CONF-951160--1

UCRL-JC-121727
PREPRINT

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This paper was prepared for submittal to the
Sustainable Transportation'95
Northeast Sustainable Energy Association
Rhode Island, Conn.
November 13-15, 1995

October 3, 1995

Lawrence Livermore National Laboratory

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Abstract

In response to the 1990 Clean Air Act, the California Air Resources Board (CARB) developed a compliance plan known as the Low Emission Vehicle Program. An integral part of that program was a sales mandate to the top seven automobile manufacturers requiring the percentage of Zero Emission Vehicles (ZEVs) sold in California to be 2% in 1998, 5% in 2001 and 10% by 2003. Currently available ZEV technology will probably not meet customer demand for range and moderate cost.

A potential option to meet the CARB mandate is to use two Lawrence Livermore National Laboratory (LLNL) technologies, namely, zinc-air refuelable batteries (ZARBs) and electromechanical batteries (EMBs, i.e., flywheels) to develop a ZEV with a 384 kilometer (240 mile) urban range. This vehicle uses a 40 kW, 70 kWh ZARB for energy storage combined with a 102 kW, 0.5 kWh EMB for power peaking. These technologies are sufficiently near-term and cost-effective to plausibly be in production by the 1999-2001 time frame for stationary and initial vehicular applications.

Unlike many other ZEVs currently being developed by industry, our proposed ZEV has range, acceleration, and size consistent with larger conventional passenger vehicles available today. Our life-cycle cost projections for this technology are lower than for Pb-acid battery ZEVs. We have used our Hybrid Vehicle Evaluation Code (HVEC) to simulate the performance of the vehicle and to size the various components. The use of conservative subsystem performance parameters and the resulting vehicle performance are discussed in detail.

Overview of Concept

The concept of the powertrain of this all-electric vehicle is to use a 40 kW Zinc-air refuelable battery for average power demands in combination with a 102 EMB which provides peak power for acceleration and recaptures braking energy. The power required of the ZARB is set by the steady-state hill climb performance demanded. The power produced by the ZARB is limited by the area of the air electrode which is the ZARB dominant cost component. Using the 0.5 kW-hr EMB to provide peak power and the 70 kW-hr energy storage of the ZARB to provide the range, minimizes the cost of the powertrain.

We have determined the power and energy necessary for each of the two batteries by applying our vehicle simulation code known as the Hybrid Vehicle Evaluation Code (HVEC, Ref. 1). This code uses engineering models of the major components of the powertrain (ZARB, EMB, drive motor and controller) along with selected vehicle parameters (weight, cross sectional area, drag coefficient, rolling coefficient, accessory load, etc.) to determine the energy consumption on a second-by-second basis over selected driving cycles. For the current vehicle we have chosen to use the US EPA Urban Driving Schedule. Vehicle parameters used in the delivery van concept vehicle are: empty weight 1,700 kg, drag coefficient 0.38, cross-sectional area 2.7 m^2, rolling coefficient 0.008, payload 500 kg and an accessory load of 1,000 watts.

The vehicle code has been validated by comparison to the performance of several high performance electric vehicles. Thus it accurately predicts the unidirectional energy flow between the ZARB and the drive motor, the EMB and accessories and the bidirectional energy flow into and out of the EMB to the drive motor. In this way the energy used per kilometer and hence the range is determined. Since the driving cycle is only about 10 km in length it is repeated until the zinc fuel is consumed. The EMB energy is constrained to be the same at the end of the simulation as the beginning. In addition to the driving cycle demands, the hill climb requirements are predicted by HVEC. Thus with a few iterations the power required for the desired hill climb performance is found. A commercially available AC induction motor with 102 kW peak power was selected to give resonable acceleration. The predicted performance of the concept vehicle is a range of 240 miles (384 km) over the EPA urban driving cycle; acceleration of 0-60 mph in 12 seconds; short-term hill climb (2.5 km at full load) grade of 5.3% at 60 mph; continuous grade of 3% at 60 mph; and a top speed of greater than 62 mph.

