Reprint of

The Electric Fuel™ System Solution for an Electric Vehicle

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Electric Fuel™

The Electric Fuel™ System Solution for an Electric Vehicle

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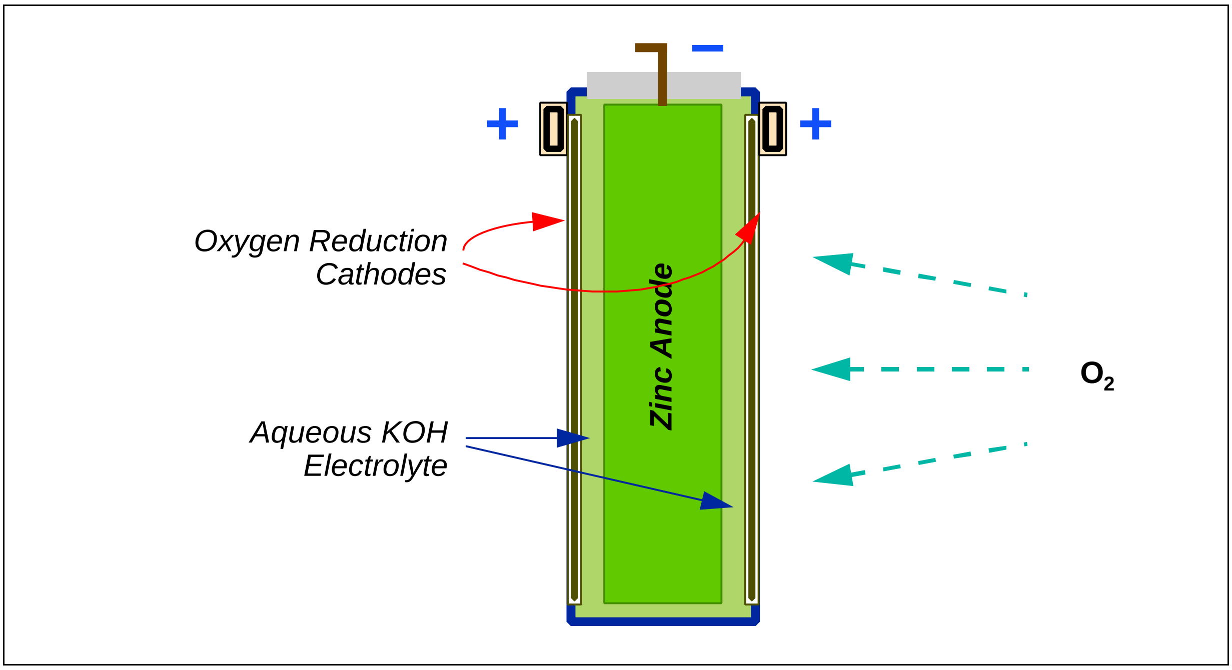
1. Technology Overview

The Electric Fuel Limited (EFL) zinc-air battery system for electric vehicles comprises three linked system elements:

1. the on-board discharge-only zinc-air battery pack, which today is characterized by specific energy of more than 200 Wh/kg and specific peak power of 100 W/kg at 80% DOD (the specific peak power is projected to rise to more than 150 W/kg by 1998);
2. refueling stations for fast and convenient mechanical exchange of “Electric Fuel” cassettes, to get vehicles back on the road after a stop of only a few minutes; and
3. regeneration centers for centralized recycling of the cassettes, making the most efficient and environmentally sound use of electricity to recharge the active zinc material.

The battery is built from 20-kWh modules of 66 cells connected in series, and the modules can be arranged in any combination of series and parallel connections, and in any practical quantity, according to the requirements of the vehicle, motor and controller. Each cell comprises a central static anode bed 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 in a separator envelope, flanked on two sides by the company’s high-power air (oxygen reduction) cathodes. Cell capacity to 80% zinc utilization is 246 ampere-hours in this design. The battery contains subsystems for air provision and heat management. A schematic diagram of the cell is shown in Figure 1.

Figure 1. Schematic diagram of EFL zinc-air cell



During 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 set of equations describing the complete reaction is shown here:

At the anode: $Zn + 4\,OH^- = Zn\,(OH)_4^{2-} + 2e$ ($E_o = -1.25$ V)

$Zn\,(OH)_4^{2-} = ZnO + 2\,OH^- + H_2O$

At the cathode: $O_2 + 2H_2O + 4e = 4\,OH^-$ ($E_o = +0.40$ V)

Overall reaction: $2Zn + O_2 = 2ZnO$ ($E_o = 1.65$ V)

E_o is the standard potential for the reaction. Theoretical specific energy, according to the overall reaction equation, is 1,350 Wh/kg. Demonstrated practical specific energy in a full-sized electric vehicle battery is more than 200 Wh/kg with this design. Nominal voltage at C/5 discharge rate is about 1.16 V.

