New Developments in the Electric Fuel Zinc-Air System

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Abstract

Electric Fuel is engaged in the design, development and commercialization of its proprietary zinc-air battery technology for electric vehicles, consumer electronic products and defense 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.

1. Electric Vehicles

Electric Fuel 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 refueling. Electric Fuel 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 Wh kg^{-1} and specific peak power of 90 W kg^{-1} at 80% DOD;

b. refueling stations for mechanical exchange of batteries and zinc anodes; and,

c. zinc anode regeneration facilities for centralized recycling of the zinc anodes.

The system elements are shown schematically in Fig. 1.

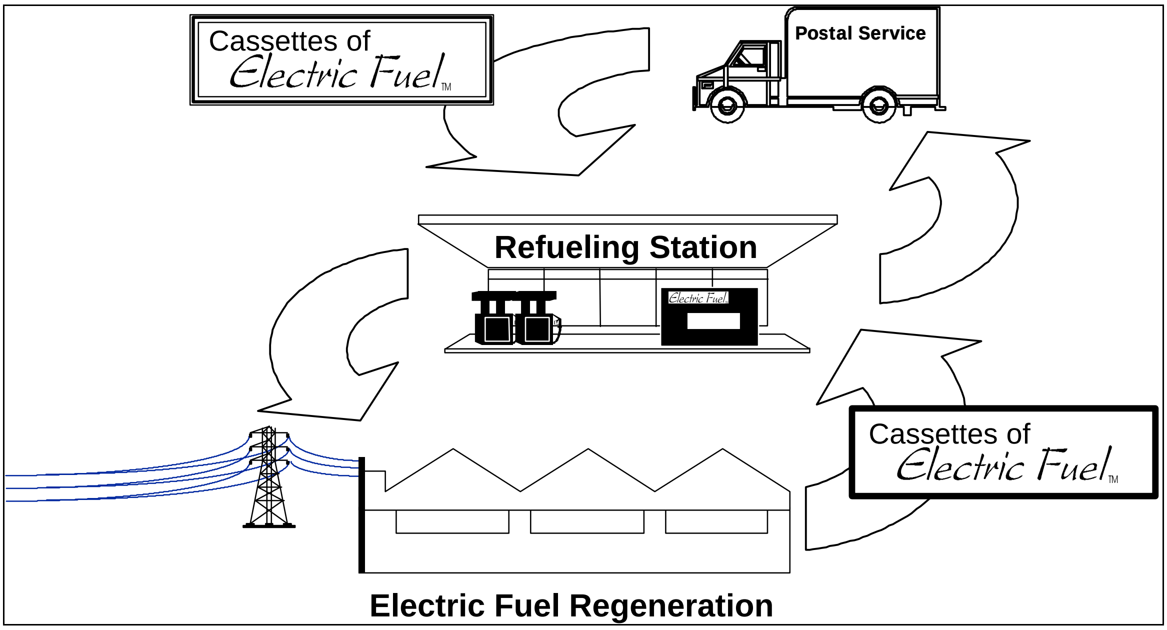

Fig. 1: Schematic of Electric Fuel System Operation

This system has been the subject of various papers [1-4].

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.