*This work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Zinc-Air Battery

LLNL has developed a prototype Zinc-air refuelable battery which is refueled by periodic exchange of the spent electrolyte for zinc particles entrained in fresh KOH electrolyte. The battery consumes zinc metal and atmospheric oxygen, and produces reaction product consisting of a dissolved potassium zincate and a liquid suspension of zinc oxides according to the net reactions:

$$\begin{aligned} Zn + 1/2\ O_2\ (air) + KOH &= KZnOOH_{aq} \\ KZnOOH_{aq} &= ZnO + KOH \end{aligned} \qquad (1)$$

In the battery, the 1 mm size zinc fuel particles are stored in hoppers, from which they are gravity fed into individual cells where they are completely consumed during discharge. This battery has an energy density of 140 Wh/kg and a mass density of 1.5 kg/liter. Thus it is 5 times lighter and 3 times smaller than Pb-acid batteries with the same stored energy. A 6 cell engineering prototype ZARB in series with the nearly full complement of Pb-acid batteries was recently demonstrated on a 6 ton electric shuttle bus (Ref. 2). This demonstrated the successful operation under representative road load vibrations and accelerations of the key invention of the ZARB – the self feeding cell. Zinc pellets fall continuously from the overlying hopper into a narrow (<3 mm) opening at the top of each cell as shown in Fig 1. Because the cell gap is only a few times larger than the particles, the particles do not close pack - even under strong vibrations. Rather, particle bridging causes voids to develop which establishes a particle packing density of about 40%. Electrolyte is slowly pumped upward through the cell and the hopper to remove heat and reaction products. The expanded bed of particles offers little resistance to electrolyte flow. The wedge-shaped cell allows dissolving zinc particles to fall into the increasingly narrow gap thus maintaining the gap/particle size ratio (<5) needed for bridging. Air is pumped into the side of the cell where it diffuses through the air electrode to participate in the power producing reaction. Parasitic losses from electrolyte and air pumping, and shunt currents are about 1% of gross power (Ref. 3).

Refueling is accomplished by draining the spent electrolyte and flowing the fresh electrolyte fast enough to drive the zinc particles along the bottom of the horizontal fill tubes which connect the hoppers at the top of each cell. Figure 2 shows the cell from the air electrode side with the horizontal fill tubes above the hoppers, oriented into the page. The particles fall through slots (6 x 16 mm) into the hoppers from which they feed into to the wedge-shaped cells. Anodes would be shorted through particles in the fill tubes if the air supply was not shut off during filling. Electrolyte flow is continued for a brief time after the filling to clear the fill tubes of excess particles. Based on experimental fill times of multiple cell stacks, we estimate a series parallel cell arrangement can be recharged in less than 10 minutes.

Recovery of metallic zinc from the spent electrolyte is accomplished by a combined electrochemical and mechanical process. Zinc is recovered from spent battery reaction products by deposition onto a non-adhering metal substrate under conditions that produce "mossy zinc." This form of zinc is about 15 to 20% of full density. The mossy zinc is then pressed into 1 mm diameter by 1 mm long cylindrical pellets of 60% density using a pin and die press. Note that there are no toxic materials in the fuel cycle although concentrated KOH is highly corrosive.

One of the most important aspects of the ZARB is the design flexibility it allows. The number of cells and the aggregate area of the air electrodes determines the power while the size of the storage tank (total hopper volume) determines the energy stored. These components are largely independent of each other allowing the battery designer to optimize both power and energy for each particular type of vehicle. The design rule for weight for a battery of desired peak power (P) and nominal energy (E) are given by:

$$W = 2.8\ kg/kW_{peak} * P + 6.5\ kg/kWh * E \qquad (2)$$

The battery volume in liters is given by:

$$V = 3.0\ l/kW * P + 4\ l/kWh * E \qquad (3)$$

Thus our concept vehicle's battery of 40 kW power and 70 kWh storage weighs 567 kg (1,247 lbs) in 400 liters (14.1 cubic ft).