Projected unit price of the electric vehicle battery in volume production is DM 120 per battery-kWh.

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 powered vehicle to ‘refuel’ in an amount of time comparable to gasoline refueling. It currently takes one minute, 40 seconds to refuel a 20-kWh battery module.

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 gasoline system, without the negative environmental impacts of refineries.

The recharging/recycling process includes the following steps:

a. Disassembly, in which the discharged anode cassettes are mechanically taken apart and the zinc oxide discharge product (along with residual, undischarged zinc) is removed

b. Dissolution, in which zinc oxide is dissolved in a KOH solution to form a zincate-rich feed, according to the following equation:

$$ZnO + 2KOH + H_2O = K_2Zn(OH)_4$$

c. Electrowinning, in which the zincate solution is electrolyzed in an electrowinning bath according to the following equation:

$$K_2Zn(OH)_4 = Zn + 2KOH + H_2O + \tfrac{1}{2}O_2$$

d. Reassembly, in which the electrowon zinc (together with residual charged zinc that was not discharged) is compacted onto the current collector frame and inserted into its separator.

2. Cell Performance

As discussed in Section 1, the EFL zinc-air battery is comprised of cells connected in series within modules, and modules can be connected in parallel or in series.

Figure 2 shows voltage vs. current (V-I) curves for a typical single zinc-air cell discharged at a constant-current C/4 discharge rate. The constant-current discharge was interrupted 10 times for high-current polarizations, and a separate V-I curve was plotted for each set of polarizations. Open-circuit voltage (OCV) is also shown, as are curves showing the separately calculated contribution to cell voltage drop of the air electrode (primarily from oxygen evolution polarization) and from ohmic resistance in the electrolyte.

Figure 2. Single-cell voltage vs. current. Each line represents a set of high-current polarizations at the discharged capacity indicated. Also shown are open circuit voltage (OCV), and the relative contributions to voltage drop at the air electrode (AE) and from the electrolyte.

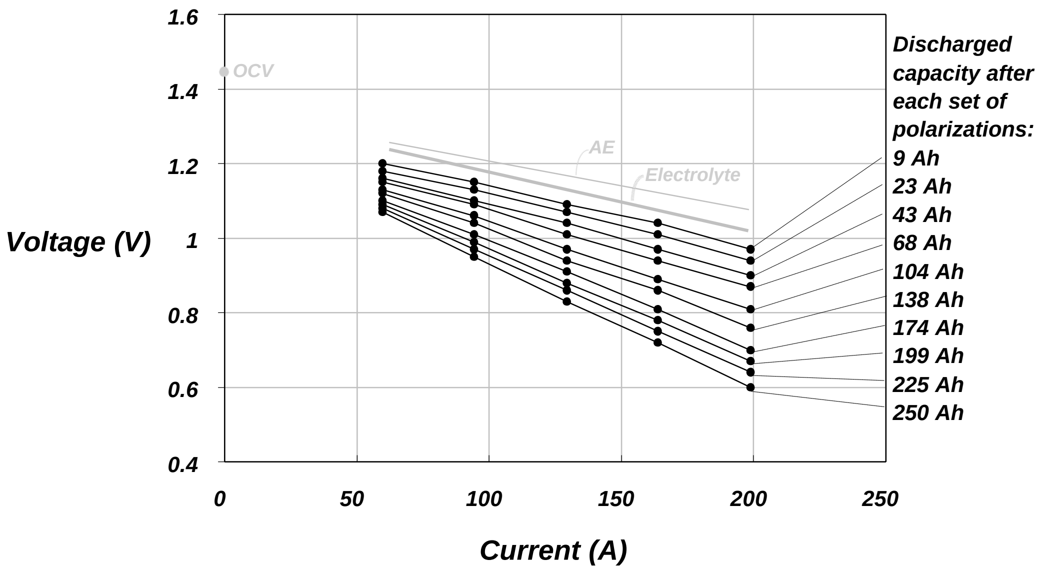
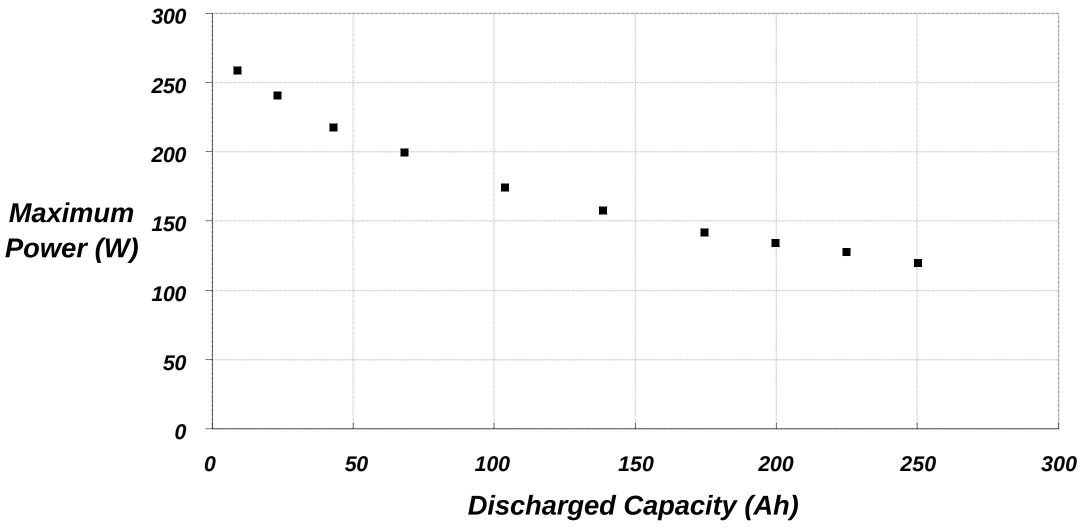