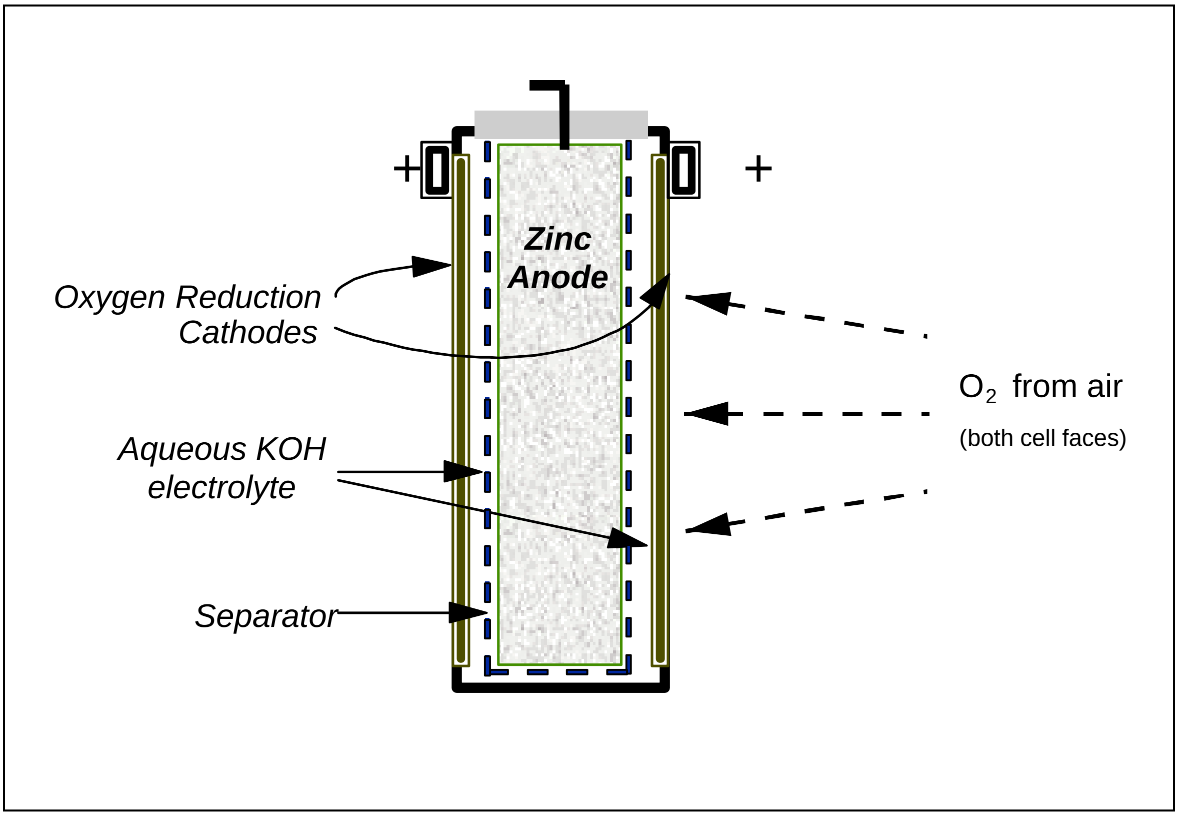

Fig. 2: Schematic diagram of Electric Fuel Zinc-Air Cell

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:

$$2\ Zn + O_2 = 2\ ZnO\ (E_o = 1.65\ V)$$

where E_o is the standard potential for the reaction. Theoretical specific energy according to the overall reaction equation is 1,350 Wh kg^{-1}. Practical specific energy of around 200 Wh kg^{-1} in various full size EV batteries has allowed vehicle ranges per refueling in excess of 300 km to be demonstrated regularly in normal driving. Nominal discharge voltage at the five hour rate is about 1.15 V per cell.

The on-board battery is "refueled" 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 refueling machine that allows a zinc-air battery powered vehicle to "refuel" in an amount of time comparable to gasoline refueling. The depleted cassettes are electrochemically recharged and mechanically recycled external to the battery. With commercial implementation, regeneration of the cassettes will take place at centralized facilities serving regional networks of refueling 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 fueled vehicles.

The regeneration process is shown schematically in Fig. 3, and has been discussed in several papers [5,6].

