ELSEVIER

Journal of Power Sources 80 (1999) 171–179

JOURNAL OF POWER SOURCES

New developments in the Electric Fuel Ltd. zinc/air system

Jonathan Goldstein *, Ian Brown, Binyamin Koretz

Electric Fuel Ltd., 5 Kiryat Mada Street, Har Hotzvim, P.O. Box 23707, Jerusalem 91230, Israel

Abstract

Electric Fuel Ltd. is engaged in the design, development and commercialization of its proprietary zinc/air battery technology for electric vehicles, consumer electronic products and defence applications. To meet the challenging requirements for propelling an all-electric bus, the Vehicle Division sought a unique solution: an all electric battery–battery hybrid propulsion system. The high energy zinc/air battery is coupled with a high-power auxiliary battery. The combined system offers zero emission, high power and long range in an economically viable package. The consumer battery group has developed a high power primary zinc/air cell aimed at cellular phone users, offering extended use, convenience and low cost.

Keywords: Zinc/air batteries; Applications/electric vehicles

1. A battery system for electric vehicles

Electric Fuel Ltd. (EFL) has developed a high-energy zinc/air battery system, designed to allow electric vehicles to compete with conventional vehicles in price, performance, convenience and safety, while offering superior range, highway speed, equivalent cargo capacity and quick refuelling. EFL concentrates its current technology and commercialization effort toward fleets, which it envisions to be the early adopters of electric vehicles.

The EFL zinc/air battery system for electric vehicles comprises three linked system elements:

(a) the on-board discharge-only zinc/air battery pack, which today is characterized by specific energy of about 200 W h kg^{-1} and specific peak power of 90 W kg^{-1} at 80% DOD
(b) refuelling stations for mechanical exchange of batteries and zinc anodes
(c) zinc anode regeneration facilities for centralized recycling of the zinc anodes.

The system elements are shown schematically in Fig. 1, and has been the subject of various papers [1–4].

1.1. The zinc/air cell

The cell comprises a central static replaceable anode cassette of 'Electric Fuel' which is a slurry of electrochemically generated zinc particles in a potassium hydroxide solution compacted onto a current collection frame and inserted into a separator envelope, flanked on two sides by the company's high-power air (oxygen) reduction cathodes. The basic EFL zinc/air cell is shown schematically in Fig. 2.

During cell discharge, zinc at the anode is consumed by conversion to zinc oxide, and at the cathode, oxygen from the air is electrochemically reduced to hydroxide ions. The overall cell reaction is:

$$2\,\mathrm{Zn} + \mathrm{O}_2 = 2\,\mathrm{ZnO} \quad (E_o = 1.65\,\mathrm{V})$$

where E_o is the standard potential for the reaction. Theoretical specific energy, according to the overall reaction equation, is 1350 W h kg^{-1}. Practical specific energies of around 200 W h kg^{-1} in various full size EV batteries have allowed vehicle ranges per refuelling in excess of 300 km to be demonstrated regularly in normal driving. Nominal discharge voltage at the 5-h rate is about 1.15 V per cell.

The on-board battery is 'refuelled' or mechanically recharged by exchanging spent Electric Fuel 'cassettes'—the zinc anode including current collector frame and separator envelope—with fresh cassettes. This is accomplished by an automated refuelling machine that allows a zinc/air battery powered vehicle to 'refuel' in an amount of time comparable to gasoline refuelling. The depleted cassettes are electrochemically recharged and mechanically recycled external to the battery. With commercial implementation,

---

* Corresponding author. Tel.: +972-2-589 0890; Fax: +972-2-532 2252; E-mail: info@electric-fuel.com

