CONSTRUCTION AND PERFORMANCE OF A HIGH VOLTAGE ZINC BROMINE BATTERY IN AN ELECTRIC VEHICLE

David H. Swan, Blake Dickinson, Murali Arikara, Manohar Prabhu,
ITS, University of California, Davis

Abstract

This paper describes the design, construction, testing and installation of a 391 volt, 35 kWh zinc bromine battery in an electric vehicle. This research project, was referred to as the "Endura Project" and it resulted in the construction of the highest voltage zinc bromine battery ever to be used in an electric vehicle.

The zinc bromine battery is a high energy density battery that utilizes low cost materials (predominantly polyethylene plastic). It has a relatively high energy density (60 to 70 Wh/kg of battery weight) and is modular in its construction. It utilizes a water cooling loop and normally operates between 32 and 45 °C.

The Endura project constructed a state of the art zinc bromine battery, used an advanced charging system, and an advanced AC propulsion system. These components were integrated in a Geo Prizm and used to compete in the APS Electric 500 in Phoenix, AZ (3rd place, 3/94), the World Clean Air Rally in LA (1st Place, 4/94) and the 1994 American Tour de Sol (2nd Place 5/94).

Introduction

The Endura project encompassed three advanced electric vehicle technologies. A high voltage zinc bromine battery system, an inductive link charging system, and an advanced AC propulsion system. The battery was constructed from 4 fifty-four-cell stacks in series (total of 216 cells) and two polyethylene electrolyte storage tanks. The charging system consisted of two 6.6 kW chargers operated in parallel. Each charger was connected to an inductive port and filter box. The outputs of the chargers were paralleled after the filter boxes and the charger control was linked to the battery control system for end of charge. The propulsion system used a 3 phase inverter and a 50 kW motor/inverter system with an integrated 100 amp DC/DC for the vehicle 12 volt system.

Picture 1 The Endura Team

The 35 kWh zinc bromine battery constructed for this project was named California 1 (CA1) in recognition of this technology's applicability to the 1998 ZEV mandates.

The authors of this paper have been actively researching the use of zinc bromine technology for electric vehicle use since 1989 [1,2,3]. This research has included two 5 kWh modules attaining a specific energy of 56 Wh/kg (3 hour rate) and a peak power of 56 W/kg at 50% DOD, and also three 22.5 kWh batteries attaining a specific energy of approximately 61 Wh/kg at the 3 hour rate. Other independent results for a 5 kWh zinc bromine battery can be found in the references [4].

In March 1994, the CA1 battery was installed into a 1994 Geo Prizm. This car has completed over 3000 km in testing and competition and was able to travel over 280 km on a single charge. The Endura project from conceptualization to competition (including the construction of the CA1 battery) was done in 3 months. During this time the stringent safety requirements to enter the

Phoenix race were met. Considering the 1992 accident at the same race, [5] the CA1 battery design was closely scrutinized. Approval to race required that no higher risk be associated with the CA1 then the other battery technologies [6].

Zinc Bromine Battery Technology

The zinc bromine battery is an ambient-temperature, flowing-electrolyte battery that utilizes zinc bromide as its electrolyte. The electrolyte is aqueous and undergoes the reactions shown in Table 1.

Table 1. Zinc Bromine Battery Reactions

Electrode	Charge	Discharge
Negative	$Zn^{++}(aq) + 2e^- \rightarrow Zn(s)$	$Zn(s) \rightarrow Zn^{++}(aq) + 2e^-$
Positive	$2Br^-(aq) \rightarrow Br_2(aq) + 2e^-$	$Br_2(aq) + 2e^- \rightarrow 2Br^-(aq)$

During charge metallic zinc plates out on a solid surface (reduction) and bromine evolves (oxidation). Discharge is the reverse reaction. The microporous separator allows cations and anions to cross between the two electrolyte streams. Theoretical energy density for the zinc bromine couple is 440 Wh/kg. A schematic of a single cell is shown in Figure 1. Unlike conventional batteries, the electrolyte is stored in containers separate from the electrodes. In principle the battery energy and power density can be adjusted by changing the quantity of electrolyte carried or by increasing the number of cells in the battery.