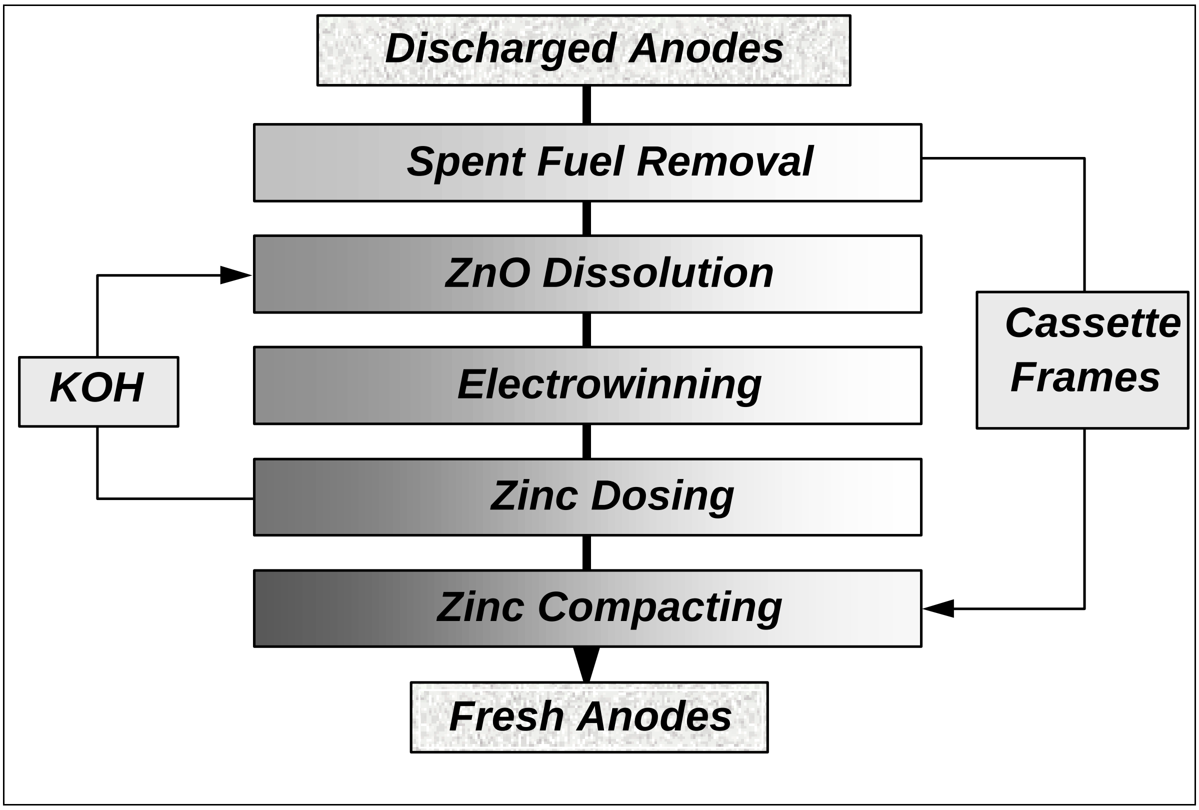

Fig. 3: Schematic of Regeneration Process

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 set-up 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, the zinc corrosion rate should be minimal in order to achieve low battery self discharge rates, 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.

Table 1: Optimized Electrowinning Conditions

Anodes	Nickel louvres
Cathodes	Magnesium plates
Current Density / mA cm^{-2}	100 200
Temperature / ^{o}C	40 70
Electrolyte Concentration / M KOH	7 8
Zincate Concentration / g (zinc) L^{-1}	30 40

The electrolyte feedstock is compatible with the alkaline electrolyte composition in the discharge cell and has 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 direct chemical solubility in KOH of zinc oxide, which is the major battery discharge product in the spent cassettes. This 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 our 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 Electric Fuel system compared with other advanced batteries [3].

To date, Electric Fuel has constructed demonstration regeneration plants in Bet Shemesh, near Jerusalem, and at Trofarello in Italy, each capable of regenerating 10 kg zinc per hour. 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 SpA. Edison is a long-standing strategic partner of Electric Fuel 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 per hour, was completed in early 1996. This plant supplied zinc to support the fleet of Deutsche Post EV's 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 Electric Fuel batteries. These vehicles were driven by regular Deutsche Post drivers on city and suburban routes on a daily basis. Typical ranges between zinc refueling were 300 to 350 km. Deutsche Post confirmed the high performance of the system and that the Electric Fuel zinc-air battery is the best system for this application when compared to all other EV battery technologies. Electric Fuel is now organizing a consortium to bring the technology to large scale commercial implementation.

