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The Electromechanical Battery: The New Kid on the Block

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ABSTRACT

In a funded program at the Lawrence Livermore National Laboratory new materials and novel designs are being incorporated into a new approach to an old concept — flywheel energy storage. Modular devices, dubbed "electromechanical batteries" (EMB) are being developed that should represent an important alternative to the electrochemical storage battery for use in electric vehicles or for stationary applications, such as computer back-up power or utility load-leveling.

INTRODUCTION

Efficient, reliable, and cost-effective means for storing electrical energy is becoming an increasing need in our electricity-oriented society. For the transportation sector the need for energy storage means, now acute, is for better batteries to power electrical vehicles of all types. As yet no electrochemical battery exists that provides a wholly satisfactory answer to this need. For the electric utilities — and for many of their customers — the need for energy storage for load-leveling and power conditioning is growing, fueled both by the increasing sensitivity of computers and new manufacturing plants to power interruptions and by the economic advantages of load-leveling. In California these diverse uses of energy storage systems are becoming increasingly important as we move toward the use of alternative energy sources (such as wind and solar energy), and as the time approaches when State-mandated electric vehicle quotas must be met.

One possible answer to the entire spectrum of needs just outlined is the "electromechanical battery". The EMB has the potential to resolve all of the energy storage issues in a manner superior to the electrochemical battery in all important attributes, namely, specific energy (kWh/kg), specific power (kW/kg), energy recovery efficiency (kWh out vs. kWh in), cycle and calendar lifetime, and amortized capital cost.

By our definition an EMB is a modular energy storage device consisting of a high-speed rotor, fabricated from fiber composite, and having an integrally mounted generator/motor. The rotor spins in vacuo, inside a hermetically sealed chamber. In our proposed embodiment of the EMB the rotor is supported by "magnetic bearings", that is, a bearing system that utilizes magnetic forces to support the rotor against gravity. Several considerations, including the desire for long service lifetime, the problems of heat-removal in a vacuum, and of the consequent need to minimize frictional losses, make the use of magnetic bearings a virtual necessity.

The idea of storing energy in flywheels is, of course, a very old one. In fact, the concept of using fiber composites to achieve maximal energy density in flywheel energy storage systems was studied in the United States in federally sponsored programs in the 1970s. The general approaches to the design of such flywheels [1] were well understood at that time and substantial progress toward implementing the new ideas had been made before the programs were canceled in 1982.

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In recent years there has been a rebirth of interest in the subject, stimulated by new materials, new design concepts, and new urgency to meet today's needs. In the remainder of this article we will briefly describe the particular features of the new breed of EMB that we are developing at the Laboratory, discuss some aspects of its use, and conclude with a summary of the results to date in our funded program. Some of the material in this paper has been covered in previous papers. [2,3]

In the program at LLNL some novel approaches have been taken in addressing a central problem — the magnetic bearing — to the end of simplification, with an expected consequent increase in reliability and reduction in cost (relative to "conventional" magnetic bearings). A demonstration EMB module has also been designed and fabricated. This module, now in preliminary testing, is intended to store approximately 2 kWh, and to have the very high output power rating of 200 kW, achieved by virtue of the novel generator/motor configuration that it employs.

DESIGN FEATURES

The principal design features of our version of the EMB are shown schematically in Fig. 1, which is a sectioned view of a small module. For use in an all-electric or in a hybrid-electric automobile the module would have outside dimensions of order 25 cm and would store approximately 1.0 kWh. The rotor of the module is shown as being made up of nested cylindrical shells [1] that are fabricated of high-strength graphite fiber/epoxy composite. These shells are coupled to each other mechanically by "separators" that transmit torques but do not transfer substantial radial forces between the shells. As mentioned earlier, the rotor and its associated components are housed in a sealed, evacuated, chamber.

