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MASTER

LAWRENCE
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LABORATORY

MAGNETIC FUSION ENERGY PROGRAM

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ABOUT THE COVER

Plasma formed inside a Baseball test magnet, showing the fan-shape characteristic of a plasma in the magnetic field of a mirror machine. Two major mirror experiments are under way at LLL. Baseball II, a superconducting experiment to study principles of fusion reactor startup and steady-state operation, and 2XIIIB, a pulsed-field experiment aimed at studying the stability of high-density plasmas. 2XIIIB has produced plasma temperatures of 13 keV (the highest ever attained in a fusion experiment), hot-plasma densities of $1.2 \times 10^{14} \text{ cm}^{-3}$, and plasma confinement times exceeding 5 ms. Both 2XIIIB and Baseball II use energetic neutral beams to create and sustain the plasma, and both experiments are currently being upgraded to increase plasma temperatures, densities, and confinement times. For a description of recent progress in the Laboratory's magnetic fusion energy program, see the articles beginning on pp. 1 and 10.

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BRIEFS

ADVANCED ENERGY SYSTEMS

LLL Magnetic Fusion Energy Program: An Overview

In recent months, major progress has been made in the LLL magnetic fusion energy program toward developing a technically feasible approach to the generation of fusion power. Highlights are a tenfold improvement in plasma confinement, new highs in plasma temperature and pressure, and plasma startup by neutral beam injection.

Building a Better Bottle: New Mirror Ideas

To improve the economics of mirror fusion reactors, we are exploring ways to improve the containment quality (Q factor) of mirror systems. Field reversal is one of several intriguing Q-enhancement possibilities.

SCIENCE AND TECHNOLOGY

Flywheel-Battery Hybrid: A New Concept for Vehicle Propulsion

A new flywheel-battery hybrid promises to improve both the range and performance of electric vehicles, making them competitive with today's internal-combustion vehicles for urban commuting.

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Briefs

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

ROCKETBORNE X-RAY ASTRONOMY EXPERIMENT SUCCESSFUL

On June 5, a two-stage sounding rocket carrying x-ray instrumentation was launched from ERDA's rocket range at Barking Sands, Kauai, Hawaii. Scientific objectives were threefold: measure the time dependence of the x rays emitted by Circinus X-1 (a possible blackhole), search for x-ray emissions from several faint supernova remnants near the galaxy's center, and determine the spatial distribution and spectrum of x rays from the Lupus Loop, an old supernova that now appears as an extended, weak source of soft x rays. LLL discovered the soft emissions from the Lupus Loop about three years ago.

The two-stage, solid-fuel Terrier-Sandhawk rocket attained an apogee of more than 300 km. After 8 min of data acquisition above the atmosphere, the 200-kg payload fell into the ocean and was successfully recovered. All payload components operated as designed, scanning the appropriate stellar regions. The recovered camera film has been processed; data reduction is in progress.

Preliminary results show x rays from Circinus X-1. These data will now be searched for the characteristic time signature of blackholes. We found a weak, previously undetected soft x-ray source near the supernova remnant SN185. If this association is confirmed by final analysis, this discovery is exciting because the remnant's age is known; the present data possibly can be compared with those from past experiments to address the question of evolution in supernova remnants. Finally, the Lupus Loop was clearly observed on two scans. The data indicate an x-ray source several degrees in extent whose spatial structure is not spherically symmetrical. Details,

including the spectra of these and other observed sources, will be forthcoming.

The payload's instrumentation included large-area, gas-filled proportional counters sensitive to photons in the energy range 200 eV to 20 keV. Good low-energy sensitivity resulted from the counter's extremely thin plastic entrance windows. These plastic films, made by LLL, have thicknesses less than the wavelength of visible light and support pressures in excess of 100 kPa when the payload is in the vacuum of space. A star sensor and movie camera aligned with the proportional counters measured and photographed the starfield so that, after the flight, the counter's pointing direction could be determined to within 1 s of arc.

Radio commands from the ground station controlled the payload during flight. The coordinate system of the inertial platform in the payload's attitude control system was made into a scaled transformation of the celestial sphere. We superimposed the platform's telemetered outputs onto the transformation and determined the rocket aspect to about 1°. Then, by radio command, we fired appropriate gas jets in the attitude control system by radio command, altering the payload's scan direction and rate.

This launch was another in a series of x-ray astronomy experiments conducted by LLL with rocket systems designed and developed by Sandia Laboratories, Albuquerque. Over a 10-year span, we have pioneered work in soft x-ray astronomy, locating many previously undetected sources, making the first measurements of x-ray absorption by interstellar dust (an important astronomical distance indicator), and detecting silicon enhancement in supernova remnants beyond the expected cosmic abundances. Details of the 10-year series and the payload ground-control systems were presented in the April 1975 *Energy and Technology Review* (UCRL-52000-75-4), p. 16.

ADVANCED ENERGY SYSTEMS

LLL MAGNETIC FUSION ENERGY PROGRAM: AN OVERVIEW

Over the last 12 months, significant progress has been made in the LLL magnetic fusion energy program. In the 2XIB experiment, we have achieved a tenfold improvement in the plasma confinement factor (the product of plasma density and confinement time), pushed plasma temperature and pressure to values never before reached in a magnetic fusion experiment, and demonstrated - for the first time - plasma startup by neutral beam injection. A new laser-pellet startup technique for Baseball IIT has been successfully tested and is now being incorporated in the experiment. Technological improvements have been realized, such as a breakthrough in fabricating niobium-tin conductors for superconducting magnets. These successes, together with complementary progress in theory and reactor design, have led to our proposal to build the MX facility, which could put us on the threshold of a mirror fusion reactor.

Progress toward the goal of fusion power can be gauged by three criteria:

- Understanding the physics of ionized gases plasma at the ultra-high temperatures required for fusion.
- Developing the specialized technology needed to create and confine fusion plasmas.
- Achieving the plasma conditions - temperature, particle density, and particle confinement time - required to permit self-sustaining nuclear fusion reactions.

In recent months, major progress has been made in the LLL magnetic fusion energy program toward meeting all three of these criteria. This progress has been mainly accomplished in the 2XIB mirror experiment. Based on our successes and on the theoretical work that led to them, the Laboratory proposes to build a much larger mirror experiment, MX, aimed at demonstrating plasma conditions approaching those needed in a mirror fusion reactor.

Viewed as a whole, our magnetic fusion energy program is devoted to a broadly based study of the magnetic mirror idea and its special technology, to conceptual studies of mirror fusion reactors, and to

a search for ways of improving on the basic mirror concept. The program's primary goal is to develop a technically and economically feasible approach to the generation of fusion power.

Magnetic Confinement Principles

The conceptual basis for any magnetic confinement fusion system derives from the fact that energetic charged particles can be trapped on the field lines of a properly shaped magnetic field, provided the field is intense enough. Two basic field configurations exist: closed and open. Both configurations have their

To reflect the program change recently announced by ERDA, the LLL Controlled Thermonuclear Research (CTR) Division has been changed to the Magnetic Fusion Energy Division.

advantages and disadvantages, so both are under investigation in world fusion research.

In closed systems, the field lines on which plasma particles are trapped lie wholly within a toroidal (doughnut-shaped) chamber; particles can escape only by diffusing across the field lines until they hit the chamber wall. In open systems, such as mirror machines, the field lines enter and leave the confinement zone through the chamber ends. Particle escape along the field lines is inhibited by intensifying the end fields. Particles approaching these regions (the mirrors) are then reflected, provided they are not directed too nearly parallel to the field lines. Escape through the mirrors occurs when interparticle collisions or other processes deflect a particle so that its vector is nearly parallel to the field lines.