0378-7753/99/$ - see front matter
PII: S0378-7753(98)00260-2

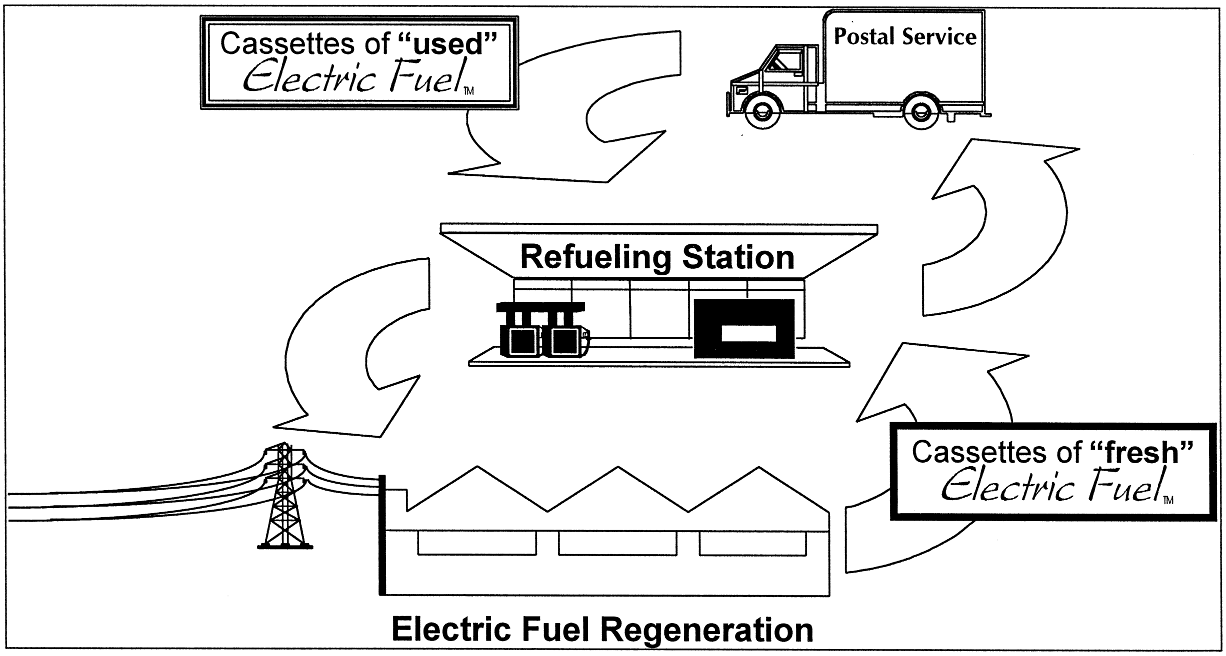

Fig. 1. Schematic diagram of the Electric Fuel Ltd. system operation.

regeneration of the cassettes will take place at centralized facilities serving regional networks of refuelling stations. In this way the zinc anode recharging/recycling facility would assume a parallel role in a zinc/air-based transportation system to that held by oil refineries in today's fuel distribution system, without the negative environmental impacts of refineries or point-source pollution of conventionally fuelled vehicles. The regeneration process is shown schematically in Fig. 3, and has been discussed in several papers [5,6].

1.2. Zinc regeneration

Since its inception in 1990, one of the primary goals of the project has been to optimize the regeneration process, and especially the zinc electrowinning cell, in order to give a process setup that could consistently provide fresh zinc with acceptable performance characteristics for the subsequent discharge. On the one hand, zinc with a high surface area, low apparent density, and dendritic morphology was required in order to provide high power levels and enable binderless compaction onto a current collector to give an adequately robust anode plate. On the other hand, zinc corrosion rate should be minimal in order to achieve low self-discharge rates of the battery, and the process should effectively allow for closed-cycle operation with minimal additives and effluents, with a means for utilization of the residual zinc returning in partially discharged plates. The basic optimized electrowinning zinc conditions [5,6] are summarized in Table 1.

The electrolyte feedstock is compatible with the alkaline electrolyte composition in the discharge cell and has a

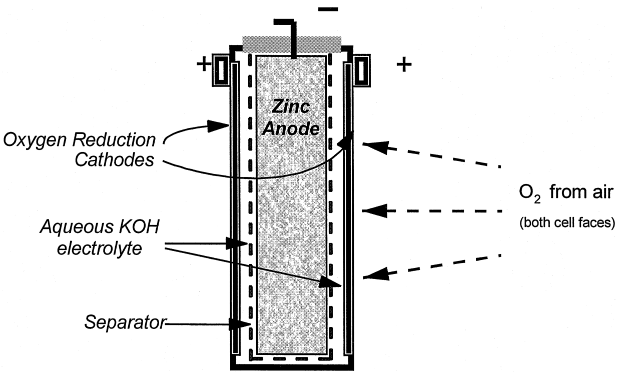

Fig. 2. Schematic diagram of the Electric Fuel Ltd. zinc/air cell.