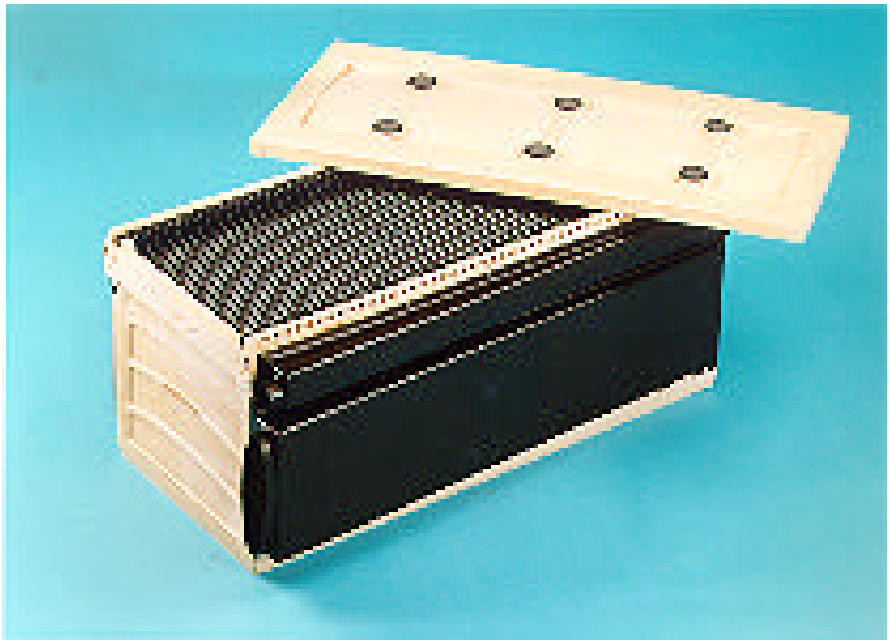

Fig. 4: Electric Fuel Zinc-Air 47-Cell Battery Module

The Electric Fuel 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 kWh, 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, Electric Fuel 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. Electric Fuel's latest generation of battery is currently 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 kWh. (A comparison of the two generations of battery is shown in Table 2.) A 314 kWh 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 (discussed below).

Table 2: Electric Fuel Vehicle Batteries

Characteristic	Test Prototypes 1994-1998	Current Generation
Basic Unit	Block of 22 cells	Module of 47 cells
Thermal Management	Active Water Cooled	Active Air Cooled
Energy Capacity kWh	6.25	17.4
Peak Power @ 80% DoD kW	2.9	7.82
Weight kg	34	87
Size mm	320 x 330 x260	310 x 350 x 726
Specific Energy Wh kg^{-1}	183	200
Specific Power @80% DOD W kg^{-1}	85	90

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, gradeability 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 a full day energy capacity of 300-400 kWh.

Table 3: Summary of Vehicle Performance Specifications

Parameter	**Condition**	**Performance Specification**
Top Speed	@ 0% Grade, Gross Vehicle Weight (GVW)	44 mph 50 mph (goal)
Performance on Grade: *16% Grade* *2.5% Grade*	Seated Load Weight (SLW) , 23 C	 7 mph 44 mph
Vehicle Acceleration *0 -> 10 mph* *0 -> 20 mph* *0 -> 30 mph* *0 ->40 mph*	Seated Load Weight (SLW), 0% Grade, 23 C	 5.6 sec 10.1 sec 19.0 sec 34.0 sec

Clearly, an all-electric zero emissions 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 9,000 kg of batteries. The curb weight plus the lead-acid battery pack would exceed the gross vehicle weight of the bus, with zero passengers on board. At the same time, a conventional 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 being is developed by GE and Electric Fuel 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.