Magnetic-confinement fusion research is dominated by the need to satisfy stringent quantitative requirements. One such requirement involves $n\tau$, the confinement factor (product of particle density and confinement time). Self-sustaining reactions become possible only when the $n\tau$ of a fusion fuel charge is large enough for the fusion energy released to exceed the energy required to heat that fuel charge. In general, to extract power from controlled fusion reactions, we need an $n\tau$ of at least 10^{13} to 10^{14} particles/cm³-s. In addition, economic requirements can be met only if the fuel particle density itself is high enough for the fusion power released (which varies as n^2) to "pay"

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for the capital cost of creating the confining magnetic field. The achievement of these requirements can be compromised by the problems caused by plasma instabilities, namely the tendency of a magnetically confined plasma to escape because of turbulence and other modes of unstable behavior.

Present excitement and optimism in the LLL mirror program stems from the fact that in 2XIIB we have not only suppressed plasma instabilities but demonstrated that a high-temperature, high-density plasma can be created and confined by the magnetic field.¹ This plasma exerts an outward pressure on the confining field that almost equals the maximum inward pressure exertable by the field. In the language of fusion research, the 2XIIB plasma is a "high-beta" plasma, beta being the ratio of internal plasma pressure to maximum external magnetic pressure. Under normal circumstances, a beta of one is the maximum value for this parameter.

In simple cases the plasma, at a beta of one, will completely exclude the magnetic field from its interior; at beta values close to one, the interior field will be greatly weakened relative to its value when the plasma is not present. For mirror systems there are, therefore, two reasons to push toward high beta values. The first is economic: high beta means efficient utilization of the magnetic field. The second concerns confinement: high beta means an enhanced mirroring effect, since weakening the magnetic field between the mirrors increases the relative strength of the end fields.

Enhancing mirror confinement is an important subsidiary goal of the LLL mirror program.

LLL Mirror Experimental Program

The experimental elements of our mirror program comprise two major confinement experiments (2XIIB and Baseball), a joint LLL-LBL program for developing high-intensity neutral beam sources (energetic neutral atom beams used to create and heat plasmas), studies into the direct conversion of charged-particle kinetic energy to electricity, and development of superconducting magnet coils. Each of these elements is aimed at solving problems that relate directly to our final goal - practical mirror fusion reactors.

2XIIB Update. The 2XIIB machine is a pulsed-field mirror experiment equipped with an array of neutral beam sources capable of producing hundreds of amperes equivalent of focused neutral atoms at energies of 10 to 20 keV (Fig. 1). In experiments last Fall,² we were able to stabilize high-frequency instabilities in the 2XIIB plasma by injecting a low-energy plasma stream through the ends of the machine. When stabilized, the lifetime of the confined plasma was shown to increase with increasing plasma-ion mean energy, in approximate agreement with the theory for quiescent mirror-confined plasma.

In subsequent experiments, encouraging new results have been obtained in 2XIIB relating both to confinement and to the practical question of plasma startup. Startup refers to the issue of how to initiate

THE SEARCH FOR FUSION POWER

Fusion power is potentially a safe source of energy based on universally available and virtually limitless fuels. Deuterium, fusion's eventual primary fuel, is a stable isotope of hydrogen. The supply of deuterium in the world's oceans could sustain present world energy consumption for 100 billion years - 10 times the estimated age of our universe. It also appears likely that pure fusion reactors, as they evolve, will pose a smaller hazard to man and his environment than any other major power source except solar energy.

For fusion power to become an economic reality, however, practical methods must be found for: (1) heating fusion fuel (plasma) above its ignition temperature, (2) confining this super-hot plasma long enough for energy output to exceed input, and (3) converting the released energy to useable forms (electricity and process heat). Scientists have been working on these problems for more than two decades now and, while many scientific and economic problems have yet to be resolved, major progress has been made.

One approach to fusion research is magnetic confinement, which calls for containing very hot, high-density plasma in specially shaped magnetic fields. There are two basic confinement configurations: open-ended machines (mirror or theta pinch) and closed toroidal machines (Tokamak). In U.S. magnetic-confinement research, LLL has the prime responsibility for pursuing the mirror machine. Mirror fusion reactors offer the advantage of high power density coupled with relatively small size; that is, a mirror reactor may be successful at the several hundred megawatts level, one-tenth the anticipated toroidal machine levels. Also, the mirror concept is one of the few magnetic-confinement approaches capable of steady-state operation, an important factor in achieving the ultimate fusion energy goal: commercial electric power generation. The accompanying article describes recent progress in the LLL magnetic fusion energy program.

Fig. 1. 2XIIIB mirror machine viewed from the top. The plasma guns are on the upper right diagonal. The two circular tanks house the neutral beam sources. In recent experiments on 2XIIIB, we have improved plasma confinement tenfold, pushed plasma temperature and pressure to new highs, and demonstrated plasma startup by neutral beam injection.

and build up a fusion plasma within a dc magnetic field such as would be used in a mirror reactor. Because of the great technical difficulty and extra expense associated with providing pulsed fields in a reactor, we had long believed that the pulsed plasma target used in previous 2XIIIB experiments would not be suitable for reactor startup.

Addressing this issue in the latest 2XIIIB operation, we found that:

- Plasma buildup can be accomplished in a static magnetic field using only a plasma stream as the initiating 'target, provided the available neutral beam current is high enough (in excess of about 100 A). The hot plasma so produced is then indistinguishable from the ones produced by the more cumbersome technique of bombarding a transient target plasma generated by plasma injection and magnetic compression.

- A stabilizing plasma stream can be produced by admitting hydrogen gas into a baffled gas box outside

one of the mirrors after initial plasma buildup. This gas is then ionized by energetic charged particles escaping through the mirrors from the previously produced hot plasma.

- With this new stream technique, we were able to raise the hot plasma density to $1.2 \times 10^{14} \text{ cm}^{-3}$, a factor of 3 or more above the highest values achieved earlier, and to maintain this level for as long as the sources could be operated (5 ms).

- At the new higher densities, the plasma beta value increased to at least 1.0, with indications that it could be even higher. This result is most significant in terms of the possibility of exploiting the high-beta self-confining effects mentioned earlier.

What do these new data mean for the future of the mirror program? They demonstrate three important results. First, a plasma stream can stabilize a hot mirror-confined plasma so that it approaches the quiescent state needed for reactor operation. Second, it is possible to push the plasma pressure so high that

Fig. 2. Baseball II: (left) superconducting magnet coil shaped like baseball seam; (bottom) magnet coil above its housing unit. The Baseball facility is now being modified to include high-current neutral beam sources and a new laser-pellet technique for creating startup plasmas. With these new components, our immediate goals are to reach a high-density regime ($\sim 10^{13} \text{ cm}^{-3}$) with ion energies above 10 keV.

the plasma's presence deepens the magnetic well within which it is trapped, enhancing its own confinement. Third, we now have a startup method that can operate in a dc magnetic field, thereby solving an important practical problem for future mirror devices.

Baseball IIT. The second major confinement experiment in the LLL mirror program is Baseball IIT. The Baseball II facility (Fig. 2) was first put into operation in 1971. As suggested by its name, the experiment has as its most important element a superconducting magnet coil shaped like a baseball seam (Fig. 2). This coil produces a deep magnetic-well mirror field, similar to that in 2XHB except that the field is dc and is more intense.