The innermost shell of the rotor supports on its inner surface a special array of permanent-magnet bars (the "Halbach array" — described later) made of high-field permanent magnet material, for example, the material NdFeB. Inside this magnet array is a re-entrant cylinder made of insulating material that functions as a vacuum barrier through which the magnetic field of the rotating array is coupled inductively to multi-phase stator windings. In this manner the windings are made accessible for cooling, either by forced air or by the flow of liquid coolant. Note that the entire generator/motor assembly is "ironless", a design feature that leads to high operating efficiency and low standby losses (because of the absence of hysteresis losses). Owing to the high rotation speed of the rotor (of order of 200,000 RPM for the 1.0 kWh shown in Fig. 1) the design also leads to very high specific powers — 5 to 10 kW/kg — up to two orders of magnitude greater than those typical of electrochemical cells.

Shown also in Fig. 1, albeit only schematically, are the magnetic bearings, with their permanent-magnet exciters. These bearings, which will not be discussed here in detail, employ NdFeB magnets. Owing to the high remnant field of NdFeB (1.25 Tesla), only a few grams of this material will be required to provide the magneto-motive force needed to support the rotor and its magnet array. However, the magnetic bearings themselves represent the most challenging of the design problems for an EMB. As a consequence we have made a special effort to develop simplified versions of the magnetic bearing, one embodiment of which is employed in the EMB module that has been constructed.

The vacuum chamber within which the rotor assembly and its associated parts are housed is a sealed, evacuated, metal housing reinforced with fiber composite. This reinforcement is intended both to sustain inward atmospheric forces and also to provide the first level of defense against the consequences of rotor failure. Safe containment of the debris and of the energy released upon rotor failure is essential for any vehicular use of EMBs, or when they are to be used in a manned area. Certainly the problem is eased if several small, rather than one or two large, modules are used to achieve a given stored energy.

To address the containment issue adequately will require a test program, and we are planning such tests early in our present program. However, it is our belief that the experience gained in the aircraft industry, where somewhat similar problems are encountered in the failure of turbo-jet engines, can offer guidance. For example, a NASA report [4] describes structures containing only a few kilograms of woven polymeric fiber that provide safe containment in the event of blade failure in large jet turbines. We therefore visualize the EMB modules in a vehicle, in addition to having their individual containment, being surrounded by a light-weight "egg crate" composite structure that supports the EMB and provides additional containment and isolation from the consequences of failure of adjacent EMBs. It is important to note in this connection that the failure of highly stressed fiber composites is in no way similar to the failure mode of metals under tensile stress. Earlier tests [5] have indicated that, owing to the nature of the composite itself, failure under tensile loading results in an amorphous mass of low-strength material, rather than in shrapnel, as is the case with metallic flywheels.

The EMB module illustrated in Fig. 1 has its spherical vacuum chamber shown with spring supports (symbolically representing gimbals). If a gimballed mount is used it has the effect of greatly reducing the restraining forces that must be exerted by the magnetic bearings, in vehicular uses, in order to overcome motional effects. Whether or not gimballing is employed we believe that it will be necessary — in both vehicular and stationary applications — to provide "backup" bearings to accommodate shock loads, either from impacts (in vehicles), or seismic effects (in stationary systems).

POWER ELECTRONICS AND THE ISSUE OF EFFICIENCY

Not shown in Fig. 1 is the solid-state power electronics system needed to convert and control the inward and outward flows of electrical energy to the EMB module. For vehicular uses is appears that the preferred drive systems will be ac-based ones. For example, the drive train on the GM "Impact" demonstration electric auto employs variable-frequency ac induction motors. While all EMBs must use combinations of rectifiers and inverters in ac drive systems, in the case of the EMB with its multi-phase ac output another route may be taken: the use of the "matrix converter" [6] to convert multi-phase, variable frequency, ac to another (variable) ac frequency. The matrix converter, which is a bi-directional system, uses pulse-width modulation techniques to dissect and resynthesize ac waveforms. Matrix converters are intrinsically higher in efficiency than rectifier/inverter based systems. As a result of the high efficiencies of both the Halbach array generator/motor and the matrix converter we predict that the energy recovery efficiency of EMB modules using these design features can be very high — of order 95%. This efficiency is to be contrasted with the typical high-load efficiencies of electrochemical cells of 60 to 70%. As a direct result, both electric and hybrid-electric vehicles, when driven in typical urban settings, are predicted to have substantially increased range (for the same amount of stored energy expended, or fuel consumed) if EMBs are used in place of electrochemical cells. In the case of the all-electric auto the gains expected are striking: an increase of nearly a factor of two in range is predicted. Put another way, the primary energy (energy that must be supplied by the economy) required to drive such a vehicle a given number of miles in urban settings would be up to a factor of two smaller than if powered by ordinary batteries, and of order a factor of five less than if that same vehicle were to be powered with an internal combustion energy.

