware-based controllers. For example, manufacturers will be able to make precise adjustments for variations in the temperature of a part or to compensate for the minute wear that inevitably occurs on tool tips or grinding wheels. Such adjustments today are crude approximations, and many bad parts are discarded. In agile manufacturing, sensors are introduced so that real-time adjustments are based on measurements taken as a part is being made. In addition, many controllers can rapidly communicate over a network for enhanced production coordination. If a single tool breaks in a series of coupled machines, the work-around action can be taken much more quickly.

LLNL researchers have been designing controllers for the DOE for several decades. The Large Optics Diamond Turning Machine at Livermore is a good example of a device operated by a controller with specialized sensors. This machine can routinely cut a few nanometers (one-ten-thousandth the thickness of a human hair) off the surface of materials. What makes our expertise and the idea of a generic controller relevant and practical is the stunning increase in computer power and the decrease in cost of personal computers during the last 10 years. Companies that previously spent up to $150,000 for controllers will be able to perform more flexible functions for about $5,000.

Essential to the generic, intelligent controller we are designing is the Manufacturing Operating System (MOS), as shown in the illustration. Redesigning hardware is not

The "heart and brains" of the manufacturing process is the controll shown in the center. In traditional manufacturing, this component i piece of prewired hardware. In agile manufacturing, an intelligent controller with replaceable software modules flexibly defines a manufactured part and the entire process by which a product is made. The modules being developed by LLNL are in yellow.

necessary; software is adapted when unanticipated tasks arise. Users can reconfigure their own controller to do the applications they want. Proof of the MOS concept was demonstrated on a three-axis milling machine at Los Alamos in March 1995, just six months after the project was initiated. Ultimately, the MOS will help the U.S. to recapture market dominance in machine tool manufacturing, and it will revolutionize the way most manufacturing is done.

Under the three-year CRADA, which began in late 1994, Livermore is developing the underlying real-time operating software for agile manufacturing. Los Alamos is writing human-interface software, and ICON is writing application-specific modules that can be inserted into the controller. The plan is to divide the controller into well-defined modules that correspond with known functions in current controllers and that provide extended and improved services in future controllers. One module can direct the trajectory of a machine tool, another can solve logic problems, another can coordinate tasks, and so forth. Application modules can be specific to a milling machine, a lathe, or virtually any other manufacturing process. Third parties—with their own software or specialized modules—can simply plug them in to add new functions. ICON also is working with General Motors, which is interested in more agile manufacturing of auto parts, and Pratt-Whitney, which makes jet engines.

By the fall of 1996, we expect to have the first release of our new software completed and running. In Burleson's words, "Our mission is to help industry move from focusing on a specific product to focusing on the overall process." By doing so, the effort in agile manufacturing will streamline product development in the U.S., reduce costs and make them more predictable, enhance the range and quality of manufactured products, and shorten time to market.

Key Words: agile manufacturing, intelligent controller, Manufacturing Operating System (MOS).