During the initial operation of Baseball II, experiments were directed toward studying the plasma buildup process, using a low-energy, low-current neutral beam source. While stable plasmas with lifetimes approaching 1 s were produced, plasma density was limited to low values (about 10^9 cm^{-3}) by the onset of high-frequency plasma instabilities. Now, however, we have shown in 2XHB that the combination of high-current neutral beams plus plasma stream stabilization can be used to create and sustain a fusion plasma. Work is therefore in progress to install high-current neutral beam sources in Baseball IIT, together with the means for creating a target plasma to initiate the buildup process.

This target plasma is to be created by a technique borrowed from the laser fusion program.³ A tiny droplet of frozen ammonia, launched from a capillary jet outside the apparatus, is aimed by means of an in-flight, computer-controlled, electrostatic course-correction system. At the target point, this droplet is zapped by twin beams of focused high-intensity infrared light from a high-power CO_2 laser, creating an ionized target plasma. While this plasma remains trapped, it provides a target on which buildup may be performed with the high-current neutral beam sources.

Final assembly of these new components in Baseball IIT is nearing completion; initial tests are slated for August. With the possibility of dc operation and with the higher fields available, we feel that Baseball IIT will add important new insight to our understanding of mirror confinement.

Neutral Beam Development. Our successes in 2XHB were made possible by the development of high-current, highly focused, neutral beam modules. The development of these, and of new generations of sources with even greater capabilities, stems from a joint LLL-LBL program initiated several years ago.

Fig. 3. One of the 1.5-m-high transformers that will power the Laboratory's new high-power beam test facility. When we test the new 80- and 120-keV neutral-beam source modules now being developed, the entire power of the transformer will be channeled into beam power in a source module approximately the size of that shown in the foreground.

The basic source module, 12 of which are used in 2XHB, has a voltage rating of 20 keV and delivers a nominal 50 A equivalent current of neutral deuterium atoms into a $10 \times 20\text{-cm}$ area at a distance of 3 m. The length of the beam pulse is 10 ms, although longer pulses have been achieved in tests. With a 10-ms pulse length, each module can deliver upwards of 5 to 10 kJ of energy in the form of energetic neutrals; the 12-source array on 2XHB thus has a nominal capability on the order of 100 kJ. To put this in perspective, 100 kJ represents a quantity of energy equal to the kinetic energy content of 140 litres of plasma at a temperature of 10 keV (about $100\,000\,000^\circ\text{C}$ kinetic temperature) and a density of $3 \times 10^{14} \text{ particles/cm}^3$ (reactor density).

To achieve even higher plasma ion temperatures, we must increase the energy of the neutral beam atoms. Source modules are now being developed with beam energies of 40, 80, and 120 keV. We will test the 80- and 120-keV modules in a new high-power beam test facility now under construction at LLL. To give some idea of the beam powers involved — tens of megawatts — Fig. 3 is a photo of one of the transformers

that will be used to power the test facility; in front is a 50-A source module. The entire power of the huge transformer will be channeled into beam power in a source module roughly the size of the one shown.

Developments such as these new source modules are significant not only for their applications to fusion experiments but also for their relevance to fusion reactors. As a solution to the problems of heating and fueling fusion reactors, the neutral beam technique is recognized as one of the most promising methods yet proposed.

Direct Conversion. A fusion plasma consists of a collection of rapidly moving charged particles, which represent elementary electrical currents. Thus, under the right conditions, fusion plasma is a medium uniquely well suited to the direct extraction of electrical energy. Studies have been under way at LLL for several years to test the technique of direct conversion as it would be applied to a mirror fusion reactor.

These tests, consisting of proofs-of-principle carried out on a scaled-down apparatus, have been highly successful. Overall conversion efficiencies of 86% — plasma energy to direct electrical power — have been measured, in close agreement with theoretical predictions based on a computer code. A photograph of the test apparatus appears in Fig. 4.

The conversion technique resembles a Van de Graaf particle accelerator operated in reverse. Charged particles — ions and electrons — escaping through the mirrors enter a "magnetic expander" nozzle, where their random motion is converted to an outwardly directed stream. At the end of the expander, the electrons are diverted and collected at ground potential — the negative terminal of the direct converter. The ions, which carry the lion's share of the escaping energy, pass into a collector consisting of a series of electrodes biased positively to progressively higher potentials. Within the collector, ions are decelerated electrostatically and, after they have given up most of their kinetic energy, are diverted and deposited on a collector electrode. In effect, the direct converter thus becomes a multiterminal, high-voltage dc generator from which electrical energy can be tapped directly.

In theory, the efficiency of such a converter can approach 100%; in practice, it will be limited by economic constraints. Efficiencies between 60 and 80% seem possible, depending on design and cost considerations.

In a mirror reactor, a direct converter serves a twofold function. It not only recovers energy from charged fusion-reaction products (helium nuclei in the case of the deuterium-tritium reaction) but also

Fig. 4. Test apparatus for direct conversion studies at LLL. Charged particles escape through the mirror and race-track coils (short green cylinders in right foreground), enter the expander magnet (center) where their random motion is converted to an outwardly directed stream, and are then diverted to the collector tank (upper left cylinder) and decelerated electrostatically.

Fig. 5. Power flow diagram for a fusion reactor. Mirror fusion reactors are visualized as driven systems, i.e., ones in which plasma temperature and particle density are maintained in steady state by injecting intense beams of energetic neutral atoms. The electrical power needed to generate these beams will be tapped from the reactor's power conversion system; most if not all of this recirculated power will be obtained from the direct converter. This converter will extract energy both from the charged fusion-reaction products and from unreacted fuel ions.

recovers energy from unburned fuel ions (see Fig. 5). In this way it improves the reactor's power balance, in that a large part of the energy invested in heating the plasma (through neutral beam injection) can be recovered electrically and recirculated back to the injectors. For this purpose, the high plasma temperature needed for a mirror reactor represents an advantage, since the efficiency and power-handling ability of a direct converter improves with increasing plasma temperature.

Superconductor Development. At the heart of any magnetic-confinement method of fusion power generation are the magnet coils that generate the confining field. If this is a steady-state field, as in the mirror machine, it requires a continuous flow of current — thousands of amperes — in the conductors of the coils. If these conductors were ordinary copper, the power dissipated in creating the requisite magnetic

fields would be very large — hundreds of millions of watts — making it virtually impossible to achieve a positive power balance from the reactor. The strange phenomenon of superconductivity (perfect electrical conduction with no energy dissipation) exhibited by certain alloys and intermetallic compounds when refrigerated to the temperature of liquid helium provides an answer to this dilemma.

Expertise at LLNL in superconductor technology has been developing for many years. The first application to fusion research was the Baseball II magnet. Scientists at the Laboratory have been working with industry groups to develop even better superconductors. Their most recent success represents a marvel of advanced technology — with a down-to-earth practicality. They have developed a method for creating a "copper" busbar that carries a 10 000-A current with no detectable electrical

resistance. The superconducting material is an intermetallic compound of niobium and tin. Although discovered many years ago at Bell Laboratories, this superconductor has been difficult to apply for other than small coils because of its very brittle nature.