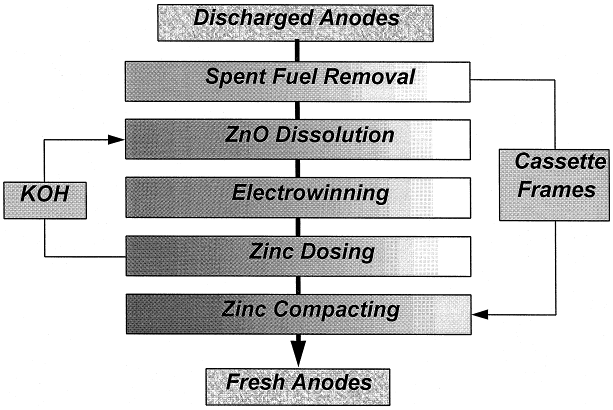

Fig. 3. Schematic diagram of the zinc regeneration process.

Table 1
Optimized electrowinning conditions

Anodes	Nickel louvres
Cathodes	Magnesium plates
Current density	100–200 mA cm^{-2}
Temperature	40–70°C
Electrolyte concentration	7–8 M KOH
Zincate concentration	30–40 g l^{-1}

conductivity close to the maximum conductivity for KOH over this temperature range, assuring low ohmic drop. The dissolved zinc concentration of 30–40 g l^{-1} (as zincate) is within the range of solubility in KOH of zinc oxide, which is the major battery discharge product in the spent cassettes. This concentration allows facile in-plant solubilization of incoming zinc oxide in minimum time and volume of depleted electrolyte feedstock.

An electrowinning current density of 100–200 mA cm^{-2} is adequate for good zinc morphology and compact plant dimensions under the operating conditions of Table 1. In a previous paper [5], we indicated that at the fleet test-demonstration stage, a reasonable goal was to reduce the electrowinning cell voltage to about 2.2 V. This is important for reducing energy losses in the plant and achieving a high effective overall energy cycle efficiency for the EFL system compared with other advanced batteries [3].

To date, EFL has constructed demonstration regeneration plants in Bet Shemesh, near Jerusalem, and at Trofarello in Italy, each capable of regenerating 10 kg zinc/h. The Bet Shemesh plant produces zinc for ongoing testing and demonstration of vehicles in Israel and elsewhere. The Trofarello plant is being used to provide zinc for a small fleet of vehicles operated by the Italian energy company Edison. Edison is a long-standing strategic partner of EFL and has licensed the technology for use in Italy, France, Spain and Portugal.

Construction of a scaled-up regeneration plant in Bremen, Germany, capable of producing 100 kg zinc/h, was completed in early 1996. This plant supplied zinc to support the fleet of Deutsche Post EVs during its field test of the zinc/air battery system. In the course of the field test over 60,000 km were clocked up on 13 vehicles (Mercedes MB410 and Vito vans) fitted with EFL batteries. These vehicles were driven by regular Deutsche Post drivers on city and suburban routes on a daily basis. Typical ranges between zinc refuelling were 300 to 350 km. Deutsche Post confirmed the high performance of the system and that the EFL zinc/air battery is the best system for this application when compared to all other EV battery technologies. EFL is now organizing a consortium to bring the technology to large scale commercial implementation.

2. The Electric Fuel Ltd. vehicle battery

The EFL vehicle battery tested from 1994 to 1998 was based on water-cooled battery blocks each consisting of 22 cells. Each block had a capacity of 6.25 kW h, and weighed approximately 32 kg. These blocks were arranged on trays, which were then mounted in electric vehicles. These batteries have undergone extensive field testing in Europe.