To illustrate the point just made, Fig. 2 is a graphical plot of the "energy conservation factor" (ECF) calculated for a particular vehicle for which the drag-versus-speed and fuel consumption parameters were known (the calculation was performed several years ago). By integration over a particular simulated urban driving cycle (the "seven-mode federal urban cycle") the kilowatt-hours required could be evaluated, along with the primary energy requirements (including refinery and fuel trucking energy requirements) when in the internal-combustion mode. Assuming now that an electric drive was substituted, with regenerative braking but with the same vehicular drag coefficients, the calculation was then repeated, now including charging and discharging efficiencies and electric utility efficiencies. The result of the calculation is to give the ECF as a function of the energy recovery efficiency (ERE) of the electrical energy storage system. Two effects are immediately obvious from the figure: If the ERE is of order 90% or higher (as with the EMB) the gains from the use of regenerative braking are substantial, whereas at the 60 to 70% level they are only modest. Second, even with regenerative braking the positive effect on the nation's primary energy demands if ordinary batteries are used is only half that if EMBs are used in all-electric autos used in urban settings.

MODULE SIZES; SPECIAL DESIGN ISSUES AND ROTOR STABILITY

The EMB module that we have been describing, at the 1.0 kWh level, is one that is sized for automotive applications. There are many reasons for choosing a small module size for this application. Among the compelling reasons is the fact that both the efficiency and the specific power of the generator/motor are higher for smaller units, owing to their higher rotation speed. Another reason for small units is the issue of containment, discussed earlier. A still further reason is the minimization of gyroscopic effects. These scale down as the fourth power of the physical size of the rotor. At the 1.0 kWh module level the gyroscopic moment of the rotor is about the same as a car flywheel at full speed.

For other applications, both vehicular and stationary, we would expect to scale up the energy storage capacity per module somewhat. For example, for computer UPS (uninterruptable power supply) applications or for power-conditioning applications 5 kWh modules might be more suitable. For load-leveling, bulk energy storage, and large vehicles (for example, locomotives) 25 kWh modules seem appropriate. For such large EMBs, where high specific energy is less important than low capital cost per kWh the fiber of choice might not be graphite (presently expensive per kWh stored) but instead the workhorse fiber, E-glass, would likely be used, maintained at freezer-level temperatures to minimize stress-corrosion effects.

Our choice of a multi-shell configuration for the rotor of our EMBs is based on both materials-related and economic considerations. The materials-related one has to do with the mechanical properties of fiber composites, as follows: to achieve the maximum possible strength in hoop tension (thus, maximal stored kinetic energy as limited by centrifugal forces), the cylindrical shells are made to be fabricated (by automated filament winding processes) with the fiber filaments oriented azimuthally. It follows that, although maximal strength against hoop tensile stresses is achieved, it is at the sacrifice of tensile strength in the radial direction, where only the inter-filament tensile strength of the epoxy resin is operative. However, owing to the radial gradient of centrifugal forces (resulting in hoop forces varying with the square of the radius) internal radial stresses will arise within the body of a ring of finite radial thickness. As was found in early experiments where thick-ring rotors were used [7] these stresses can cause rotor failure, by delamination, at hoop stress levels far below the predicted tensile strength of the thick ring. Theoretical calculations based on the stress-strain equations for anisotropic materials [8] show that these stresses vary roughly as the square of the radial thickness of the ring. However, they become tolerable if the radial thickness of the ring is limited to approximately 10% of the ring radius. This feature has been incorporated in our designs, particularly for the outermost rings. Another feature of our particular multi-ring designs takes advantage of the benefits of small amounts of mass loading on the inner surface of the rings. The beneficial effects of mass loading are threefold: first, loading the inner (less stressed) rings increases the amount of energy stored per unit volume of the composite, with only a modest decrease in the specific energy. Second, loading diminishes the amount by which the gap between adjacent rings grows under increasing centrifugal stress, thus simplifying the design of the separators between the rings. Third, loading reduces the radial tensile stress within the rings by introducing a compressional term ("negative radial tensile stress") at the inner surface of the ring, in that way diminishing the magnitude of the radial tensile stress within the remainder of the body of the ring. The addition of even modest amounts of loading permits the use of somewhat thicker rings without fear of failure from delamination. In our design it is important to note that the magnets of the Halbach array generator/motor already provide mass loading on the innermost ring.