The new fabrication technique for niobium-tin conductor involves repeatedly drawing down a high-tin bronze billet in which niobium rods have been inserted and then heat-treating the composite to form Nb_3Sn on the rods' outer surfaces.⁴ In this way a 15×5 -mm conductor can be formed containing over 600 000 Nb_3Sn filaments embedded in a copper matrix. This multifilamentary conductor is less brittle and can be handled like an ordinary busbar — i.e., it can be wound onto a large coil form in a manner similar to winding an ordinary copper coil.

When refrigerated to liquid-helium temperatures, a coil wound from Nb_3Sn conductor loses all electrical resistance and is capable of generating very high magnetic fields (12 T). Once energized, the only energy dissipated is that associated with heat leakage through the cryogenic insulation surrounding the cooled coil. This leakage can be kept very small, so that in essence the coil becomes a permanent magnet — but one capable of producing much higher fields than possible with any permanent magnet material.

Successes in Mirror Theory

One of the most important aspects of our recent successes in mirror research is easy to overlook if only the results themselves are considered. This aspect is the role played by theoretical developments in increasing our understanding of mirror confinement.

In 2XIIIB the breakthrough in performance came after a theoretically predicted stabilization method — the use of a plasma stream — was used. The basic theory that predicted the effectiveness of this technique was worked out nearly 10 years ago, but its implementation had to await clear evidence — first seen in 2XIIIB — that it was relevant and applicable. Building on that evidence, recent work by the theory group has resulted in a detailed theoretical picture of the stabilization of mirror confinement. This theory has been successful in predicting the time-dependent behavior of plasma buildup and confinement in 2XIIIB. It can also be applied in predicting the stability and confinement properties of plasma in a scaled-up system of reactor size.

To illustrate the accuracy with which it is now possible to predict plasma behavior in the stabilized 2XIIIB plasma, Fig. 6 is a plot comparing the experimentally measured plasma buildup in 2XIIIB to that predicted by the theoretical buildup equations.

Fig. 6. Comparison of experimentally measured plasma buildup in 2XIIIB (solid curve) to theoretical predictions (dots). The closeness of these data illustrates how accurately we can now predict plasma behavior with theoretical calculations.

The agreement here is so close that the two curves virtually coincide.

Another important area where theory supplies a guide post for experiment is in calculating the rate of leakage of particles from mirror systems owing to interparticle collisions — the so-called "classical" mirror losses. As a result of several years of refinement, LLL now has available so-called computer codes that can be used to predict classical mirror losses in almost any situation. These codes are used as checkpoints against which experiments can be compared and also for carrying out reactor design calculations.

Looking toward the future, and toward the important task of finding means to improve the confinement quality of mirror systems, we again look to theory to guide the way. The confinement quality factor, Q , is defined as the ratio of fusion power released to heating power input to the plasma. Theory shows that, within what are deemed practical limits on the mirror ratio (ratio of field at the mirrors to that at the low point of the field between mirrors), Q is in the range 1.0 to 1.5 for unaugmented mirror systems. Though it is possible to design reactors based on Q values as low as this, high efficiencies in the injection and direct-conversion systems are then needed, and a substantial recirculated power component must be handled. Thus there is a growing emphasis on Q enhancement techniques.

One important Q -enhancement possibility is to create a so-called field-reversed state in a mirror-confined plasma. Field reversal corresponds to a plasma state in which the plasma currents are so configured and so strong that deep within the plasma these currents cause the interior magnetic field lines to bend back and close on themselves. For this situation — corresponding to a state where beta is greater than unity — confinement of the interior plasma should be considerably enhanced over normal mirror confinement. We do not yet know whether this state can be achieved, but theory indicates that it should be possible if the neutral-beam current levels are high enough. Preparations are being made to test this possibility in 2XIIB.

Other methods of enhancing Q are also being considered, starting with theoretical evaluations. One example, on which early work has been done at other laboratories, is the enhancement of mirror containment that should occur in the presence of strong radio-frequency fields applied to the plasma at the mirrors. These or similar methods may lead to increases in Q that would have a very favorable impact on the

economics of mirror reactors. Q enhancement is discussed in greater detail in the article beginning on p. 10.

Plans and Prospects

As of today, theory and experiment indicate that an experiment the size of 2XIIB, impressive though its results are, cannot do more than carry us to the threshold of the reactor regime. To achieve longer confinement times will require yet higher plasma temperatures and larger plasmas. To this end, LLL is proposing to build the MX facility, a scaled-up experiment in which it will be possible to increase plasma temperature fivefold over 2XIIB (to 50 keV) and increase plasma volume fiftyfold. A visualization of MX is shown in Fig. 7. The MX experiment would be equipped with an array of neutral beam sources capable of building up and maintaining a high-beta plasma at temperatures where $n\tau$ would be 10^{12} cm⁻³-s, or a factor of 10 larger than that in 2XIIB. MX would be scheduled for first operation about 1981; its success could put us on the threshold of demonstrating the feasibility of mirror systems as fusion reactors.

In contemplating steps beyond MX, we have considered three alternatives, in ascending order of their demands on confinement. Least demanding would be a materials testing facility, FERF (fusion engineering research facility), a non-self-sustaining driven reactor that would use the deuterium-tritium reaction and produce a high flux of 14-MeV neutrons for testing radiation damage to the reactor chamber wall and breeding blankets. Reasonable success in MX would be all that would be required to provide the physics input needed to build FERF, which would be expected to come on line in the mid-1980's.

Next in physics demands beyond a mirror FERF would be a fusion-fission hybrid reactor. This would be a mirror reactor with a blanket that incorporated a subcritical lattice of thorium or depleted uranium. Such a device could not only produce net electrical power (fission-augmented) but, perhaps more important, be able to breed uranium-233 or plutonium at a cost apparently competitive with the fission breeder reactor. Particularly in the case of the thorium/uranium-233 cycle, fusion-fission might be attractive as an interim application of fusion technology, before its full deployment in a pure-fusion power economy. However, such a hybrid would be subject to some of the concerns now facing the fission breeder.

Fig. 7. Proposed MX facility for testing the scientific feasibility of the mirror approach to fusion. Over 12 m high, MX will provide a transition from present small mirror experiments to large steady-state devices.

Finally, the pure-fusion mirror reactor, although the most demanding, remains the central goal of the LLL mirror program. Our studies show that, given classical confinement, mirror fusion reactors could be built, albeit at a cost higher than present power systems. However, because the cost projections are sensitive to Q , we feel that prospects are good for reducing these costs as we discover and prove out methods for enhancing confinement. Certainly the mirror system,

with its many advantages already perceived, is one of the most promising approaches to fusion power in all its aspects.

Key Words. Baseball IIT; controlled thermonuclear reactions; direct energy conversion; FERG; fusion; fusion reactors; magnet coils; magnetic mirrors; mirror machines; mirrors; MX; neutral particle beams; neutral particle beams - injection; plasma - heating; superconducting magnets; Two X; 2XIIB.

BUILDING A BETTER BOTTLE: NEW MIRROR IDEAS

As described in the preceding article, the LLL mirror program is primarily directed toward a steady-state fusion reactor based on a superconducting magnet, neutral beam injection, and direct conversion. In addition, a portion of our theory and design efforts is aimed at exploring ways to improve the confinement quality, or Q , of mirror systems, since increasing the Q factor would have a favorable impact on reactor economics. In these exploratory studies, we are mainly

considering those ideas that use the physics and technology already being developed in the program. Thus some ideas - such as field reversal - can be tested directly in the 2XIIB or Baseball IIT experiments and in the proposed MX experiment.