Figure 3 shows the maximum cell power as a function of discharged capacity, derived from the voltage-current measurements from each of the series of polarizations shown in Figure 2.

Figure 3. Single-cell maximum power as a function of discharged capacity. (Derived from voltage-current measurements shown in Figure 2)



The results shown in Figure 3 are typical for the cell design currently in production at EFL. Cells of various designs under development at EFL's laboratories are achieving maximum power of over 200 W at 80% DOD, with lower weight, meaning that battery specific peak power will be in range of 150-200 W/kg within the next three years.

3. Battery Performance

Figure 4 is a V-I curve for a four-module (264-cell) battery at 80% DOD. This 80-kWh version of the EFL zinc-air battery is suitable for a range of passenger cars and small commercial vehicles.

Figure 4. 264-cell battery voltage vs. current

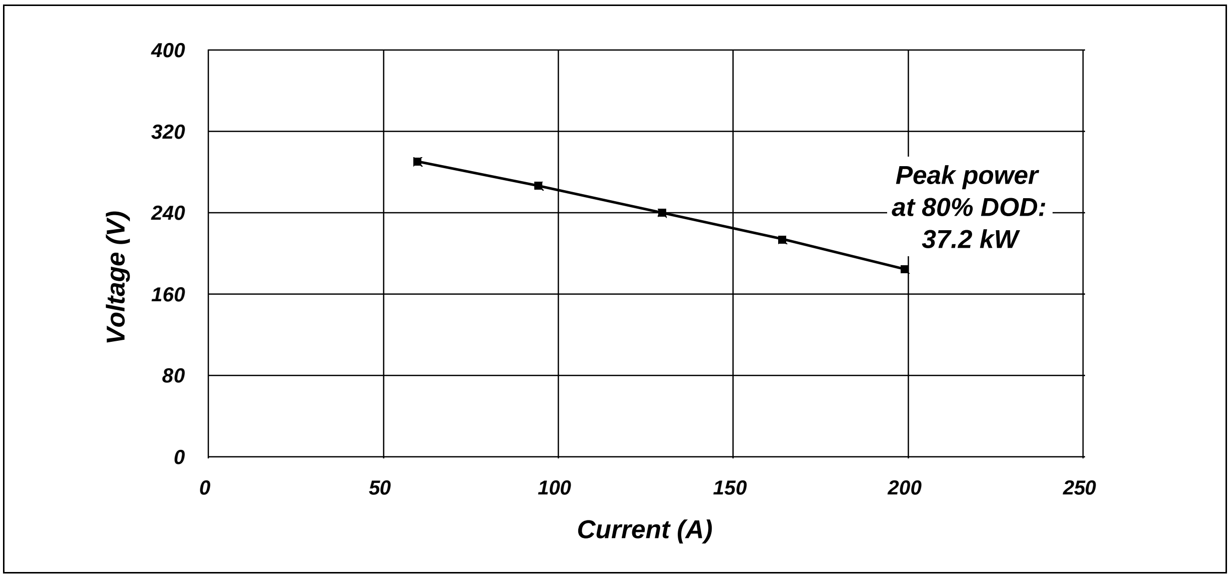


Table 1 summarizes key performance parameters for the module, and for the 8-module, 528-cell battery that was installed and tested in a Mercedes 180E van. This battery was used to drive the van 689 kilometers at a constant speed of 64 km/h in a certified test on a dynamometer in Southern California in November 1994.