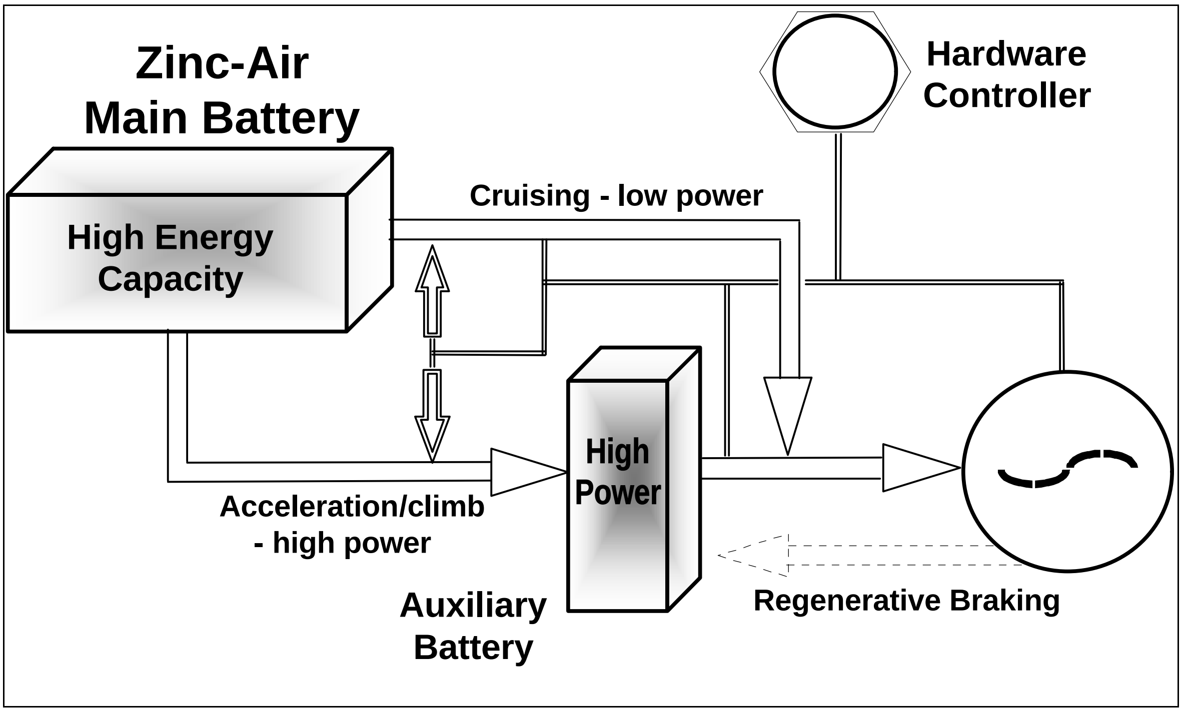

Fig. 5: Schematic of All-Electric Hybrid Electric Propulsion System

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

- Increased driving range due to improved system efficiency during acceleration and regenerative retarding (capture of energy during vehicle deceleration).
- Increased power for acceleration, merging into traffic, and hill climbing.
- Significantly lower vehicle maintenance cost from reduced brake wear and tear.

Moreover, a hybrid propulsion system allows the designers to select and specify propulsion system components without compromising or trading-off the inherent attractive properties of each system element, which is usually necessary for arriving at acceptable power/energy ratios in single battery electric vehicles. This will be discussed more specifically below.

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

The auxiliary power battery has been selected for its power and cycling characteristics with minimal reference to its energy density. The high power density Ni-Cd batteries provide acceleration and a power absorption function during vehicle deceleration or regenerative retarding.

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 Ni-Cd battery, which then performs as the traction battery (permanent source of drive power) in a series arrangement. Alternatively, the Ni-Cd 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 and 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 kWh of energy capacity, in a total battery package weighing approximately 2166 kg.