In the early days of magnetic-confinement fusion research, the central problem was to find a magnetic bottle that would contain a plasma for more than a fleeting instant. That day is past; 2XIIB has shown that dense, hot plasma can be confined, free from disruptive instabilities, for extended times. Mirror

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researchers are therefore increasingly turning their attention to a different problem, one essentially of economics. To produce net power from a mirror fusion reactor, power must be recirculated to heat and replenish the combusting fusion fuel; this requirement places important constraints on system efficiency.

Up to a point, lower confinement efficiency can be compensated for by increasing the efficiency of the neutral beam injection system, the direct converter, and the thermal conversion plant. However, the price for this tradeoff is increased complexity and capital cost. It becomes worthwhile, therefore, to consider means for augmenting the confinement efficiency of the basic mirror containment cell, or magnetic bottle.

Q Enhancement

A simple index of confinement efficiency as it relates to fusion needs is the quantity Q , defined as the ratio of fusion energy released to total energy input to the plasma (in the form of energetic neutral beams or any other heating input). To produce a net electrical output from the reactor, Q must exceed a minimum value that is determined by the efficiencies of the heating and energy conversion systems. If these efficiencies are high, lower Q values can be tolerated, and vice versa. For example, if the energy-recovery and injection efficiency are both 80%, energy "breakeven" would occur at $Q = 0.56$; if both are 50%, it would require Q of 3.0 to achieve breakeven. Thus Q values suitable for economic net power will depend on an interplay between cost vs Q of the confinement system and cost vs efficiency of the heating and recovery systems.

The Q values for stable plasmas in unaugmented mirror confinement cells can be calculated theoretically. At optimum plasma-ion temperatures (about 150 keV mean ion energy), these values range between about 1.0 and 1.5 for the deuterium-tritium reaction,⁵ depending on the value of mirror ratio assumed (ratio of field at the mirrors to that at the lowest field point between the mirrors). When it is possible to envisage a mirror reactor based on Q values in this range, cost analysis indicates that enhancing Q by even relatively small increments would lessen overall reactor costs, mostly because of the resultant reduction in recirculated power. Figure 8, taken from one such analysis, illustrates the effect on reactor capital cost caused by changing Q from its classical value (here about 1.1). It is apparent that a twofold improvement would make a substantial difference.

Possible Approaches. How do particles leak through

Fig. 8. Impact of Q enhancement on overall reactor costs. Even relatively small increases in Q would reduce reactor capital costs; a twofold improvement would make a substantial difference.

mirrors and how can we reduce this loss rate? The mode of particle escape through the mirrors is easy to comprehend if the basic idea of particle confinement in a mirror system is understood. Consider that the motion of an ion in a mirror field is broken down into two components: motion directed parallel and perpendicular to the field lines.

Motion perpendicular to the field lines is circular in character, since the magnetic field bends the particle orbit back on itself, as in a cyclotron. As an ion moves toward a region of higher field intensity (the mirror), where the field lines squeeze together, it spins in a smaller circle and at a higher speed, owing to the higher field strength. Higher rotational energy implies that kinetic energy must transfer from the parallel motion, i.e., the ion slows down. If the initial parallel energy is small enough (that is, if the ion is not directed too nearly parallel to the field lines before it enters the mirror region), then the ion will be stopped and turned around in its path. It can be trapped between the two mirrors, therefore, and will continue to fly back and forth between them like a billiard ball bouncing back and forth across a billiard table.

The ion will remain trapped until some process deflects it too nearly parallel to the field lines for the

mirror action to be operative. In a stable plasma, the only important such process is the effect of collisions between ions. But since these same collisions may also result in a fusion reaction, Q will be determined by a quantitative evaluation of the relative probabilities of loss-producing collisions vs fusion-producing collisions. It is from calculations of this type that the Q values previously quoted were deduced.

One additional fact is needed to round out the picture of plasma confinement by mirrors. We have to this point only discussed the confinement of the plasma ions — deuterons or tritons. What of the electrons? Confinement of electrons in a mirror machine differs from that of the ions. Because electrons are much lighter and thus much more mobile than ions, they collide with each other and with the ions at a much higher rate than that at which the ions collide with each other. Thus they would *a priori* tend to escape much more rapidly than the ions. This cannot continue to be the case, however, for as the electrons attempt to rush out, they leave behind an excess of ions — namely a positive charge excess.

In a fusion plasma, it takes only a tiny fractional disparity of charge densities to create a large positive potential — a so-called “ambipolar potential” — which will hold the remaining electrons in by electrostatic attraction. The ambipolar potential will build until the rate of electron loss is slowed, just equaling the rate of ion loss. At this balance point, all but the highest energy electrons are held in by the ambipolar potential. In terms of ion confinement, the price paid is that the presence of the positive ambipolar potential expels any ions not tightly enough trapped by the mirrors, thus somewhat reducing the mean ion confinement time, and with it, Q .

This then is the basic mirror idea: ions magnetically confined, electrons electrostatically confined, both escaping as a result of collisions that deflect the particles into the “loss cone” defined by the combined effect of the mirrors and the ambipolar potential — repulsive for the ions and attractive for the electrons.

How do we reduce the mirror loss rate and enhance Q ? Over the years many ideas have been suggested, and the most promising of these are being studied theoretically, in preparation for their possible test in the laboratory. These ideas include:

- Enhancing the mirroring action of the ions by spinning up their rotational speed through cyclotron action imparted by resonant radio-frequency fields acting on the ions as they approach the mirrors (Fig. 9).

- Improving the mirroring action on the ions by achieving confined-plasma pressures high enough that, owing to its own diamagnetic effect, the plasma digs a deeper well for itself between the mirrors, thereby enhancing the mirror ratio over its value in the absence of the plasma. Evidence that such high-beta states are possible can be adduced from the 2X11B data.

- Stringing mirror cells in series, under plasma conditions where ions that escape out the ends of an interior cell have a finite probability of being retrapped before they reach the end cells. In a variant of this idea, the string of mirror cells would be bent back on itself, forming a mirror-torus hybrid (Fig. 10). Studies in the United Kingdom have shown that such systems might retain the advantages (such as high beta) of mirror systems, while gaining some of the advantages of toroidal systems.

- Operating in the so-called “two-component” mode. In a long mirror machine, enhanced Q values become possible if the operation mode involves the bombardment of a dense, relatively low-temperature (10-keV) tritium plasma by high-power beams of energetic deuterium atoms (about 200-keV energy). In this mode, the power of the beams acts to heat the

Fig. 9. One Q -enhancement scheme being studied theoretically is the addition of radio-frequency (r-f) fields to act on the ions as they approach the mirrors. These fields would enhance the mirroring action of the ions.

Fig. 10. Another Q-enhancement idea being pursued is the mirror-torus hybrid, like the schematic layout shown here for a six-cell design. Such a hybrid would minimize the problem of particle escape through the mirrors.

dense tritium plasma to an intermediate temperature, while the energetic deuterium ions during the time that they are slowing down (transferring energy to the tritium plasma) have a relatively high probability of reacting with the tritons. Two-component operation would have the advantage of high stability, due to the stabilizing effect of the lower-temperature tritium plasma, and would minimize ambipolar effects; however, it would have the disadvantage of requiring a very long plasma. This length requirement might be ameliorated by the use of multiple mirrors or by other end-stopping techniques.

- Creating a field-reversal state within the mirror cell. In this intriguing possibility – described in more detail below – plasma currents are made so high that they produce their own pattern of closed field lines within the confinement cell.