Having proven its zinc/air technology, EFL has worked in recent years on re-engineering the battery for the mass market. This effort has been directed at improving the performance, manufacturability and reliability of the battery, while at the same time reducing the overall manufacturing cost. EFL's latest generation of battery is currently

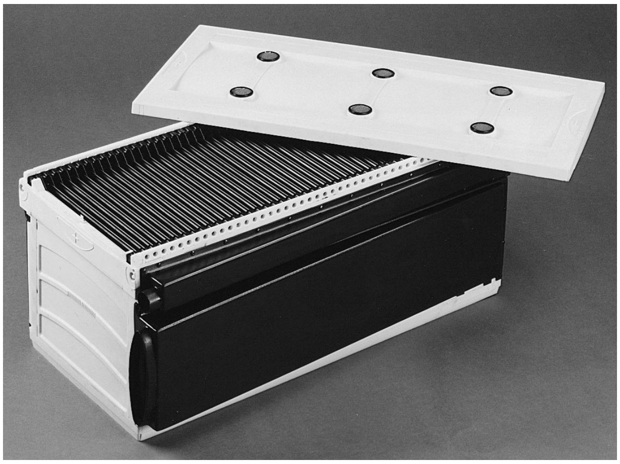

Fig. 4. The battery module, containing 47 cells.

Table 2
EFL vehicle batteries

Characteristic	Units	Test prototypes (1994–1998)	Current status (1998)
Basic unit		block of 22 cells	module of 47 cells
Thermal management		active-water cooled	active-air cooled
Energy capacity	kW h	6.25	17.4
Peak power at 80% DOD	kW	2.9	7.82
Weight	kg	34	87
Size	mm	320 × 330 × 260	310 × 350 × 726
Specific energy	W h kg^{-1}	183	200
Specific power at 80% DOD	W kg^{-1}	85	90

Table 3
Summary of vehicle performance specifications

Parameter	Condition	Performance specification
Top speed	at 0% grade, gross vehicle weight (GVW)	44 mph, with a goal of 50 mph
Performance on a grade of:	seated load weight (SLW), 23 C	
16%		7 mph
2.5%		44 mph
Vehicle acceleration	seated load weight (SLW), 0% grade, 23 C	
0 → 10 mph		5.6 s
0 → 20 mph		10.1 s
0 → 30 mph		19.0 s
0 → 40 mph		34.0 s

undergoing field tests in Israel. It features a simplified air-cooled thermal management system, and is constructed of individual cells which are inserted into a module casing. The basic module consists of 47 cells, weighs less than 87 kg and has a capacity of 17.4 kW h (Fig. 4). (A comparison of the two generations of battery is shown in Table 2.) A 314 kW h version of this battery—the largest capacity traction battery ever installed in an electric vehicle—will be used in the USA all-electric demonstration bus program (Section 3).

3. The clean all-electric hybrid bus

Conventional transit buses in the USA are designed to meet a set of 'White Book' performance specifications that cover vehicle acceleration, gradability and top speed, at Seated Load Weight (SLW) and Gross Vehicle Weight (GVW). The specifications laid down by the New York City Transit Authority for a low- or zero-emission bus are summarized in Table 3. In addition, bus performance is often referenced to standard drive cycles, such as the Central Business District (CBD-14) transient drive cycle, or the New York City Bus cycle. An analysis of the performance of the prototype bus against these specifications and cycles indicates that the bus will require peak traction power of approximately 130 to 140 kW at the wheels [7]. Accounting for drive-train losses and vehicle accessory load of about 20 kW (hotelling, ramps, doors, etc.), the vehicle battery must be capable of supplying approximately 190 kW of power to meet peak demand. The battery must have an energy capacity of 300–400 kW h for a full day's operation.

Clearly, an all-electric, zero emission, 40-ft. transit bus which has a gross vehicle weight of over 18 tons, and which is required to have a daily range of 150–250 km, cannot be realized using conventional, electrically rechargeable, storage batteries. For example, to meet New York City Transit Authority's performance and range requirements in an electric transit bus using today's lead/acid batteries would require approximately 9000 kg of batteries. The curb weight plus the lead/acid battery pack would exceed the gross vehicle weight of the bus, with no passengers on board. At the same time, a conventional