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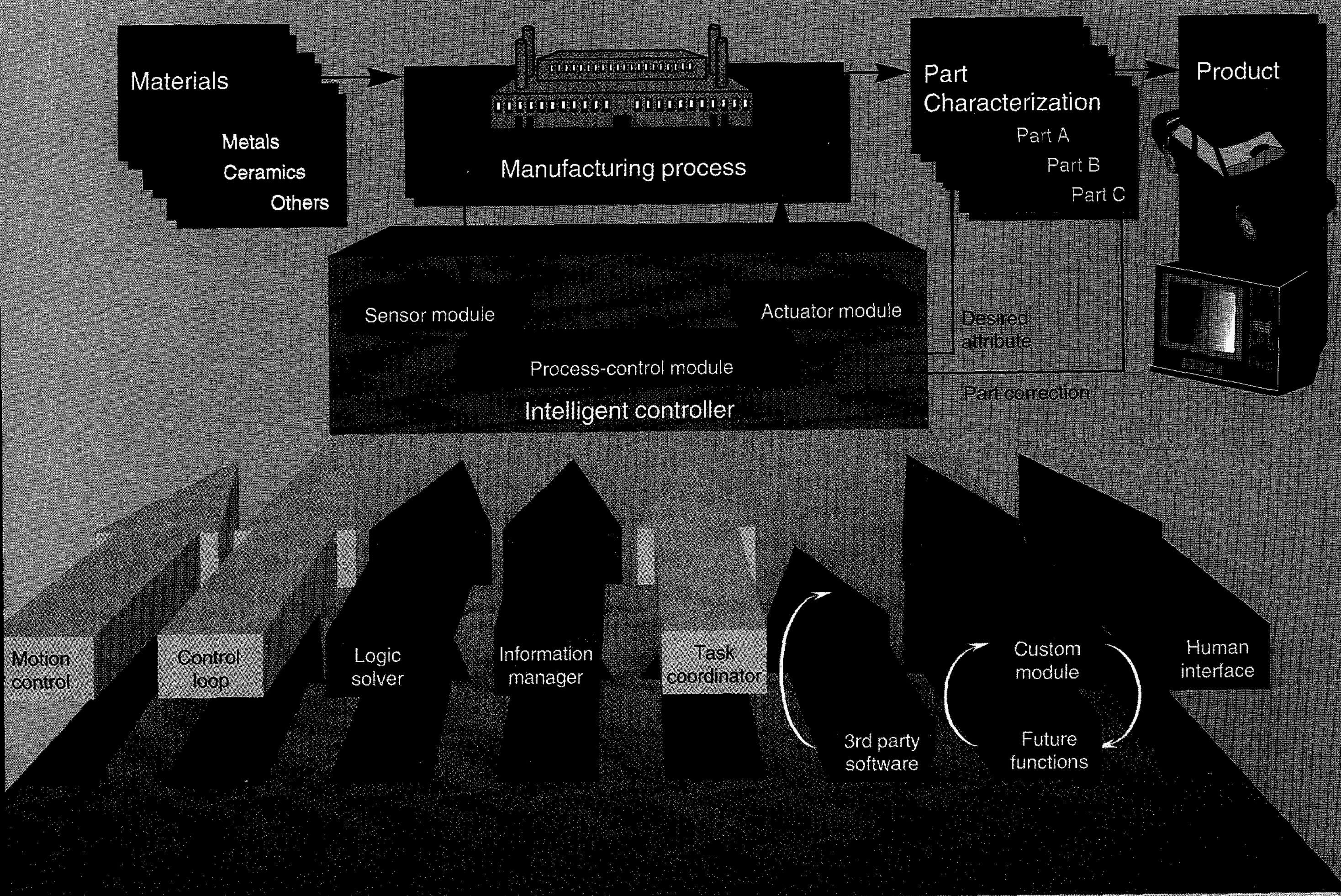

MACHO: Collaboration Is Key to Success

Using technology originally developed for the Strategic Defense Initiative and collaborators around the world, the Livermore MACHO (MAssive Compact Halo Objects) team now has evidence that MACHOs may make up over half the "dark matter" of the universe. MACHOs are not as readily visible as stars; but with a system of high-resolution, wide-angle cameras using CCD sensors and massively parallel computers, microlensing events can be observed from the Great Melbourne Telescope at Mt. Stromlo. Results also indicate that the Milky Way is not a simple, disc-like structure, but may be a "barred" spiral galaxy.

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A New Look at an Old Idea— The Electromechanical Battery

A new breed of Livermore-developed, flywheel-based energy storage systems uses new materials, new technologies, and new thinking to develop a new electromechanical battery (EMB). Its efficiency is measured in terms of specific power of 5 to 10 kW/kg, energy recovery of 90 to 95%, specific energy of 100 Wh/kg, and a service lifetime estimated to be over ten years. The EMB's strength lies in its integrated system, which employs a high-speed rotor made of graphite fiber composite, magnetic bearings, and a magnet design that applies the Halbach magnet array. Livermore CRADAs with Trinity Flywheel Batteries, Westinghouse Electric, and General Motors are focusing on the end uses of the EMB in cars, load leveling for electric utilities, and bulk energy storage.

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