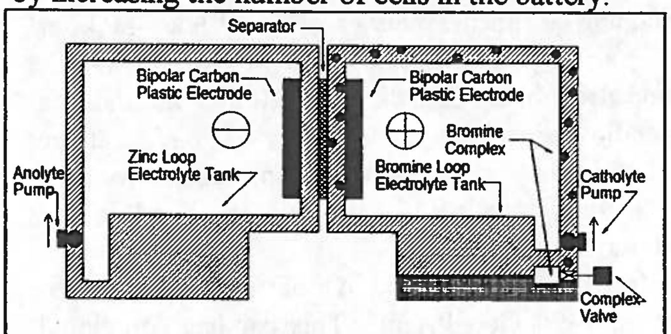


Figure 1. Schematic of the Zinc Bromine System

The California 1, Zinc Bromine Battery

The California 1 battery design consists of two stack towers, two electrolyte tanks, an electrolyte pumping system, a control system, and a cooling system. Each stack tower consists of two individual 54 cell bipolar stacks. The stacks were supplied electrolyte from common anolyte and catholyte tanks and electrically connected in series. Each stack is nominally 100 amp hours at C/3 discharge rate. The cooling system is shared with the propulsion system (single fluid, one radiator). The CA1 battery system is schematically shown in Figure 2. The primary components are described as follows:

1. Electrolyte - The electrolyte is a solution of zinc bromide (molarity greater then 2) with quaternary salt additives. The quaternary salts form a strong association with bromine, reducing its vapor pressure without affecting its electrochemical properties.
2. Electrolyte Holding Tanks - Two tanks are used to hold the electrolyte. The tank that supplies electrolyte to the anode side on discharge is referred to as the anolyte tank. The tank that supplies electrolyte to the cathode on discharge is referred to as the catholyte. Both are constructed of heavy plastic. No electrochemical reactions occur in the tanks. In addition, the anolyte tank has a heat exchanger built into it. Water is circulated through the heat exchanger in order to control the temperature of the battery system.
3. Electrode Stacks - The electrode stacks consist of a number of bipolar cells arranged so that they form an electrical circuit in series. A monopolar stack can be constructed, but a bipolar one is favored due to simplicity of construction. Each cell is made up of a plate of conductive plastic (bipolar electrode plate) and a microporous separator. The anolyte of one cell is separated from the catholyte by the microporous separator. The anolyte side of the bipolar plate has shallow grooves on the plastic; on the catholyte side a carbon paper is bonded to the conductive plastic to significantly increase surface area and reduce overpotential.
4. Electrolyte Pumping System - The electrolyte pumping system provides electrolyte from the holding tanks to the individual cells in the stack. Two pumps, one for each tank, circulate the

electrolyte to each side of the cells with the flow returning to the respective holding tanks.

5. Battery Management System - The management system controls the operation of the battery. It monitors temperature and current and controls the electrolyte pumping system, cooling system and safety systems.
6. Battery Containment Vessel - The containment vessel structurally holds and isolates the electrolyte tanks and battery stack from the rest of the electric vehicle.

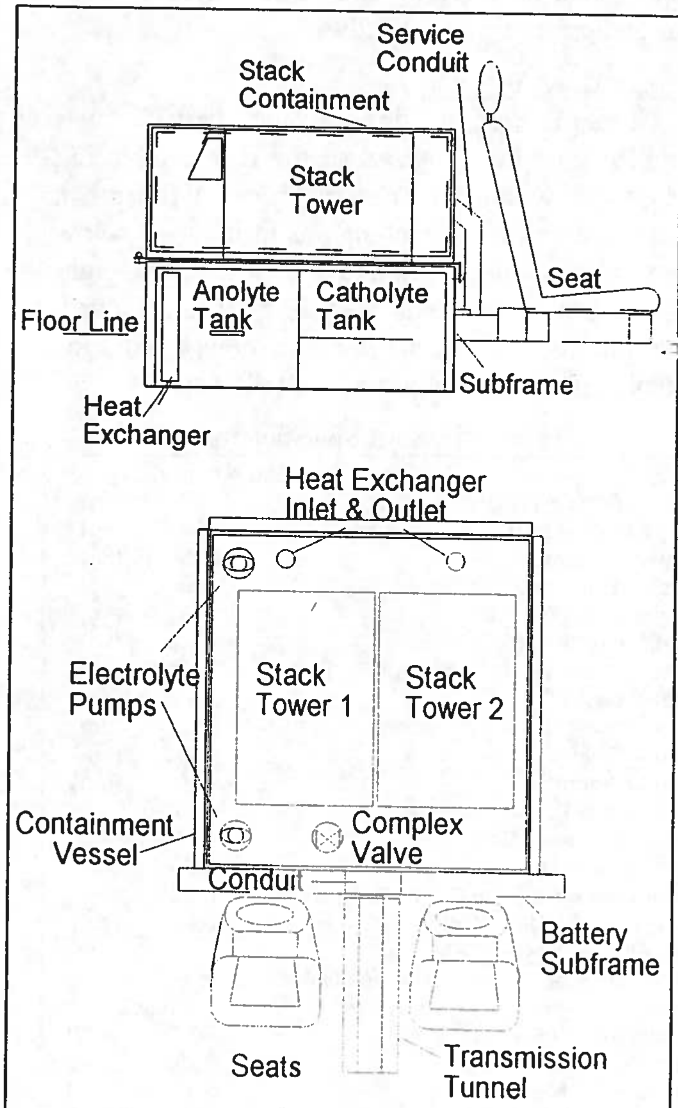
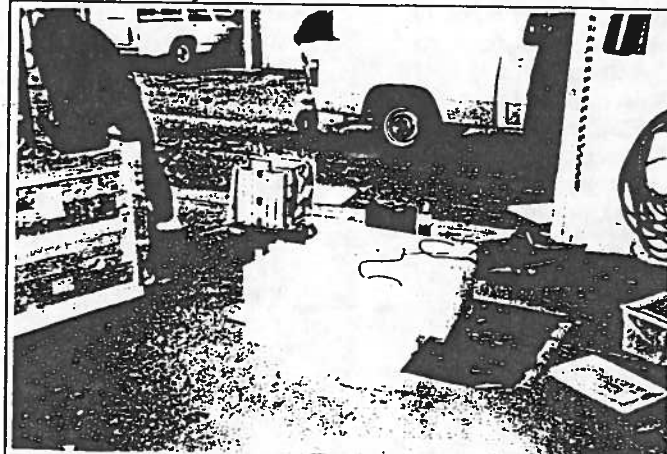