Major ZARB technical issues still to be resolved include stability of the fuel cycle and electrolyte stability over a large number of zinc recovery operations, integrity of the air electrode/frame seal, dynamics of the self-feeding cells, and integration with LLNL's growing expertise in EMBs for vehicle use. We have not encountered fundamental or insurmountable problems with the fuel cycle. Nevertheless, extended cycling needs to be demonstrated in view of the possibility of progressive changes in chemical composition and their affect on morphology of the zinc deposit or discharge efficiency of the battery. The battery depends on maintenance of a fluid reaction product during discharge, even at loadings as high as 300 g-Zn/liter of electrolyte, by forming a pumpable syspension of finely divided zince oxide. The complete fuel cycle is depicted in Fig. 3.

Electromechanical Battery

LLNL is also developing EMBs for both ZEV and hybrid vehicle applications. The EMB contains a high speed rotor integrated with an iron-less generator, housed in a hard sealed vacuum vessel and containment structure. High efficiency power conditioning electronics for converting the three-phase output of the generator to the typical direct current vehicle electrical bus complete the EMB system. The Livermore design makes use of a special arrangement of the permanent magnets known as the "Halbach Array" in the inner annulus of the rotor that yields an extremely uniform dipole magnetic field. A new Nd-Fe-B magnetic material is used to create the rotating magnetic field. This field couples through a re-entrant glass-ceramic sleeve vacuum barrier in the center of the rotor, to three-phase windings that are outside the vacuum barrier. Thus there are no heat producing elements that must be cooled within the vacuum housing. A sectioned view of the EMB is shown in Fig. 4.

The maximum kinetic energy that can be stored in a given geometry flywheel is proportional to the tensile strength of the rotor material and the volume of the rotor. However, the weight of the rotor is proportional to its density. Currently, the best material for this application is a fiber-composite made from graphite fibers in an epoxy matrix. We are using commercially available fibers that have strengths of 7.0 GPa (1,000,000 psi) which is an improvement by a factor of 5 over the last 20 years (Ref. 4).

The adverse torque that results from rotating the axis of rotation of an EMB suggests that the best orientation for a flywheel in a vehicle is with its rotation axis vertical. Thus there is no adverse torque applied for normal turns. The adverse torque is also proportional to the rate at which the rotational axis is rotated. Thus, hills do not create severe adverse torque whereas hitting a paving curb might. This adverse torque is also proportional to the fourth power of the rotor radius and this sets an upper limit on the desirable rotor diameter.

In the laboratory we have demonstrated up to 1 kWh of stored energy along with power output of 100 kW in a prototype EMB that routinely spins at 60,000 rpm. System efficiencies, the ratio of the output energy to the input energy, have been measured in excess of 92%. The total weight of the EMB will depend on the weight of the containment structure which is currently under intense development. A number of intentional rotor burst tests have given new insight into the fragmentation and abrasion forces that must be mitigated from rotor failure. Both passive magnetic and mechanical bearings are being used in Laboratory prototypes. Although passive magnetic bearings will give the best system performance, their development is not yet complete (Ref. 6). The vehicle designer has the option of reducing the total energy storage in the EMB to a minimum that covers the acceleration, regenerative braking and short duration hill climb requirements to minimize losses due to currently available mechanical bearing technology. The 0.5 kWh EMB will conservatively accommodate these requirements. We believe that a near-term 0.5 kWh EMB system will weigh less than 75 kg (165 lbs) and occupy less than 40 liters (1.4 cubic ft).

Conclusions

A new ZEV concept vehicle has been described based on two LLNL technologies: the zinc-air rapidly refuelable battery and the electromechanical secondary battery. Based on detailed vehicle simulation it is projected that this vehicle will have a range of 384 km (240 miles). The development of the single vehicle zinc recovery unit will enable this vehicle to come to the marketplace by using the existing electrical power distribution infrastructure. The ZARB and the EMB are sufficiently attractive and environmentally friendly technologies that their development should be continued. LLNL is actively seeking industrial partnerships to bring these components to the marketplace.