A further practical advantage of the multi-shell design is that it eliminates the necessity of using spokes to connect the central hub of the flywheel to its rim (as in single-rim designs). The design of this part of single-rim flywheels has turned out to be very difficult in earlier flywheel work.

STABILITY ISSUES; ROTOR DYNAMICS AND BALANCING

In the design of high-speed rotating machinery the issue of stability must always be faced. In the design of conventional metal flywheels there are well-known prescriptions, including precision balancing and tight tolerances in the bearings whereby vibrations and the tendencies for unstable behavior are minimized. The case of the multi-ring fiber composite rotor is very different, on several counts. First, the multi-ring structure itself has body resonances that arise from the coupled nature of the several rings. Second, it is difficult to contemplate achieving a state of precision balance of a filament wound fiber composite structure in a production environment, let alone having that state of balance remain constant over the entire speed range of the rotor as it undergoes radial dilations.

The first of these two concerns — unstable body resonances — was addressed several years ago theoretically and checked experimentally [9]. It was then shown that instability can be avoided if the lowest mode of transverse oscillation (as determined by the effective spring constants of the separators) is made to lie above the highest operating speed of the rotor. Another kind of body resonance that can cause trouble can be present if the rotor body is elongated too much. In such cases flexural vibration modes can appear within the operating speed range with attendant deleterious effects. Our approach to this latter problem includes limiting the axial length of the rotor to a roughly "square" aspect ratio, thus precluding these resonances from appearing within the operating speed range.

The second one of these rotor-dynamic issues, avoiding the need for precision balancing, we address in a manner familiar to rotor dynamicists. We arrange the compliance of the bearings and their mounts to be such that the resonance frequency associated with the mass of the rotor and that compliance is very much lower than our intended operating speed range. Thus in spinning up the rotor from standstill it will pass through that resonance early on. Provided the degree of unbalance is modest and provided damping means are provided, the resonance response will be limited in amplitude and the rotor will enter a "super-critical" regime. In this regime the rotor will spin about its own center of rotation, displaced slightly from the center of symmetry of the bearing system. If all other rotor resonances have been pushed above the operating speed range the effects of residual unbalance will be minimal. The validity of this general approach (i.e., of super-critical operation) of a multi-ring flywheel system was demonstrated in tests performed in the 1970s. [10]

There remains a generic class of rotor-dynamic instabilities that involve the entire system — rotor, bearings, and generator/motor. These are the so-called "whirl" instabilities. [11] The tendency for such instabilities to arise occurs in those situations where dissipative losses in the body of the rotor, or displacement-dependent torques in the bearing system and/or in the generator/motor can arise. Under any of these circumstances out-of-phase torques that exert destabilizing forces on the center-of-mass of the rotor can arise that can drive the rotor into unstable radial oscillations. Stabilizing whirl instabilities then becomes a quantitative matter, i.e., it depends on such considerations as the amount of damping that is built into the bearing supports, or how low the mechanical hysteresis in the rotor body can be made relative to the damping effects. We have taken these effects into account in the design of our systems. For example, in the case of the destabilizing effects of the generator/motor (particularly at the high power levels we are contemplating) we believe that our use of the Halbach array (discussed later) will minimize its role in stimulating whirl-type instabilities.