Table 4: Preliminary Battery Configuration of All-Electric Hybrid Bus

	Zinc-Air	Ni-Cd	All-Electric Hybrid
Weight / kg	1566	600	2166
Energy Capacity / kWh	314	(21)	314
Peak Power / kW	(140)	240	240
Specific Energy / Wh kg^{-1}	200	35	145
Specific Power / W kg^{-1}	90	400	110

A demonstration full-size transit bus (Fig. 6) employing the battery-battery hybrid propulsion system is being developed in a joint program by Electric Fuel, 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.

Fig. 3: A Nova Transit bus, similar to the one used in the battery/battery hybrid demonstration

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 Electric Fuel 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 Electric Fuel 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 Electric Fuel system were discussed during a workshop in October hosted by the Los Angeles Department of Water and Power (LADWP) and organized by EPRI.

At the other end of the vehicle scale, Electric Fuel is in discusions 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 refueling cost comparable to gasoline, coupled with power, range and refueling characteristics which approximate those of gasoline scooters will enable electric to compete directly with gasoline in powering scooters.

Component Optimization: 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 mm x 350 mm x 310 mm) was used as the basis for comparison. By parametrically modeling 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 Electric Fuel 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 $80 US per kilowatt-hour 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 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 Wh kg^{-1}, a specific power of 60 W kg^{-1} and a cost of less than $60 per kilowatt-hour.

