A New Look at an Old Idea

The Electromechanical Battery

Laboratory researchers are integrating innovative materials and designs to develop highly efficient and cost-effective energy storage.

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 its "generator mode." The advanced design features a special array of permanent magnets (called a Halbach array) in the generator–motor to perform these charging and discharging functions efficiently.

The EMB offers significant advantages over other kinds of energy storage systems (see box, next page). For example, the efficiency of energy recovery (kilowatt-hours out versus kilowatt-hours in) is projected to exceed 95%, considerably better than any electrochemical battery such as a lead–acid battery. Power densities can soar to 5 to 10 kW/kg, several times that of a typical gasoline-powered engine and up to 100 times that of typical electrochemical batteries. And because of its simple design and advanced materials, an EMB is expected to run without maintenance for at least a decade.

Livermore researchers envision several small, maintenance-free modules, each with a kilowatt-hour of energy storage, for use in electric or hybrid-electric vehicles. See the prototype in Figure 1 (also see box, p. 15). Larger modules with 2 to 25 kWh of storage capacity could be employed by electrical utilities for more efficient use of their transmission lines and by factories for power conditioning. These larger units could also be used in wind and solar-electric power systems to enable them to deliver power whenever it is needed, rather than only when it is generated.

The exceptional potential of the Laboratory design has not gone unnoticed by American industry. Trinity Flywheel Batteries, Westinghouse Electric, and General Motors have all sponsored research at Livermore for vehicular and industrial applications. The efforts, which include tapping the expertise of researchers throughout the Laboratory, involve

Figure 1. Prototype of the LLNL electromechanical battery, which is based on the flywheel concept of energy storage. Left to right: high-speed rotor, rotor in motion, and enclosed battery (20 cm in diameter by 30 cm high).

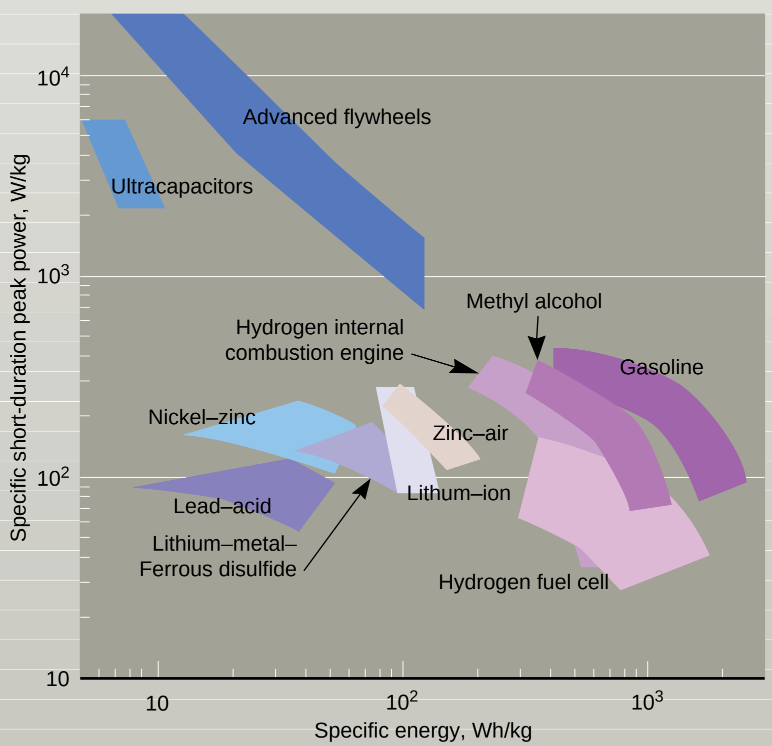
Storing Energy

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.)