Figure 2. Schematic of Endura Battery System

During charge, metallic zinc is deposited on the anode side of the bipolar plate while bromine evolves at the cathode side. The bromine becomes complexed and is stored in the catholyte tank. The dense liquid complex naturally settles at the bottom of the catholyte tank. On discharge the electrochemical process is reversed. The complex valve controls the amount of complexed bromine in the electrolyte.


Picture 2. CA1 Electrolyte Tanks and Stack

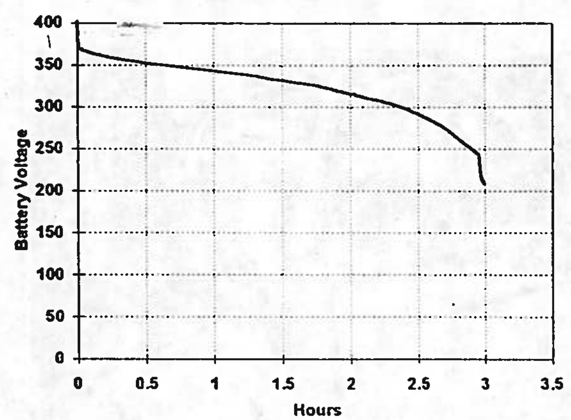

Picture 3. Electrolyte Tanks Installed in Car

California 1, Design and Performance

The CA1 battery was designed specifically for the Geo Prism chassis and the Dolphin drive system. By carefully considering the chassis weight, propulsion operating voltage, the vehicle power and energy needs, the battery capacity and number of cells was determined. Special consideration was given to electrolyte manifold design to reduce shunt currents. Table 2 and Figure 3 provide engineering data of CA1.

Table 2 CA1 Battery Specifications

Chemistry:	Zinc Bromide	
Configuration:	Two Electrolyte Tanks	
	Four 54 Cell Stacks	
Electrolyte:	2 x 100 liters	
$ZnBr_2$ molarity:	≈ 2.5	
OCV 100% SOC:	391	Volts
Charge Capacity @ C/3 Rate	-104.6	Ahr
Energy Capacity @ C/3 Rate:	-34.1	kWh
Maximum Power 50% SOC:	≈ 40	kW
Weight: Electrolyte	300	kg
4 Stacks	164	kg
Electrolyte Tanks	40	kg
Electrolyte Pump System	7	kg
Miscellaneous	7	kg
Battery Total	518	kg
Battery Containment Vessel	55	kg
Cooling System	20	kg
Cables, relays, fuses, Comp.	13	kg
Power System Total	606	kg
Charge Method:	Constant Current	
Nominal Charge Rate:	30	amps DC
End of Charge Voltage:	432	volts
Nominal Charge Power:	12	kW
Nominal Charge Time:	5 hours 0 to 100% SOC	