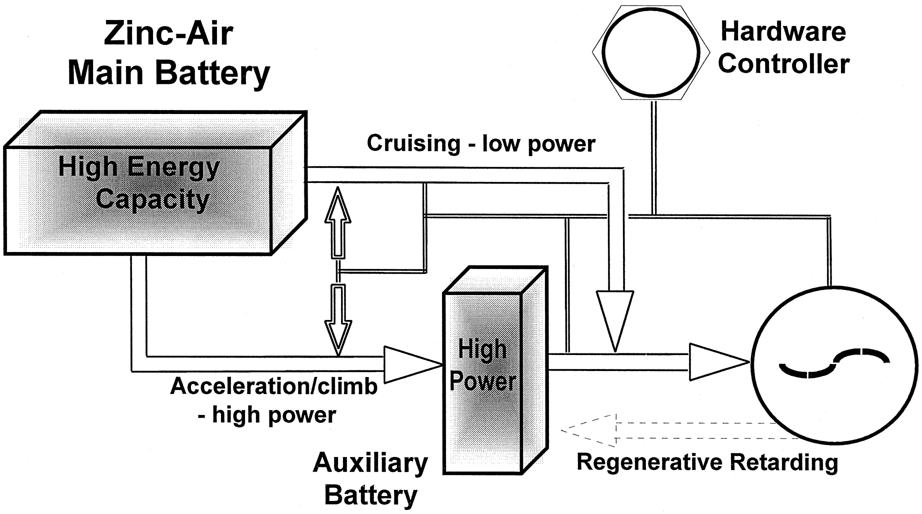

Fig. 5. Schematic diagram of all-electric hybrid electric propulsion system.

Table 4
Preliminary battery configuration of all-electric hybrid bus

	Units	Zinc/air	Nickel/cadmium	All-electric hybrid characteristics
Weight	kg	1566	600	2166
Energy stored	kW h	314	(21)	314
Peak power	kW	(140)	240	240
Specific energy	$W h kg^{-1}$	200	35	145
Specific power	$W kg^{-1}$	90	400	110

electric propulsion system using only the high-energy density zinc/air battery package in the available space under the floor will not fully meet the power and acceleration goals for the New York City Transit Authority transit bus.

An all-electric hybrid propulsion system is being developed by GE and EFL for powering buses (and other heavy-duty trucks and utility vehicles). This propulsion system has the unique ability to drive a transit bus for a full day's uninterrupted service at the same power and performance levels as a conventional diesel powered vehicle. The system is shown schematically in Fig. 5.

This system provides three features that are vital for commercial applications:

(a) increased driving range due to improved system efficiency during acceleration and regenerative braking (capture of energy during vehicle deceleration);

(b) increased power for acceleration, merging into traffic, and hill climbing;

(c) significantly lower vehicle maintenance costs, arising from reduced brake wear and tear.

Moreover, a hybrid propulsion system allows the designers to select and specify propulsion system compo-

Fig. 6. The all-electric battery–battery hybrid demonstration bus.

nents without compromising or trading-off the inherent attractive properties of each system element, something which is usually necessary for arriving at acceptable power/energy ratios in single battery electric vehicles. This is now discussed more specifically.

The main EFL zinc/air battery which is to be employed in the prototype bus is designed with a specific energy of 200 W h kg^{-1}, and an energy density of 221 W h dm^{-3}. The battery is based on six zinc/air battery modules—described earlier—mounted on a tray allowing quick battery exchange from or into the all-electric transit bus. A total of three battery trays of zinc/air batteries (18 modules) comprise the energy storage portion for the transit bus. This battery provides approximately 314 kW h of on-board energy, and weighs less than 1600 kg.

The auxiliary battery, a high power density nickel/cadmium, has been selected for its power and cycling characteristics with minimal reference to its energy density and is needed to provide acceleration and have a power absorption function during vehicle deceleration or regenerative braking.

It should be noted that there are several available configurations (and subsequent operating strategies) for this hybrid system, in much the same manner as diesel–electric hybrids can be classified from series through parallel configurations. For instance, the main zinc/air battery can be used to continuously charge the nickel/cadmium battery, which then performs as the traction battery (permanent source of drive power) in a series arrangement. Alternatively, the nickel/cadmium battery can be used in parallel with the main zinc/air battery, providing 'topping' power whenever high power is demanded. The optimal hybrid configuration will reference system characteristics as well as battery characteristics such as cycle life, charge/discharge rates and charging efficiency.

Shown in Table 4 are the characteristics of the hybrid configuration. The battery–battery hybrid when viewed as one unit will provide the bus with approximately 240 kW of peak power, and 314 kW h of energy, in a total battery package weighing approximately 2166 kg.