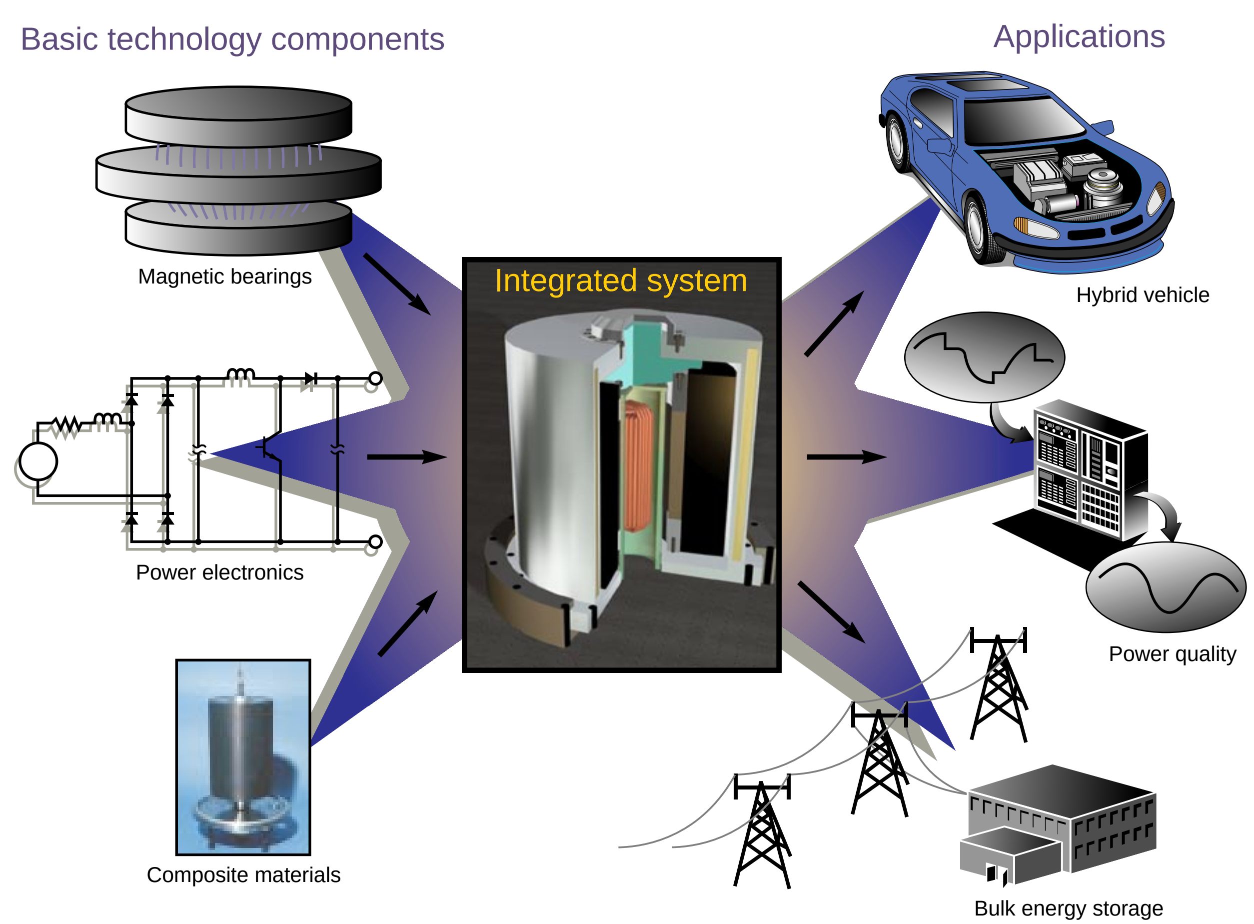


Figure 2. Concept of the flywheel battery system and its applications.

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

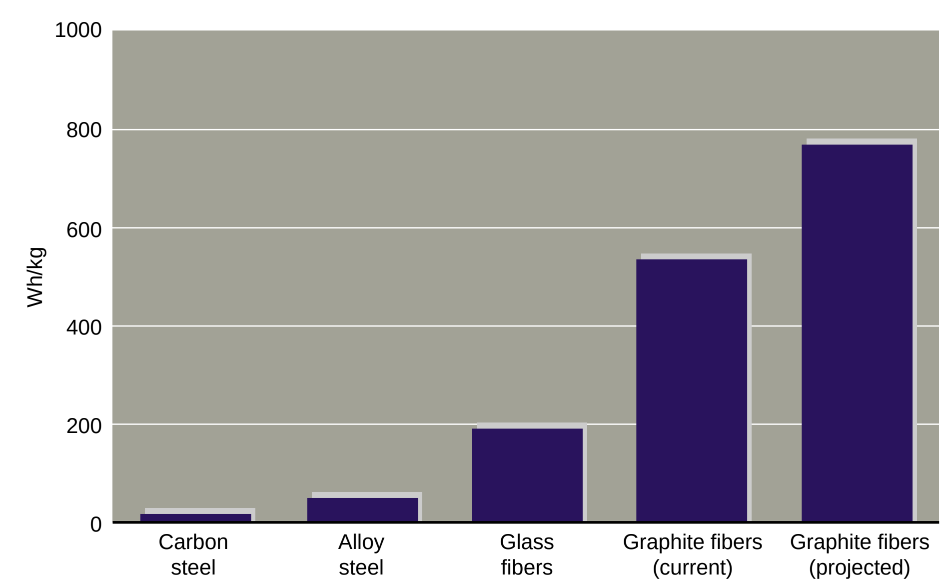


Figure 3. Steel was originally used in flywheels; but graphite, which is lighter, stores kinetic energy better.