These ideas illustrate a few of the schemes we are considering to enhance the containment efficiency of mirror confinement systems.⁶ We cannot, of course, tell in advance which schemes – or new variants – will prove to be best suited for practical application. But the very fact that we are now turning to the issue of improving the economic picture for mirror reactors is perhaps the most persuasive evidence that magnetic fusion research is turning a corner – moving from a

search for encouragement to studies of ways to improve on an already impressive level of achievement.

Field Reversal

In the past, much of our intuition (frequently wrong!) concerning the behavior of charged particles in a magnetically confined plasma was derived from experience with particle accelerators – cyclotrons, synchrotrons, and the like. But there exists a fundamental distinction between the behavior of charged particles in such devices and that of plasma particles in a fusion magnetic bottle.

In a particle accelerator, the magnetic field in which the particles move is determined entirely by the accelerator field magnets; the accelerated particles have a negligible effect on this field, since the electric currents they represent are small compared to the currents in the magnet windings. Not so for a fusion plasma. Here, in all situations of practical interest the plasma has a kinetic energy density that is not negligible compared to the energy density of the magnetic field.

The electric currents in the plasma, a necessary concomitant of confinement, can become comparable to those in the magnet field coils – that is, the plasma can argue back. In fact, the complexities of the magnetic confinement process can be traced directly to the arguments (instabilities) that the plasma comes up with in trying to evade confinement. These instabilities result when the flows of charged particles in the plasma upset the confinement process. A measure of success in confinement, therefore, is to ascertain the magnitude of plasma pressure that can be sustained by the confining field before the plasma can find a way to generate unstable, internal current-flow patterns.

One of the most remarkable aspects of our recent results in 2XIIB is the fact that high-temperature plasmas, having kinetic energy densities at least equal to the energy density of the confining field, have been confined with no evidence of gross instability. In the language of fusion research, beta – the ratio of plasma pressure to confining field pressure – approached or even exceeded unity. Indeed, here the presence of the plasma markedly influenced the strength of the magnetic field within and in the vicinity of the plasma.

Our success in 2XIIB already answers one dream of magnetic fusion research – namely to demonstrate high-beta plasma confinement at fusion temperatures. But this success stimulates us to consider anew a still more exciting prospect: field reversal.

For field reversal, the electric currents within a confined plasma have become so intense that they actually reverse the direction of the magnetic field inside the plasma, relative to its direction with no plasma present. Figure 11 illustrates such a situation as it might occur in a mirror field such as that in 2XIIB. In the context of mirror research, the main advantage of field reversal lies in the fact that the escape route for plasma particles trapped in the reversed-field region would no longer be the direct one of leakage through the mirrors; to escape confinement, these particles would first have to diffuse across the reversed-field regions, and then escape through a mirror.

Our first attempts at achieving field reversal were actually carried out in conjunction with the ASTRON program at LLL. In the ASTRON, invented by the late Nicolas Christofilos, field reversal was to be

achieved by trapping a ring of circulating electrons at energies of many million electron volts between mirrors. In these experiments, field reversal was approached but not achieved, owing to technical limitations of the method used for generating the electron ring. Nevertheless, the idea was clearly set forth, and in later experiments at Cornell University, using a different technique, small field-reversing electron rings were actually produced, demonstrating the concept's validity.

Viewed from the mirror-reactor standpoint, the idea of field reversal differs from the ASTRON concept, however. We propose to achieve field reversal using only the plasma-ion currents. This represents an extension of the high-beta state reached in 2XIIB. The advantage of such an approach is that it should be possible technically to reach field reversal using only the basic machine elements now available in 2XIIB,

Fig. 11. In a reversed-field state, the plasma currents are so arranged and so strong that they cause the interior magnetic field lines to bend back and close on themselves. With field reversal, beta is greater than unity and thus plasma confinement should be considerably enhanced over normal mirror confinement.

i.e., intense neutral beams and magnetic-well mirror fields.

How can we be sure that stable reversed-field states based on plasma-ion currents can be achieved? We cannot be sure, but indications from early reversed-field experiments with theta pinches (high-density magnetic compression experiments) in this country and abroad are encouraging. In addition, computations performed with the LLL computer code "Superlayer" show reversed-field states attained by neutral beam injection. Figure 12 presents some results from Superlayer, showing the field-line pattern of the field reversal state attained in the code run. These calculations are not conclusive, however, since simplifying assumptions made in setting up the code might conceal the true situation. Only experimentation such as that planned in 2XIIIB can provide definitive answers.

What would be the advantages of field reversal for the mirror machine? In addition to the expected increase of Q already cited, it appears from our studies that field reversal would offer the possibility of building a fusion reactor composed of relatively small modular cells. Because of the highly efficient utilization of the magnetic field offered by field reversal (plasma beta greater than 1.0), the fusion power density of a cell could be quite high without the requirement for extremely high magnetic fields. This circumstance, coupled with enhanced confinement $n\tau$ factors, would result in much improved reactor economics.

Fig. 12. Field-line pattern for field reversal attained in the Superlayer code run. Computations performed with this code show field-reversed states achieved by neutral beam injection.

The exploration of magnetic confinement of plasma in the domain where plasma currents strongly modify the confining field itself is an exciting possibility. With the recent 2XIIIB high-beta results to encourage us, we are convinced that these new plasma regimes could open the door to fusion reactor possibilities otherwise inaccessible.

Key Words. field reversal; fusion reactors; mirror machines; Q enhancement; Superlayer.

SCIENCE AND TECHNOLOGY

FLYWHEEL-BATTERY HYBRID: A NEW CONCEPT FOR VEHICLE PROPULSION

In a joint study with AiResearch Manufacturing Company, LLL has examined a new concept for powering the automobile: a flywheel-battery hybrid that can be developed for near-term use from currently available lead-acid batteries and state-of-the-art flywheel designs. To illustrate the concept, we calculated the range and performance of the hybrid power system in a typical commute vehicle and compared them to the measured range and performance of an all-battery vehicle. This comparison shows improved performance and a twofold urban-range increase for the hybrid over the all-battery power system.

Highway vehicles (automobiles, trucks, and buses) alone use over one-sixth of the energy consumed in the United States.⁷ This energy is almost entirely supplied by petroleum, making these vehicles a major contributor to our need for oil imports. Their dependence on petroleum will continue for some time since no acceptable propulsion systems are yet available that use other fuels. It is imperative, therefore, that alternative energy sources – and the propulsion systems to use them – be developed for transportation.

Electric vehicles are one alternative in that they can be energized by electric power plants fueled by coal or uranium, meeting the need for a multifuel, nonpetroleum automobile. However, electric cars have not been accepted by the driving public because the lead-acid batteries currently available have limited energy and power capacity. Satisfactory range can only be achieved at the expense of performance (acceleration, cruising speed, hill climbing). Battery recharge times are also long, idling vehicles for extended periods.

The limitations of lead-acid batteries for automotive propulsion are well known. It is also known, however, that U.S. automobile usage is dominated by short trips. As shown in Fig. 13, 75% of vehicle kilometres traveled in 1975 consists of trips of 80 km or less; trips of 32 km or less make up over 50% of the total.⁸ Although the data do not indicate the frequencies of

these trips, they do indicate that most are to and from work, and thus are once-a-day round trips. Electric vehicles powered by lead-acid batteries can achieve these ranges.

To make electric cars attractive to the driving public, however, their range must be maximized for urban driving and their performance improved, allowing them to compete safely on the road with vehicles using other propulsion systems. Both goals might be achieved by combining the lead-acid battery with a power booster – a fiber-composite flywheel replacing an equivalent weight of batteries.