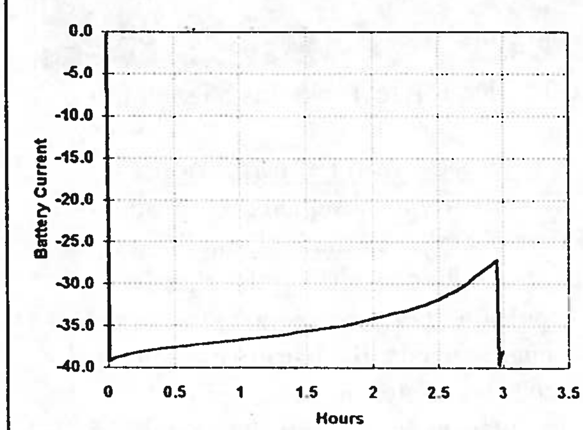


Figure 3. CA1 Performance for C/3 Discharge
-104.6 Ahr. -34.1 kWh, Battery

The discharge profiles in Figure 3 were obtained by discharging through a resistor. The current varied from 39 amps to 27.5 with an average of 34.9. Near the end of the 3 hours the resistor value was changed and resulted in the sudden increase in current and drop in voltage. The Figure 3 plots shows a load voltage changing from 370 to 240 volts. This swing was accommodated by Dolphin drive by programming. At a C/3 rate, the battery energy density was measured at 65.8 Wh/kg and a power system energy density of 56.3 Wh/kg.

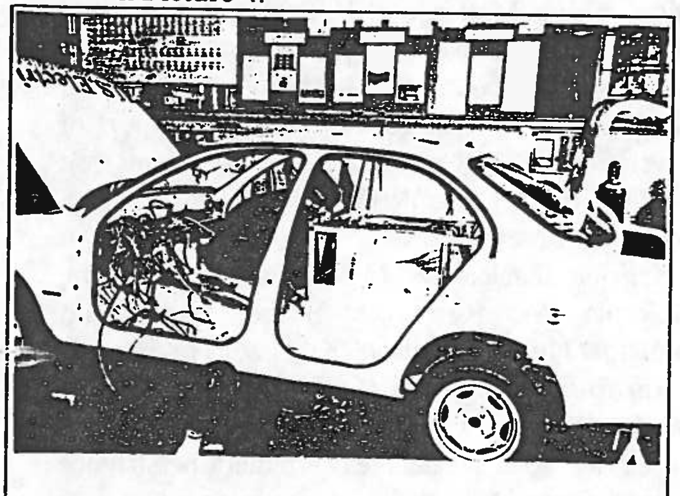
The Endura Vehicle

Through careful design, the battery was installed completely ahead of the rear axle, being built to fit within the rear subframe of the prism chassis. The vehicle weight was maintained below the gross vehicle weight and a front to rear weight distribution of approximately 50/50 was achieved. The final specifications for the completed zinc bromine powered Endura are as follows:

Table 3 Endura Specifications

Body:	1994 Geo	Prizm (Sedan)	
Gross Vehicle Weight:		1595	(kg)
Chassis Weight (Body, Propulsion)		658	(kg)
Power System		606	(kg)
Racing Roll cage, netting etc.		100	(kg)
Seats, windows, Misc.		146	(kg)
Curb Weight - Street form:		1410	(kg)
Curb Weight - Race Track form:		1459	(kg)
Wheel base:		226.5	(cm)
Overall Height:		140	(cm)
Overall Width:		168.5	(cm)
Overall Length:		434	(cm)
Tires Type/Size: Goodyear Eagle		P185/65R14	
Est. Roll. Resist Coeff.:		0.0096 kg/kg	
Frontal Area (A)		1.89	(m^2)
Estimated Aero Drag Coeff. (Cd.)		0.33	
Drag Area Product (CdA)		0.624	(m^2)
PROPULSION SYSTEM:			
Motor/Inverter	Hughes Dolphin Drive System		
Type:	3-Ph, AC	Induction	
Peak Motor Power:		50	(kW)
Base RPM		3600	(RPM)
Continuous Motor Power		20	(kW)
Maximum Motor RPM		10000	(RPM)
Motor Mass		60	(kg)
Inverter Mass		27.3	(kg)
Peak Inverter Efficiency		96%	
Peak Motor Efficiency		93%	

The battery was divided into two parts for designing the containment system - electrolyte tanks and cell stack towers. The electrolyte tanks were contained in a 3/16" thick aluminum container with a web that passed between them for structural support. The stacks were enclosed in an aluminum frame and plate system, which in addition to providing containment, triangulated the stack structurally to the containment system. The battery installation with the cover removed is shown in Picture 4.