THE GENERATOR/MOTOR

A central feature of our EMB is the design of the generator/motor. As mentioned earlier, our design is an "ironless" one, utilizing an array of magnets first described by Klaus Halbach of the Lawrence Berkeley Laboratory [12]. Figure 3 shows the dipole version of Halbach's array, together with an end-on view of one quadrant of the computer-calculated lines of force of the magnetic field that it produces. As can be seen the field interior to the magnets is both strong and highly uniform, while it is nearly canceled outside the array. The efficiency of the Halbach array is such that if one uses NdFeB as the magnet material, interior fields of order 0.5 Tesla can readily be attained.

The predicted power output and the efficiency of the generator/motor of our EMBs is remarkably high. There are no hysteresis losses in an ironless system. Windage and bearing losses, significant in ordinary motors and generators, are negligible here, and inductance effects are minimal. As a result even the small 1 kWh unit that we have described should be capable of very high power output, achieved at an extraordinarily high efficiency. Because of the inductive coupling used, with the stator windings not in an evacuated region, what little heat is produced in the stator windings can readily be handled by conventional means, i.e., by air or liquid cooling. Some example calculated parameters for such a module are:

Rotation speed	200,000 RPM
Magnetic field of Halbach array	0.5 Tesla
Length and width of winding (no. turns)	0.8 x 0.4 m. (10)
Output voltage (3-phase)	240 V rms
Conductor losses at 37.5 kW output	260 Watts
Efficiency at indicated power and speed	0.993

In our designs we have assumed the use of litzendraht wire in the stator windings to reduce no-load eddy-current losses. In the example above a conductor composed of 6 paralleled strands of 175/46 gauge litz wire was used in the windings, leading to a calculated eddy-current loss (at full speed) of about 2.0 Watts per phase. This level of loss would, if taken alone, result in a self-discharge time constant of about 160 hours for a 1 kWh rotor.

In a hybrid-electric vehicle application the calculations show that two of the above units (operated counter-rotating to minimize gyroscopic effects) should together be able to deliver 75 kW (100 hp) for several seconds with a calculated initial rate of rise of temperature of the stator windings (ignoring cooling) of about 8° C/sec.

MAGNETIC BEARINGS

The most critical technical challenge, and the one that we have paid the most attention to since the inception of our program, is that of the magnetic suspension/bearing system. To meet that challenge we have initiated a combined theoretical-experimental program with the objective of developing new classes of magnetic bearings that would be simpler, less expensive, and better suited the needs of the EMB. At this time it is still premature to discuss the detailed results of our bearing developments, but some general comments on the problem are in order.

As is well known to those skilled in the art, the first problem that must be faced in designing any magnetic suspension/bearing system is dealing with Earnshaw's Theorem [13]. This theorem, first derived for a system of electric charges, and later generalized to include magnetic systems of fixed current and magnetization, asserts the impossibility of stably levitating an object by means of static electric or magnetic forces. The theorem implies that if any object is so levitated there will always be at least one axis in space along which it is unstable. The conventional answers to resolving this dilemma either involve the use of mechanical means of stabilization along the unstable axis (as in some commercial turbo-vacuum pumps) or else involve the use of sensors and servo electronic circuits to stabilize the bearing system. There is by now in existence a substantial body of experience and of commercial products that use this latter approach. The difficulty is that most of these systems are complex and expensive, and seem not well suited for use in the vacuum environment of the EMB.

While it is not clear that continued development of the servo-type magnetic bearing will not result in a product that is both practically and economically suited for use in EMBs, we have chosen another course — the passive magnetic bearing. Examining the assumptions implicit in the derivation of Earnshaw's Theorem, one can discern circumstances where it does not apply, or is at least less demanding. For example, it does not apply to diamagnetic bodies, such as superconductors. Indeed magnetic bearings using the new high-temperature superconductors have been experimentally tested [14]. The theorem also does not exclude the use of time-varying forces to stabilize, such as may occur in systems subject to periodic forces [15,16].

Our approaches to the passive magnetic bearing utilize various combinations of "loopholes" in Earnshaw's Theorem to accomplish stability. We have experimentally tested some of these ideas, following theoretical analyses, and the results of these tests will be incorporated into our future designs. Since our presently funded project is aimed primarily at a stationary application its magnetic bearing system can be much simpler than ones needed for vehicular applications (because of the accelerations involved). However, we expect to learn much that will be helpful toward solving the bearing problem for vehicular EMBs in carrying out the present task.