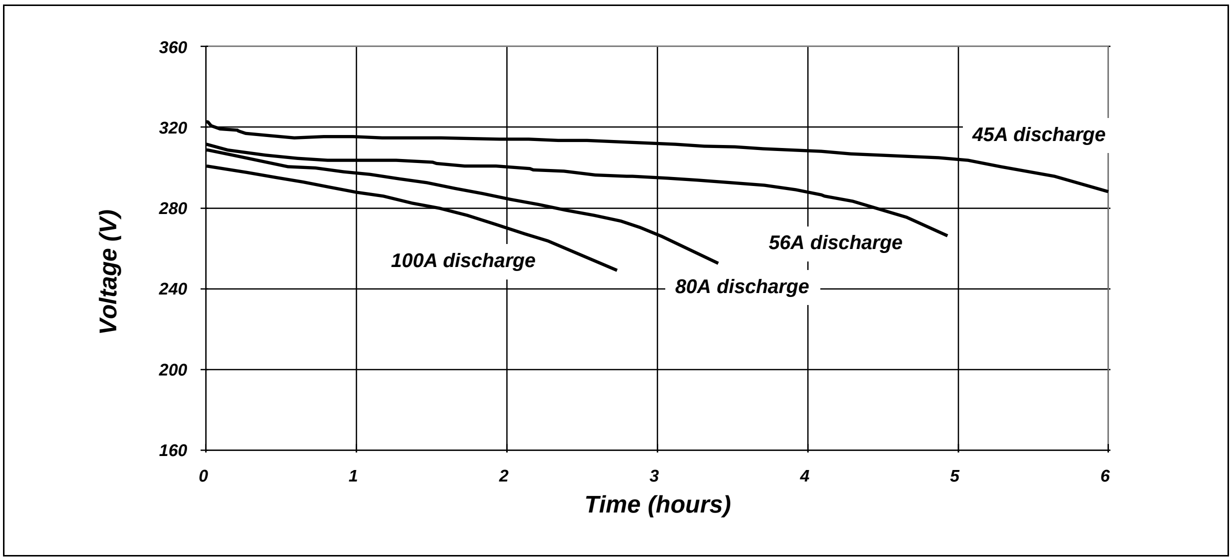
Capacity and energy figures are shown for '100% depth of discharge (DOD),' which is defined as 80% utilization of anodic zinc. Also shown in the additional usable capacity that is available after this point, although with less power. This additional energy would typically be used as reserve to ensure that a vehicle does not run out of 'fuel'.

Table 1. Battery Performance

	Battery module	**Van battery**
Number of cells	66	528 (8 modules)
Number of parallel strings	-	2
Rated Capacity at C/5, **Ah**		
to 100% DOD	246	492
additional usable	25	50
Total delivered capacity	271	542
Voltage, **V**		
OCV	94	375
Nominal, C/5	77	306
at peak power, 80% DOD	46	185
Energy at C/5, **kWh**		
to 100% DOD	18.8	150
additional usable	1.6	13
Total delivered energy	20.4	163
Power, **kW**		
constant power, C/5	3.8	30
peak power, 80% DOD	9.3	74
Weight, **kg**	89	758
Volume, **liters**	76	648
Specific Energy, total, **Wh/kg**	230	215
Energy Density, total, **Wh/liter**	269	252
Specific Power, **W/kg**		
specific constant power, C/5	42	40
specific peak power, 80% DOD	105	98
Power Density, **W/liter**		
constant power density, C/5	49	46
peak power density, 80% DOD	122	115
Range in Mercedes 180E van at 64 km/h, 77% drivetrain efficiency, **km**	-	689

Figure 5 (on the next page) shows voltage vs. time curves for discharge of the 264-cell battery at various current levels. Because of the extremely high energy density of the EFL zinc-air battery, discharge rates of under C/3 are simply not applicable to real driving situations, and we would more typically expect to see discharges in the range of C/4 to C/7.

Figure 5. **264-cell battery voltage vs. time for constant-current discharges at various discharge rates according to current levels**



A close look at the discharge results shown in Figure 5 will reveal that the capacity of the EFL zinc-air battery remains virtually constant at all discharge rates, unlike other battery technologies such as lead-acid which can experience severe drops in capacity as a result of higher discharge rates. The same advantage holds true for discharges at low temperatures: The capacity of the zinc-air battery has been shown not to be affected by cold conditions in tests to -20°C.

4. Bibliography

The following previous publications contain additional details concerning the EFL zinc-air battery system technology and performance:

B Koretz, J R Goldstein, Y Harats, M Y Korall, "A High-Power, Mechanically Rechargeable Zinc-Air Battery System for Electric Vehicles," Proceedings of the 25th International Symposium on Automotive Technology and Automation, Florence, Italy; June, 1992.

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forthcoming:

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