A full-sized demonstration transit bus (Fig. 6) employing the battery–battery hybrid propulsion system is being developed in a joint program by EFL, the Center for Sustainable Technology and the GE Center for Research and Development, with funding from the US Department of Transport and the Binational (Israel/USA) Industrial Research and Development Fund. The demonstration bus is scheduled to be on the road by the last quarter of 1999.

In an associated development, The Electric Power Research Institute (EPRI) in the United States has recently presented the preliminary results of an economic study of the EFL zinc/air system. The study is being performed by Bechtel National, a leading engineering and construction company, and Arcadis, a consulting company specializing in transportation and environmental issues. The preliminary results indicate that the costs of operating a fleet of electric buses powered by EFL zinc/air batteries are comparable to the cost of operating a fleet of diesel buses. The operation and maintenance characteristics and the economic feasibility of the EFL system were discussed during

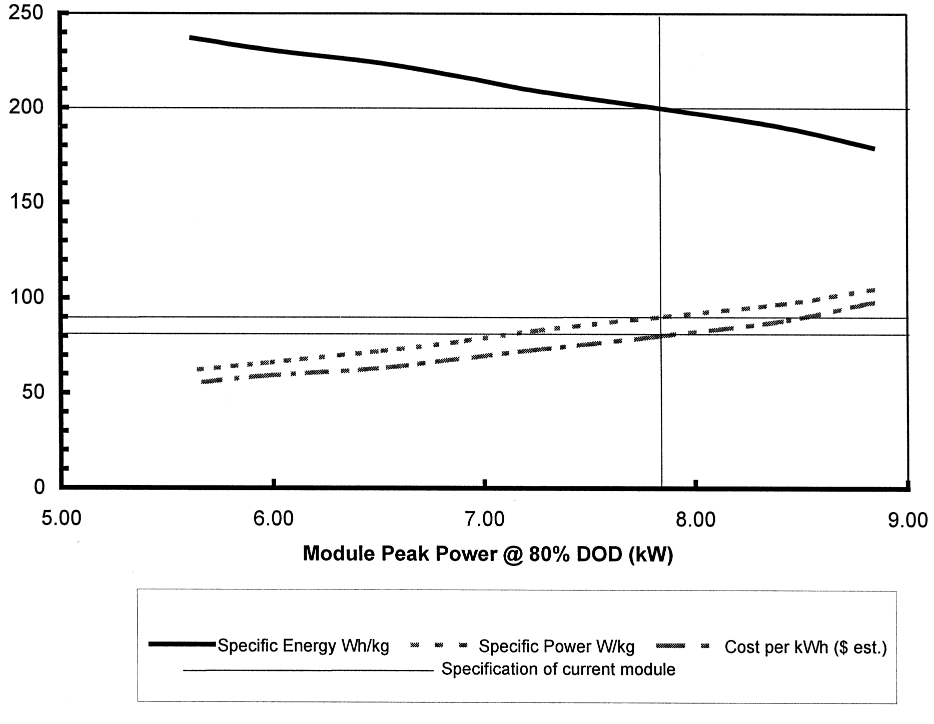

Fig. 7. Effect of power rating on specific energy, power and cost for a zinc/air module of constant dimensions.

a workshop in October hosted by the Los Angeles Department of Water and Power (LADWP) and organized by EPRI.

4. Component optimization of the main zinc / air battery

As mentioned earlier, a hybrid propulsion system allows the designers to select and specify system components without compromising or trading-off the inherent attractive properties of each system element, which is usually necessary in arriving at acceptable power/energy ratios in single battery electric vehicles. This principle is readily demonstrated by observing the characteristics of the main zinc/air battery.