STATUS OF LIVERMORE EMB PROGRAM

The funded program at Livermore to develop an EMB module for initial use in the LLNL Computer Center began in December 1992. Since initiation of this effort much progress has been made toward the goal. A first prototype unit has been designed and constructed and is in the initial phases of being tested. As mentioned earlier, the unit is designed to have a very high ratio of power to energy stored — 200 kW with a 2 kWh storage capacity. Such a high power level is not needed for the application in hand (for which only 10 kW) is needed, but it was designed into the generator/motor in response to a need perceived by a potential industrial partner.

In addition to the results described above, the following work has been performed en route to the goal:

- Design of the rotor and its containment, construction, and initial testing; procurement of all materials;
- Theoretical analyses of the stability of the rotor and bearing system;
- Finite-element and theoretical analyses of rotor stress distributions;
- Vacuum tests of sealed chamber containing a simulated rotor;
- Sub-system tests of mechanical "backup" bearings;
- Sub-system tests of support and damping elements of LLNL passive magnetic bearing designs;
- Design, construction, and operation of solid-state drive electronics.

In the work we have performed to date the emphasis has been on gaining experience and testing designs that will be of value in future work on the EMB. This experience will help us when new applications, be they vehicular or large-scale stationary systems, are contemplated. We consider that the most important step en route to proving the viability of our EMB concepts is the one we are embarked on now — designing, building, testing, and delivering such a unit for use in a real-world application.

SUMMARY AND CONCLUSIONS

We have launched a program at LLNL to design, build, and demonstrate a new breed of electromechanical battery based on several novel design concepts. This program addresses critical design issues for EMBs, with special emphasis on simplified magnetic bearings. We are taking a "systems" approach to the entire problem because of the recognition that all elements of the EMB — rotor, generator/motor, and magnetic bearings — are intimately coupled. Our projections are that EMBs designed around our concepts have the potential to meet the needs of electric and electric-hybrid vehicles in all of their technical requirements. We also clearly recognize the difficulty of satisfying the many-faceted demands of such applications. In recognition of this fact we conjecture that the first entry of EMBs into vehicular use is likely to be the hybrid-electric vehicle, with all-electric vehicles appearing later, as the cost of EMBs is driven down through the economies of large-scale production.

Although the most glamorous application of our EMBs is in vehicular uses, the value of the concept in a myriad stationary applications should not be underestimated. Here our confidence, both in achieving the technical requirements and in meeting cost constraints, is high. Stationary versions of the EMB are therefore, in our opinion, the most likely of all to appear first in the commercial arena.

Finally, although the EMB concept is a very simple one conceptually, there are many subtle points to be addressed in arriving at an economically viable system. We have mentioned several of these points. They include: issues of dynamic stability associated with all aspects of the operation; practical approaches to "passive" magnetic bearings (and/or greatly simplified "active" bearings); optimization of the energy storage through design of the rotor; enhancing the power and efficiency of the generator/motor; and finally, issues of containment and service lifetime

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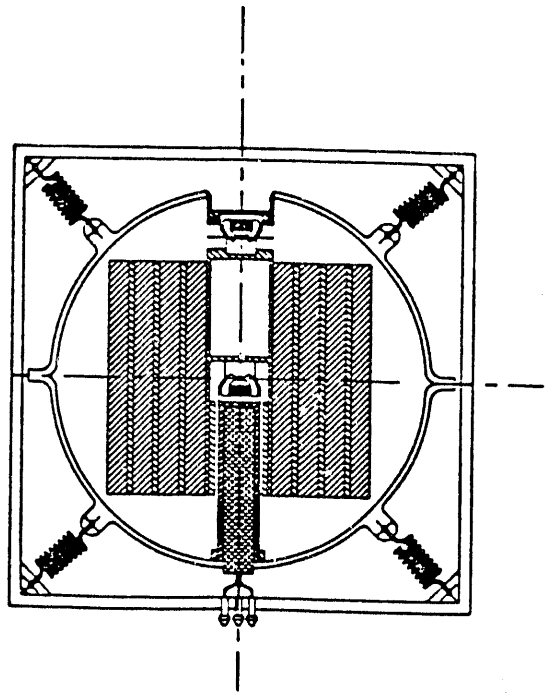