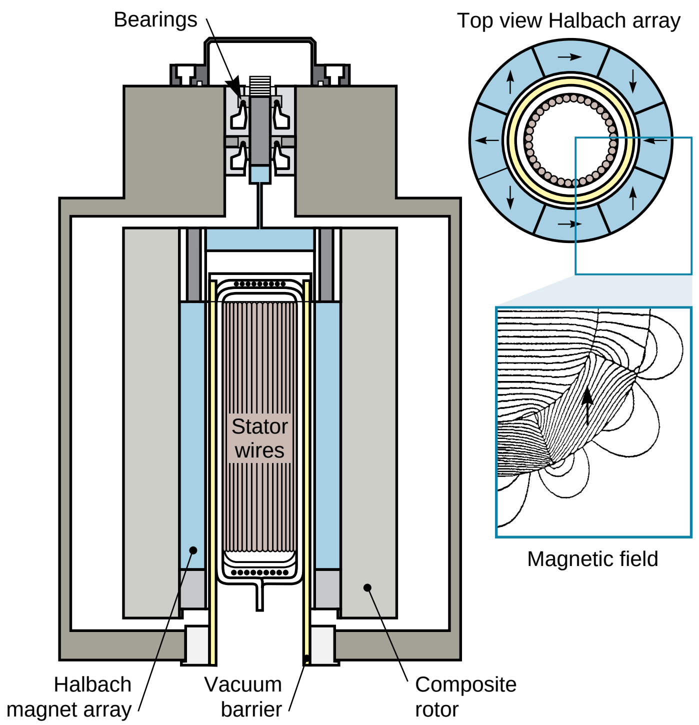


Figure 4. The Halbach permanent magnet array is an integral part of our electromechanical battery.

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

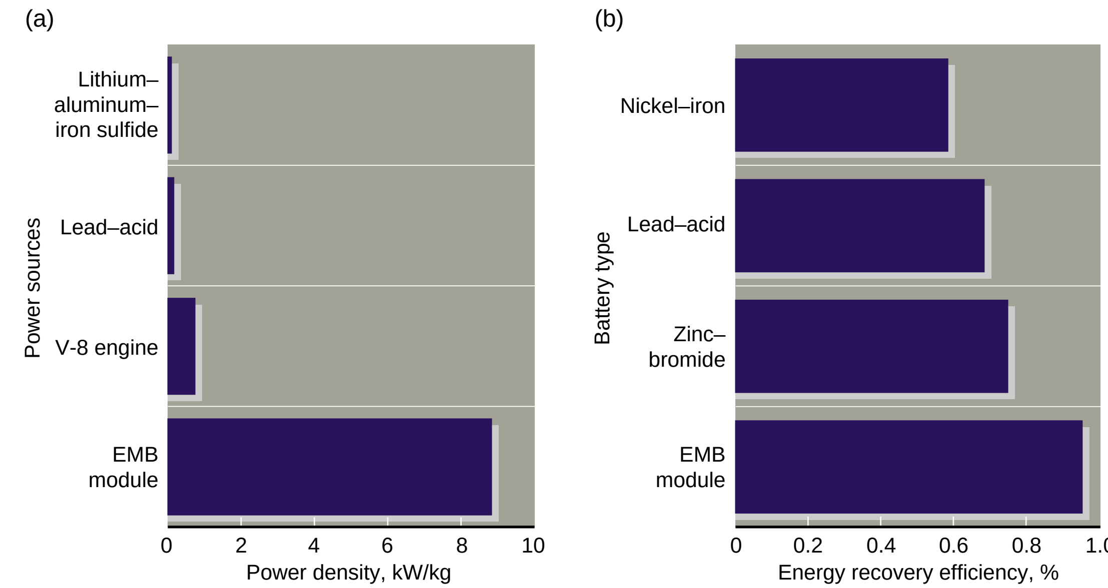


Figure 5. Various energy storage devices are compared for (a) power density and (b) energy recovery.

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

1. K. Halbach, "Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Material," *Nuclear Instruments and Methods* **169** (1980), pp. 1–10.

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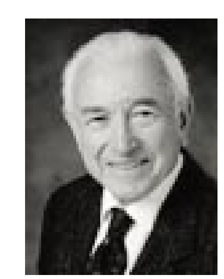
About the Scientist



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.