Picture 4 CA1, Containment Sides Removed

All electrical, control, and cooling connections were made through a vertical "conduit" at the front of the containment tank. The conduit was arranged to carry connectors to the underside of the car so that no exposed propulsion voltage cables were present in the passenger cabin.

The battery control system monitored battery temperature, electrolyte pump current, five electrolyte leak sensors, voltage and current. Backup temperature sensors were also mounted directly on the battery stacks. If the stack temperature were to rise above a preset limit, the control system would open the propulsion relays, but would continue to run the electrolyte pumps to remove the excess heat. The electrolyte pumps operated at 30 volts via a DC-DC converter. The controller regulated electrolyte pumps, cooling system operation, and complex valve position. The complex valve position was used to regulate the concentration of bromine complex entering the electrode stacks. The control system also incorporated an inertia switch for battery shut down in case of a vehicle impact.

For electrical safety, the battery system incorporated a semiconductor fuse (150 amps) and an emergency switch for the driver. A system of main relays was incorporated on both the positive and negative power cables. The relays were controlled by the battery controller, the inverter motor controller and two emergency switches.

Vehicle Performance

The goal of the Endura project was to complete the March 94, 200 km Phoenix race in two hours, averaging 100 km/hr. This race is conducted on a banked oval speedway just outside of Phoenix, AZ. The goal was not met due to higher use of the vehicle. Figure 4 presents the approximate highway battery power (operating on straight and level highway) and the measured data while on the Phoenix track. The track data represents average speed and power for 5 laps. The track data showed significantly higher power was needed than was planned for. This was the result of cornering with severe under-steer. Due to time restraints the suspension was not corrected and Endura placed third in a field of ten vehicles in the feature race with an average speed of 92.6 km/hr.

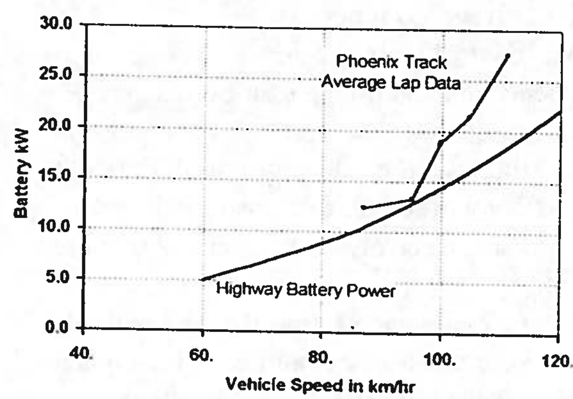


Figure 4. Endura Performance

In April 94 after significant upgrades the Endura competed in the World Clean Air road Rally, a three day event in the LA basin. Out of a field of 54 vehicles, including natural gas and hybrids, the Endura took first place with 690 points of a possible 700 (a first day range of over 160 miles in LA traffic). The nearest class competitor was at 545 points.

In May 1994, Endura competed in the American Tour de Sol, a six day cross country road rally for electric vehicles. In a class of twenty one, Endura took second place (5 minutes behind 1st place) in the American Commuter division and first place overall for a student-built vehicle (single charge range of 175 miles).

Conclusions

The CA1 battery represents successful engineering research conducted under extreme time and financial restraints. A working model of an advanced electric vehicle was built and successfully demonstrated. The Endura is one of the few electric vehicles capable of traveling and maintaining position in the high speed lane of California freeways. Several distinct advantages of the zinc bromine technology were found:

- Long range, with a reasonable vehicle weight, battery energy density of 65.8 Wh/kg (C/3).
- Battery modularity allows a custom fit and weight for a target vehicle.
- Handling is accomplished by draining the electrolyte and disassembling the basic components and moving them by hand.
- Recharging is relatively rapid and simple, constant current, no taper.
- Thermal control was achieved by standard components and an anolyte heat exchanger.
- The battery can be completely discharged and short-circuited with no damage. In this state it can be safely worked on or transported.
- No significant electrolyte shunt currents were measured.
- Operational experience found that the multiple systems were not a disadvantage. The explicit control over the battery was an advantage.

Zinc bromine technology is a viable, potentially low cost battery that can be used in the near term to meet California's needs. Its relatively high energy density makes it attractive to breaking the 100 mile range barrier while still having a payload capability.

The authors believe that the Endura project was critical in reintroducing the zinc bromine battery to EV racing and ultimately to its successful use in electric vehicles. In recognition of these accomplishments the Endura Project was named a runner up for the Saturn Team Work Award at the University of California, Davis.

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