This flywheel addition has the potential of extending the range of electric vehicles and improving their acceleration, cruising speed, and hill-climbing ability to a point competitive with internal-combustion vehicles. More important, a flywheel-battery hybrid can be developed for near-term use; the requisite lead-acid batteries and flywheel design are available now. The possibility of this hybrid surfaced from a joint investigation of flywheel-battery power systems by LLL and the AiResearch Manufacturing Company.

Hybrid Propulsion System

In this concept, the flywheel acts as a power booster for the battery. It is a mechanical device and can manage high power demands without reducing its total energy capacity. Vehicle range would thus be increased since the energy capacity of the flywheel-battery combination will be greater than the all-battery system. This is because of (1) battery load leveling – the battery supplies only low power (current) demands, the flywheel supplies the high power demands – and (2) the flywheel's ability to absorb energy (recharge) efficiently during vehicle operation. Thus, the flywheel addition can provide a vehicle with high performance without incurring the range degradation of an all-battery electric vehicle.

Vehicle kinetic energy is restored to the flywheel when traveling downhill or during any period of deceleration. The flywheel-battery hybrid is thus able to make efficient use of a regenerative braking system to recover energy.

Another important benefit that the hybrid system offers is increased battery life. In an all-battery system,

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Fig. 13. Percentage of vehicle kilometres driven by trip purpose and by length distribution. Short-distance trips dominate. Most trips are to and from work, that is, once-a-day round trips. Recreation trips include Sunday rides, weekend trips, vacations, and visits to friends and relatives. Family business covers errands, shopping, and transportation to church and school. (Ref.: 1975 *Automobile Facts and Figures*, Motor Vehicle Manufacturers Association of the U.S., Inc., Detroit, Mich., 1975.)

battery life is severely reduced by the high current drains (deep discharge) of stop-and-go performance demands. In the hybrid system, the battery can be discharged at a lower stabilized rate with the flywheel supplying peak power demands. Vehicle operating time between deep discharge cycles will be extended, increasing battery life.

Finally, the hybrid-system vehicle will necessarily be parked during the working day when operating in a commuter environment. Flywheel energy content at

the time of parking can be used to charge the battery bank rather than be lost to rundown.

The flywheel subsystem includes the flywheel, containment housing, and vacuum/tube pump. In one design, the wheel has a mass of 23 kg and an effective energy release of 750 Wh, or an energy density of 33 Wh/kg. The flywheel used for our study is similar to that shown in Fig. 14. It has a fiber composite rim and rotates at a maximum speed of approximately 40 000 rpm. The containment housing would be

maintained by the pump at a vacuum of 665 mPa, decreasing rundown losses due to windage. Rundown from 40 000 to 20 000 rpm is calculated to take 2.8 h, during which time 75% of the total energy is expended. We assume energy is extracted over this maximum-to-half-maximum rpm range during power system operation.

A lead-acid battery loses available capacity when subjected to high discharge rates. It provides highest energy at modest power demands. On the other hand, a flywheel can deliver or reaccept energy at high power levels without affecting its energy storage capacity. This capacity is limited only by the stress-bearing capability of the connected hardware, gearing, shafts, etc. For the electric vehicle, the flywheel addition satisfies the power demands of stop-and-go performance requirements that, time-averaged, represent only a modest continuous energy investment at low power levels.

In the power system proposed, the flywheel augments the battery during periods of high power demand: starting, acceleration, and hill climbing. The battery supplies cruise-and-control power plus the

energy required to replenish flywheel losses. This "split" of energy demand is shown graphically in Fig. 15. With battery power demand stabilized at a low value, specific energy is maintained near maximum, resulting in increased vehicle range. Unlike an all-battery system, this range increase is not accomplished by degraded performance since the flywheel satisfies the required high power demand.

In addition to load leveling the battery, the flywheel's ability to absorb energy (recharge) at high rates is a major contributor to increased range.

Power System Design Concept

Our hybrid electric propulsion system uses the flywheel-battery in conjunction with an infinitely variable, electromechanical transmission. The energy storage capacity of the flywheel and the torque capacity of the transmission combine to provide the torque capacity for all the normal high-power transients that occur in urban driving. This includes starting, acceleration, high-speed-passing maneuvers, uphill grades for limited distances, and energy recovery during braking. The results are increased range,

Fig. 14. Artist's conception of the flywheel under study for the flywheel-battery hybrid power system. The flywheel has a fiber composite rim and rotates at a maximum speed of about 40 000 rpm.

Fig. 15. Specific power as a function of specific energy in the flywheel-battery hybrid system. Below the crossover point, low power demand is supplied by the battery. Above the crossover point, high power demand is supplied by the flywheel. Battery specific energy is maintained near maximum, resulting in increased vehicle range without decreased performance.

Fig. 16. Schematic of power system design. Torque on the drive shaft is supplied by both mechanical (flywheel) and electrical (battery) power.

improved acceleration and performance, greater energy economy, and longer battery life.

The proposed power system, shown schematically in Fig. 16, includes the flywheel, transmission, power control unit, and traction and flywheel motor/generators. The flywheel is a laminated fiber composite design of high energy density. The transmission is a simple differential planetary gear set infinitely variable from zero to maximum vehicle speed. The microprocessor-based power control unit provides interactive control of power flow between the traction motor/generator, flywheel motor/generator, and battery. The traction and flywheel motor/generators are separately excited dc machines (their field and armature windings are separate

circuits). Both may be used in a motor or generator mode as dictated by the control requirement.

To accelerate the vehicle, the traction motor/generator is supplied with current from the flywheel motor/generator, which acts as a generator. The necessary torque for the generator is supplied by the deceleration of the flywheel, which also reacts through the gears to supply additional accelerating torque to the shaft of the traction motor/generator. The flywheel is also mechanically coupled to the planet carrier. Because the planet carrier shaft (drive shaft) is the same as the traction motor/generator armature, there is a direct mechanical linkage from flywheel to differential. Net torque to the wheels is the sum of electrical and mechanical torque, thus the name split-path transmission.

Fig. 17. Power transmission efficiency. Total efficiency is the product of the electrical and mechanical efficiencies.

System deceleration is the reverse of acceleration. The traction motor/generator is operated as a generator and the flywheel motor/generator acts as a motor to accelerate the flywheel. The flywheel resistive torque

is again split between the ring gear and the carrier output shaft so that the two torque components decelerate the vehicle and store the deceleration energy in the flywheel.

At a constant vehicle velocity, the battery provides traction-motor power plus the power required by the flywheel motor to replenish rundown losses.

The efficiency of this split-path transmission — the product of both electrical and mechanical efficiencies — is an important feature. Figure 17 shows how it varies as a function of the mechanical torque fraction, F , for typical values of the component efficiencies. The value of F varies during any transient operation, but for the cases studied, the resulting average values are approximately 0.50, resulting in combined efficiencies of over 80%. Power is thus transmitted with a higher efficiency than possible with an all-electric drive system.