If we designate 'peak power rating' as the determinant of the zinc/air battery design, we can assess the sensitivity of the battery's other performance characteristics to this parameter, as shown in Fig. 7. A module of constant dimensions (725 × 350 × 310 mm) was used as the basis for comparison. By parametrically modelling the discharge characteristics and dimensions of a cell, the peak power capability, energy capacity, weight and cost of a module were estimated for a range of zinc anode thicknesses (which is a principal determinant of peak power capability in the EFL cell). The specification of the current module as employed in the demonstration bus is indicated on Fig. 7. The zinc/air main battery employed in the demonstration bus has a peak power capability of 140 kW at 80% DOD (each of the 18 modules can generate 7.8 kW), with projected cost of approximately US$80/kW h in large-scale production. We anticipate that field tests of the bus will show that the main battery requires a power rating significantly lower than that installed in the demonstration bus in order to maintain effective energy levels in the auxiliary battery. By reducing the specified peak power rating of the main battery to 100 kW, the battery module can be designed with significantly higher energy capacity, while costing 20% to 30% less per kilowatt-hour. It is expected that a production version of the demonstration bus will target a main battery with a specific energy of close to 240 W h kg^{-1}, a specific power of 60 W kg^{-1} and a cost of less than US$60/kW h.

At the same time, high power rate coupled with rapid and frequent cycling will be the focus of the auxiliary battery designer. Indeed, looking at this specification, in the limit we might reasonably expect to see the auxiliary battery replaced by a set of ultracapacitors, which would in theory be ideally suited to this application.

5. An electric scooter

At the other end of the vehicle scale, EFL is in discussions with various groups to develop an electric scooter employing this all-electric hybrid propulsion system concept. The low cost of the zinc/air battery, a refuelling cost comparable to gasoline, coupled with power, range and refuelling characteristics which approximate those of gasoline scooters will enable electric to compete directly with gasoline in powering scooters.

6. Zinc / air battery for cellular telephones

EFL has developed a unique, disposable, primary zinc/air battery operating at about 1.1 V per cell for powering cellular telephones and other portable electronic devices. This prismatic cell system offers high energy per unit weight and volume together with high-rate capability and good shelf life.

Initial trials with cells assembled into standard cellular telephone battery packs have given talk times exceeding 6 h in analog phones and over 15 h with digital handsets. This is typically over three times the performance level of the best rechargeable systems such as lithium ion, and in the case of the digital handset is equivalent to one month of use-time for the handset. Fig. 8 shows a 6 V Motorola battery pack (attached to a Motorola Micro Tac handset) with air holes in the pack wall to allow air access to the zinc/air cells within). Commercially, disposable zinc/air batteries such as button cells for hearing aids are of course readily available, but these are low drain and not applicable for the demanding high current and intermittent duty cycle required for cellular telephones. The EFL battery is specially adapted to perform well under these difficult conditions, and is low cost, lightweight and compact. A large niche market for such a product exists for the business traveller and other heavy users, where the user can benefit from the convenience of the EFL battery pack, such as freedom from the charger and from the charger

Fig. 8. Six-volt battery pack, with holes in the pack wall to allow air access to the zinc/air cell within, attached to a Motorola MicroTac handset.

Table 5
Comparison of current technologies

	Talk time (h)	Specific density (W h kg^{-1})	Cost (US$ per pack)
EFL zinc/air	6.2	185	8
Lithium ion	1.6	45	50
Nickel/metal hydride	1.7	44	40
Nickel/cadmium	1.2	26	20

Data are for the Slim-XT size of battery packs for Motorola MicroTac cellular phones in analog mode (discharge rate: 470 mA).

socket (the battery comes fully charged at the point of sale), and exceptionally long service life.

The main rival systems today to EFL's zinc/air battery for cellular telephones are rechargeable batteries based on lithium ion, nickel/metal hydride and nickel/cadmium technologies. These systems are compared with an EFL primary zinc/air battery in Table 1, where each battery type is contained in a standard slim XT-size pack for powering a Motorola Micro Tac cellular phone in analog mode discharge (constant discharge current of approximately 470 mA). Pack weights range from a low of 85 g for zinc/air to 104 g for lithium ion, 110 g for nickel/metal hydride and to a high of 130 g for nickel/cadmium.

As may be seen from the Table 5, the zinc/air pack gives over three times the talk time of any of the rival systems. At the pack level there is a large margin of improvement by zinc/air (see also energy densities). This is because the other (rechargeable) systems have a poor form factor (poor packing in the available space within the pack), and space is taken up by protective electronics needed to ensure safe operation of the batteries on charge and discharge. Furthermore, in order to achieve a reasonable life cycle on repeated use, these secondary systems are designed to be cycled only at a limited depth of discharge, further restricting capacity. The zinc/air cells are prismatic, enabling good packing of cells and being primary cells, the full capacity may be withdrawn.