Figure 1. Schematic cutaway drawing of modular EMB

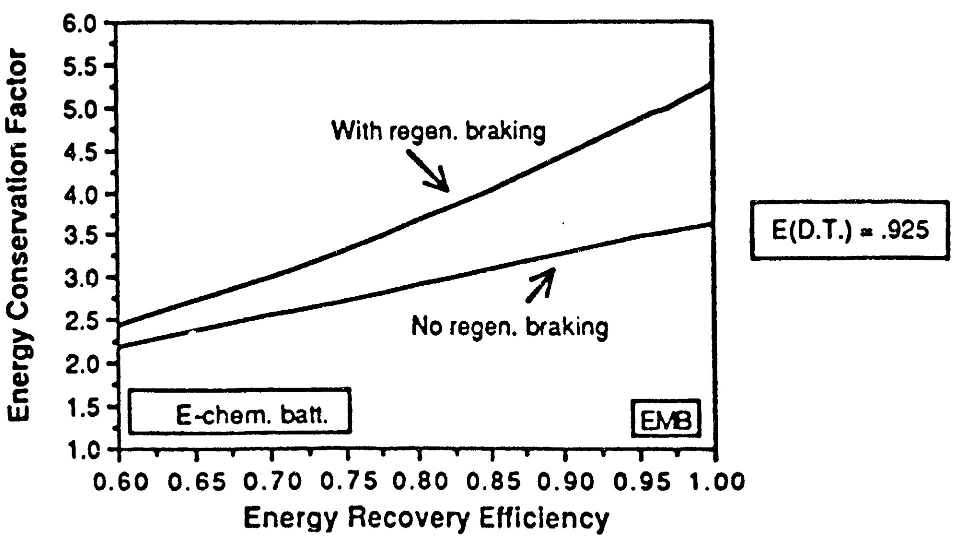

Figure 2. 'Energy Conservation Factor' calculated over Federal 7-Mode urban cycle showing importance of energy recovery efficiency. Power-time averaged drive-motor efficiency of 0.925 assumed.

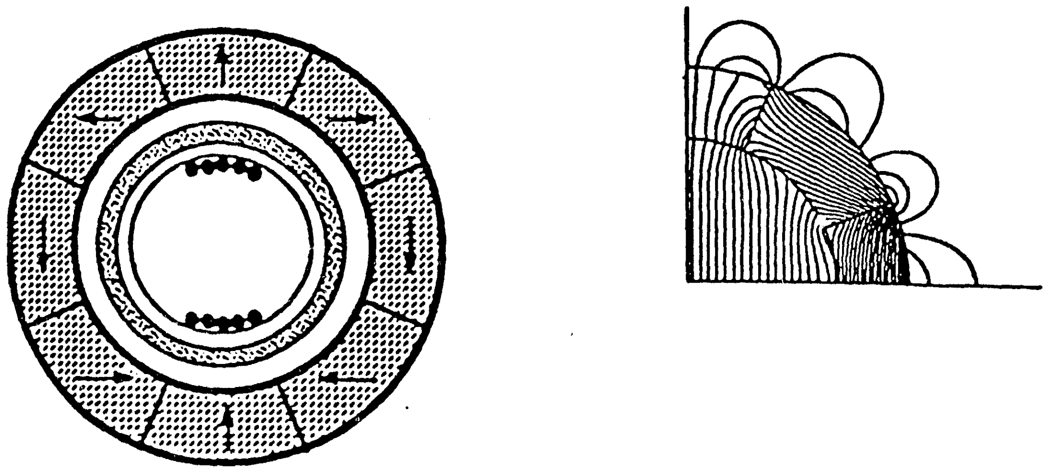

Figure 3. Left: End view of Halbach array showing vacuum barrier and some of windings. Right: Quandrant of calculated field lines.

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