To initially run up the flywheel, the flywheel motor/generator can be supplied with power from either the battery or an external source. The motor action accelerates the flywheel to its maximum speed (40 000 rpm), as shown by the "start" point in Fig. 18. The traction motor/generator is held stationary (brakes applied) during initial flywheel runup. After flywheel runup to the maximum operating level, outputs from speed sensors monitoring traction motor/generator rpm (road speed) and flywheel rpm are used by the power control unit to

Fig. 18. Flywheel speed control. The flywheel speed range is from 40 000 (start) to 20 000 rpm (end). The reduction ratio of sun gear (flywheel) to ring gear is 8:1.

hold the latter within the prescribed control band. As vehicle speed increases, flywheel rpm decreases. Thus the total kinetic energy of the vehicle and flywheel is held constant, except for transmission losses, and provides the energy required to meet acceleration demand with a margin for rpm increase adequate to accept energy during deceleration.

On long downgrades, flywheel rpm may tend to rise above 40 000 rpm. When this occurs, the starting resistor will be switched into the armature circuit of the flywheel motor/generator and the excess energy dissipated. Limited regeneration to the battery, following flywheel runup to maximum (40 000 rpm), might be used.

Hybrid System Performance

The limitations of electric vehicles powered only by existing lead-acid batteries have been discussed. To illustrate the improvements that can be realized with the hybrid power system, we chose a two-passenger commuter vehicle as a baseline design. Test weight (curb weight plus payload) was limited to 1080 kg.

The power-train weight for both the hybrid and all-battery system was maintained at 462 kg, of which 382 kg was allocated to the energy source. The hybrid energy source includes the 23-kg flywheel assembly plus 359 kg of batteries. The hybrid's traction motor/generator, sized for cruise demand, is approximately half the horsepower rating required for an all-battery vehicle of like specifications. The combined weight (54 kg) of the hybrid traction and flywheel motor/generators and transmission is considered equivalent to that of the all-battery-system traction motor. Power control unit weights are also considered equal for the two systems.

We assumed a mechanical fraction of 0.50 for the hybrid, resulting in a power transmission efficiency of 82%, as seen in Fig. 17. A 72% efficiency is assumed typical for the all-battery vehicle.

Range was calculated for the hybrid and all-battery vehicles operated both at continuous speed and according to test schedules specified in the SAE J227 Electric Vehicle Test Procedures.⁹ These comparisons, given in Table 1, show a dramatic range increase for the hybrid power system when traversing the SAE J227 driving cycles. This increased performance is achieved, however, without sacrificing performance, as shown in Table 2. The electric vehicle's extended range — due to the flywheel's ability to meet high power demands, absorb energy on deceleration, and extend battery range through load leveling — is evident.

As a further test, the hybrid system was theoretically "installed" (i.e., calculated) in an existing electric vehicle. For this comparison we used the Sundancer,¹⁰ developed by ESB Inc., as the test-bed vehicle. A battery weight of 23 kg was removed and the flywheel assembly "installed" for the hybrid performance calculations.

A comparison of actual road test results for the all-battery Sundancer to calculated test results for a hybrid Sundancer again showed the hybrid's superiority. Range is doubled (from 80-88 to 150-340 km) when the Sundancer is powered by the hybrid system and a low efficiency (70 to 82%) is assumed. To test our calculational method, we then computed the all-battery Sundancer's range; our calculated value of 82 km is well within the 80- to 88-km range of the road tests.

Typical Commute Vehicle

Electric commute vehicles with the hybrid range and acceleration shown in Tables 1 and 2 should prove more acceptable to consumers and could compete safely on the road with vehicles using other propulsion

Table 1. Calculated ranges for all-battery and hybrid baseline vehicles

Operating condition	Range, km	
	All-battery	Hybrid
48 km/h continuous	159	162
88 km/h continuous	58	67.5
Metropolitan cycle ^a	54.5	121
Residential cycle ^a	82	151

^aTest schedules specified in SAE J227 Electric Vehicle Test Procedures.

Table 2. Calculated acceleration and gradeability for the hybrid baseline vehicle

Performance criteria	Elapsed time, s
Acceleration, km/h	
0 to 48	6
0 to 88	13
40 to 88	8.5
Gradeability: 88 km/h from rest on a 5% grade ^a	21

^aVelocity could be maintained for a distance of 2.5 km.

Fig. 19. Installation of the flywheel-battery hybrid system in a General Motors Chevette. The flywheel axis is horizontal to the ground and parallel to the drive shaft.

systems. To provide an example of a typical commute vehicle with a hybrid power system installed and to serve as a theoretical model for showing how such a hybrid system would work, we arbitrarily selected the General Motors Chevette as a test vehicle. One possible installation of the hybrid power system in a Chevette is shown in Fig. 19.

This test vehicle could be modified by removing the internal combustion engine and auxiliary equipment as well as the fuel tank. A total of some 450 kg can be removed to provide for the weight of the battery-flywheel propulsion system. A more desirable arrangement may be possible with the addition of a transaxle drive, which reduces vehicle weight by eliminating the drive shaft and normal differential. Available on some foreign cars now, transaxles are expected to be available on small U.S.-manufactured vehicles within a year or two.

Adding the flywheel-hybrid propulsion system will not impose excessive loads on a commute vehicle. If necessary, the system can be divided between the front and rear of the vehicle to balance the weight distribution.

Propulsive and braking forces will not differ significantly from those of a conventional design. The addition of gyrodynamic loads imposed by a spinning

flywheel has been analyzed by AiResearch and is not considered to be a design factor as long as the stored energy in the flywheel is no more than 3 kWh with a flywheel spin axis like that shown in Fig. 19. We calculate that approximately 1 kWh of flywheel capacity can be carried in a rigidly mounted arrangement with any flywheel spin axis for each 450 kg of vehicle unloaded weight. The energy storage capacity of the flywheel can be increased to 1.5 kWh/450 kg with a longitudinal spin axis and to 2 kWh/450 kg with a vertical spin axis. In addition, these flywheel capacities can be increased substantially if a suspension (passive, active, or gimbal) is provided for the flywheel. The limit of 1 kWh/450 kg of vehicle weight can be applied to any vehicle weighing up to 13 500 kg.

This investigation has led us to conclude that the flywheel-battery hybrid can power a near-term electric vehicle that should be more acceptable to the driving public than an all-battery vehicle. The hybrid will not only provide improved performance but double vehicle range in an urban environment.

Key Words: electric cars; electric vehicles; energy storage; flywheels; transportation.

Notes and References

1. These recent achievements are briefly reported in the March 1976 *Energy and Technology Review* (52000-76-3), p. ii.
2. For a fuller description of these experiments and their results, see the November 1975 *Energy and Technology Review* (52000-75-11), p. 1.
3. The laser-pellet startup approach is described in the January 1976 *Energy and Technology Review* (52000-76-1), p. 7.
4. The Laboratory's development program for high-field superconducting magnets is described in the December 1975 *Energy and Technology Review* (52000-75-12), p. 8.
5. The D-T reaction is a prime candidate for use in first-generation fusion reactors. This reaction ($D + T \rightarrow {}^4\text{He}_2 + n + 17.6 \text{ MeV}$) has the highest reaction probability and second highest energy release among potential reactions, all involving deuterium, tritium, and helium. Thus the D-T reaction would be the easiest to initiate.
6. For more details on these and other Q-enhancement schemes being explored at LLL, see W. Condit, T. Fowler, and R. Post, *Status Report on Mirror Alternatives*, Lawrence Livermore Laboratory Rept. UCRL-52008 (1976).
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8. *1975 Automobile Facts and Figures* (Motor Vehicle Manufacturers Association of America, Detroit, 1975).
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10. R. McKee *et al.*, *Sundancer, A Test Bed Electric Vehicle*, Society of Automotive Engineers, SAE Paper No. 720188 (1972).

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