Table 5 also indicates relative costs for the various systems. The attractively low cost of zinc/air, coupled with its much longer talk time, as well as convenience of use, offers significant advantages to the consumer over the need-to-be-recharged secondary systems.

Table 6 gives a comparison of projected technologies. The expected dominant rechargeable battery systems which will emerge over the next five years will be lithium ion and lithium polymer and they will gradually replace the nickel/metal hydride and nickel/cadmium systems. The cellular phone networks will undergo a transition from analog to digital (GSM pulse) mode of operation during this period requiring lower overall current drain from the cellular phone battery.

Table 6
Comparison of projected battery technologies, when used with digital handsets such as the Nokia 6000 Series on digital mode discharge

Technology	Talk time (h)	Specific density (W h kg^{-1})	Cost (US$ per pack)
EFL zinc/air	16	> 300	6
Lithium ion	5.5	80	30
Lithium polymer	5.5	80	25

Table 7
Comparison of EFL zinc/air primary with alkaline manganese cells when used with a Motorola MicroTac cellular phone on analog mode

Technology	Talk time (h)	Specific density (W h kg^{-1})	Cost (US$ per pack)
EFL zinc/air (current)	6.2	185	8
EFL zinc/air (projected)	> 10	> 300	6
Alkaline from Energizer	2	80	6

Lithium polymer has the advantage over lithium ion in that it uses an electrolyte based on a solid polymer system rather than a liquid based one, and allows construction of prismatic, flexible cells with a better form factor and increased safety over those based on lithium ion. Lithium polymer cells may be mass produceable at a lower cost than lithium ion but it is not expected that battery packs from these cells will have significantly increased energy densities. EFL zinc/air cells will evolve to give improved performance, mainly due to the transition from metal-based to plastic-based cells with subsequent weight and volume savings. Cost per pack will also be reduced. On the basis of talk time, zinc/air is still expected to achieve over three times the performance of either lithium ion or lithium polymer systems.

Table 7 gives a comparison of performance of current EFL zinc/air cell packs with another primary system that can be considered for this application, namely zinc-alkaline manganese cells. As can be seen from the table, the alkaline pack is somewhat cheaper than the zinc/air pack but again, over three times the talk time is achieved with current zinc/air, and over five times with future zinc/air. Additionally, the zinc/air pack is lightweight, weighing only 85 g and easily conforming to the slim XT dimensions, whereas the alkaline pack is heavy at 190 g and requires insertion into a bulkier XT pack.

Note that the zinc/air pack weighs 85 g and fits into a slim XT pack, whereas the alkaline pack weighs 190 g and requires insertion into the much bulkier standard XT pack.

EFL has already produced prototype batteries for most of the popular brands of mobile telephones, and expects that pilot commercial production of cells for mobile phone batteries will begin in the third quarter of 1999.

References

[1] J.R. Goldstein, B. Koretz, IEEE Aerospace and Electronic Systems Magazine 8 (11) (1993) 34.

[2] Y. Harats, B. Koretz, J.R. Goldstein, M. Korall, Proc. of Batterien und Batteriemanagement Conference, Essen, Germany, 1995.
[3] B. Koretz, Y. Harats, J.R. Goldstein, Proc. 12th Seminar on Primary and Secondary Battery Technology and Application, Deerfield Beach, FL, 1995.
[4] J.R. Goldstein, B. Koretz, Proc. 14th International Seminar on Primary and Secondary Batteries, Fort Lauderdale, FL, 1997.
[5] J.R. Goldstein, I. Gektin, B. Koretz, Proc. 1995 Annual Meeting of the Applied Electrochemistry Division of the German Chemical Society, Duisburg, Germany, 1995.
[6] J.R. Goldstein, N. Lapidot, M. Aguf, I. Getkin, M. Givon, Proc. Joint International Meeting of the Electrochemical Society, Paris, 1997.
[7] R.D. King, J. Schwartz, M. Cardinal, L. Salasoo, X. Garrigan, Proc. EVS-15, Brussels, 1998.