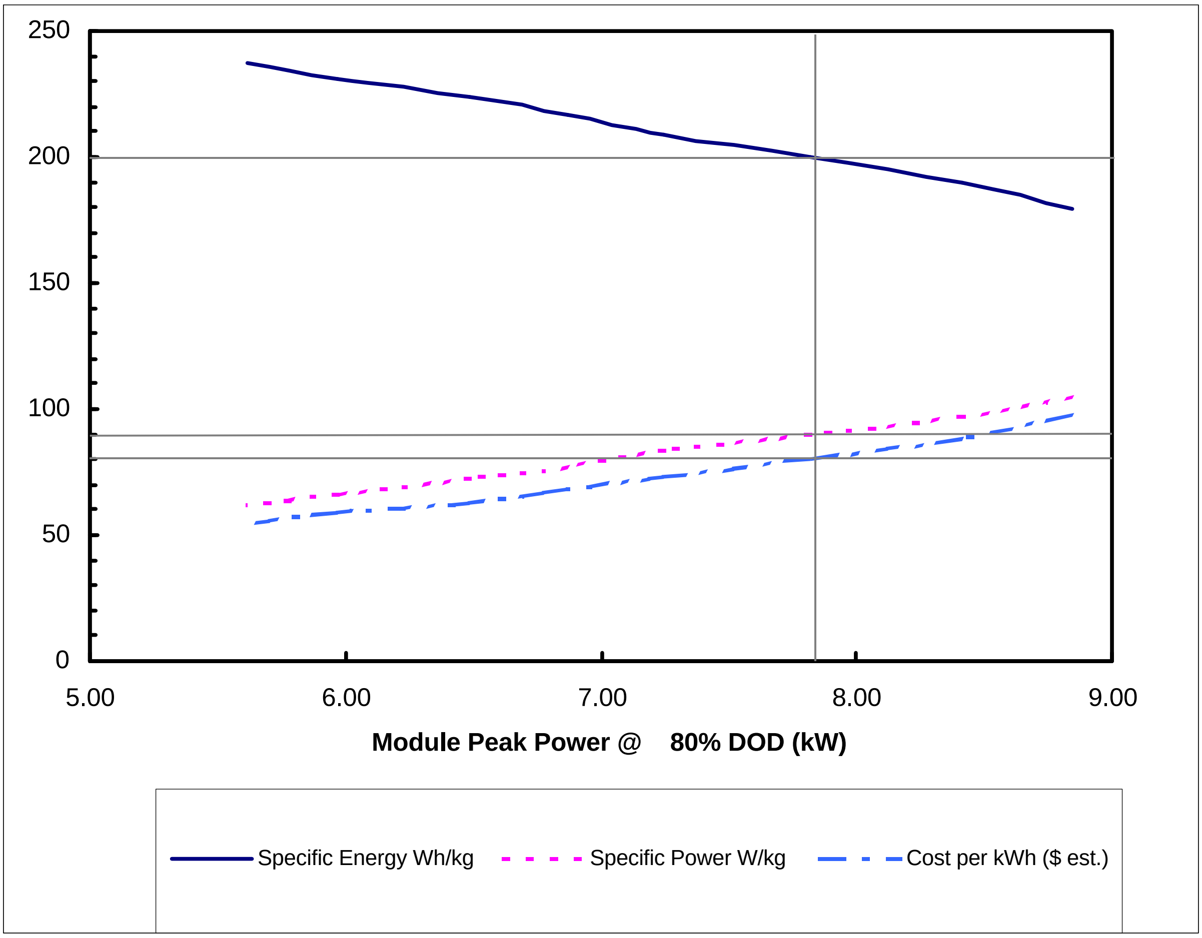

Fig. 7: Effect of Power Rating on Specific Energy, Specific Power and Specific Cost in Zinc-Air Module of Constant Dimensions

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 an ultracapacitor set, which would in theory be ideally suited to this application.

2. Electric Fuel Zinc-Air Battery for Cellular Telephones

Electric Fuel has developed a unique disposable primary zinc-air battery operating at about 1.1V 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 characteristics. Initial trials with cells assembled into standard cellular telephone battery packs have given talk times exceeding 6 hours in analog phones and over 15 hours 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 with air holes in the pack wall to allow air access to the zinc-air cells within.

Fig. 8: 6 V Motorola battery 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 Electric Fuel 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 traveler and other heavy users, where the user can benefit from the convenience of the Electric Fuel battery pack, such as freedom from the charger and from the charger socket (the battery comes fully charged at the point of sale), and exceptionally long service life.

The main rival systems today to Electric Fuel'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 Electric Fuel primary zinc-air battery in Table 1, where each battery type is contained in a standard slim XT size pack for powering a Motorola MicroTac 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 to104 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: Comparison of Current Technologies

	Talk Time Hours	Energy Density Wh kg^{-1}	Cost $US per Pack
Electric Fuel 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

Figures for Slim XT Size battery packs for Motorola MicroTac cellular phones on analog mode discharge at 470 mA

Table 5 also indicates relative costs of the various systems. The attractive low cost of zinc-air, coupled with its much longer talk time, as well as convenience of use, is considered to offer 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 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 time period requiring overall lower current drains from the cellular phone battery. Lithium-polymer has the advantage over lithium-ion in that it uses a solid polymer based electrolyte 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. Electric Fuel zinc-air cells will evolve to give improved performance, mainly due to the transition from metal cased to plastic cased 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 6: Comparison of Projected Technologies

	Talk Time Hours	Energy Density Wh kg^{-1}	Cost $US per Pack
EFL Zinc-Air	16	>300	6
Lithium-Ion	5.5	80	30
Lithium-Polymer	5.5	80	25

Figures for projected battery packs for digital handsets such as the Nokia 6000 Series on digital mode discharge.

Table 7 gives a comparison of performance of current Electric Fuel zinc-air cell packs with another primary system that can be considered for this application, namely zinc-alkaline manganese dioxide 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.

The company has already produced prototype batteries for most popular brand mobile telephones, and expects that pilot commercial production of cells for mobile phone batteries to begin in the third quarter of 1999.

Table 7: Comparison of Electric Fuel Zinc-Air Primary with Alkaline

	Talk Time Hours	Energy Density Wh kg^{-1}	Cost $US per Pack
Electric Fuel Zinc-Air(Projected)	>10	>300	6
Electric Fuel Zinc-Air (Current)	6.2	185	8
Energizer Alkaline	2	80	6

(Figures for Motorola MicroTac Cellular Phone on Analog Mode. Note the zinc-air pack weighs 85 gm and fits in to a slim XT pack, whereas, the alkaline pack weighs 190 grams and requires insertion into the much bulkier XT pack).

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