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Figure Captions:

1) Zinc pellets or particles are stored in hoppers above individual cells, and are gravity fed into the cells. Packing and clogging in the bed are prevented by the formation of bridges and voids, allowing electrolyte to circulate freely and with low hydraulic resistance.
4) The zinc-air refuelable battery fuel cycle.
2) The frame component depicted here was used in the bipolar cell stack. This plastic frame includes the hopper, the cell, and internal passages for electrolyte and air flow.
3) Cross sectional view of LLNL's electromechanical battery.

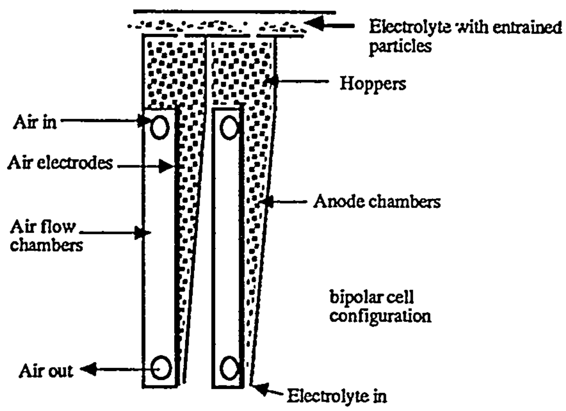

Figure 1

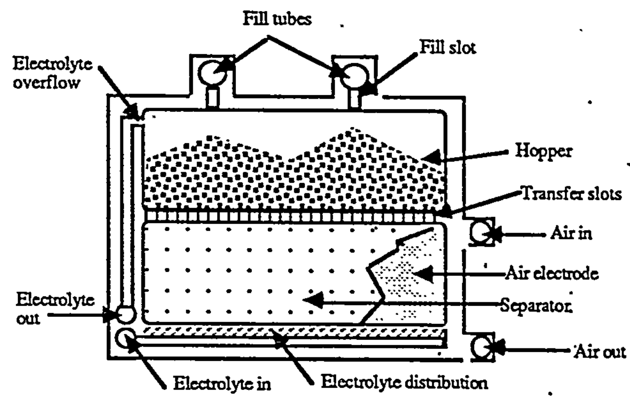

Figure 2

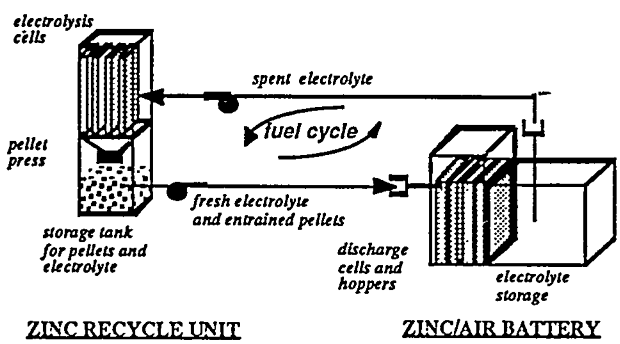

Figure 3

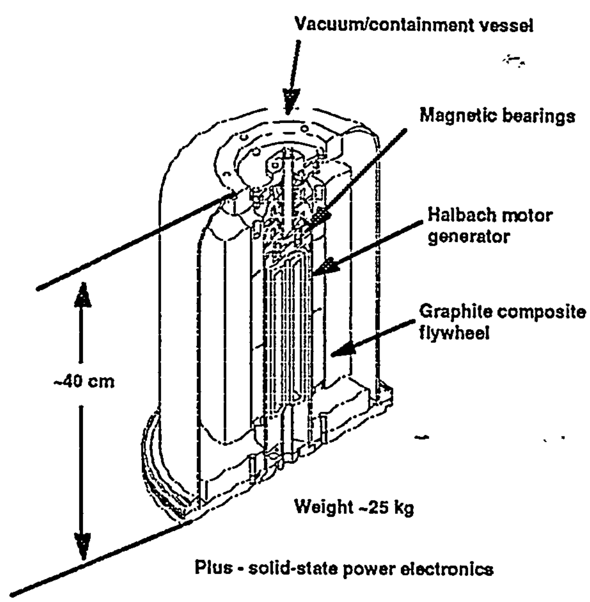

Figure 4

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