Project No. NV-26-7001-02

Zinc–Air Battery
All Electric Bus Demonstration Project

Executive Summary and Conclusions
from Phase III Final Report

March 2004

Picture 1. All Electric Bus Demonstration on Public Roads
Las Vegas, Nevada, November 2001

Executive Summary

The Zinc–Air Battery Bus Demonstration Program was initiated in 1998 through a Cooperative Agreement between FTA, CST, EFC and RTC. The aim of the program was to develop and demonstrate a full-sized all electric, zero-emission transit bus utilizing Zinc–Air battery technology, and to assess the applicability of this technology for transit. FTA provided funding under a Cooperative Agreement, with fifty-percent cost-share provided by the project partners. GE-CRD and NovaBus also participated in Phase I of the project as subcontractors.

In Phase I a propulsion system utilizing a proprietary Zinc–Air battery technology developed by EFC was integrated on a full-size transit bus, and underwent limited testing. This included selecting an appropriate bus chassis, defining the bus configuration, developing the propulsion system design and controls, fabricating necessary hardware, and conducting installation and system integration. EFC and GE-CRD were awarded a BIRD grant for a related effort that enhanced the basic bus propulsion system by including dynamic retarding capabilities, improving the energy management system and demonstrating efficient battery exchange and refueling systems for the bus.

In Phase I the Zinc–Air battery technology was integrated into a standard RTS 40-foot transit bus. It was designed to meet standard bus performance specifications including grade climbing and acceleration for city urban bus drive cycles. The propulsion system consisted of a battery-battery hybrid configuration. The Zinc–Air battery supplied 312kWh of energy and contributed up to 99kW to the power requirement. A NiCd battery pack of 22kWh supplied up to 125kW of power and allowed for energy recuperation during vehicle deceleration. Together the batteries were capable of supplying propulsion power for the 200hp traction motor via a DC-AC inverter.

The Zinc–Air battery technology, previously developed by EFC, is a high-energy Zinc–Air battery system that produces electricity through the oxidation of zinc. This system is characterized by the mechanical removal and replacement of spent battery packs from the vehicle. The Electric Fuel Zinc–Air battery system for electric vehicles comprises three linked system elements:

1. A "discharge-only" Zinc–Air battery pack comprising several modules each containing a number of cells.
2. Battery exchange stations for the mechanical exchange of batteries. Spent (and partially spent) battery modules are removed from the vehicles and regenerated modules are installed in their place. The spent battery modules are regenerated at a central facility.
3. A central regeneration facility processes spent battery modules (battery refurbishment and zinc anode recycling) and returns regenerated modules to the exchange stations.

The Zinc–Air battery in the demonstration bus consists of 18 modules, each containing 47 cells. It has a specific energy of 200Wh/kg and a specific peak power of 90W/kg (at 80-percent depth of discharge). A standard PLC provides command and control of the Zinc–Air battery system.

In Phase II, the partners in the project were EFL, GE-CRD and RTC. The aim of the Phase II project was to enhance and optimize the all-electric propulsion system and evaluate the system performance. In addition Phase II included two tests; the potential incorporation of a full scale ultracapacitors and a fast charge hardware.

In Phase III, the partners were the same as for Phase II (GE-CRD name changed to GE Global Research (GE-GRC)). This Phase III effort was in fact, the incorporation and demonstration of a pre-commercialized advanced Ultracapacitor/Battery Energy Storage System (ESS) and Energy Management System (EMS) for the zinc air all electric bus application. In addition Phase III included an advanced Pulse Width Modulated (PWM) auxiliary drive system incorporation, Environmental and Mechanical tests and investigation of the zinc-air bus acceptance by Transit Operators.

All functions of the bus were tested to verify proper operation, including the Zinc–Air battery controller, PLC, VSC, proprietary EMS, proprietary DC-AC Inverter Traction system, auxiliary sub-systems and DC-DC converters. Various parameters of all the systems, data acquisition equipment and speed measuring instruments were calibrated and optimized during two full discharge test drives. Registration and insurance for driving on public roads were obtained and public demonstration drives in Las Vegas, Washington and Albany were completed.

In the three consecutive phases a thorough and stringent performance test verified, in summary:

1 Basic Phase I configuration of zinc-air hybrid electric-electric transit bus

- The projected distance in CBDs driven by the zinc-air bus was 94 miles. When allowance is made for loading and unloading and unnecessary idling time for data recovery the design range goal of 95 miles was easily exceeded.

- The fuel consumption, energy efficiency on CBD cycle, averaged 2,943 Whr/mile.
- Effective energy available from Zinc–Air was 285kWh.
- Acceleration of the bus exceeded all FTA performance parameters and the more stringent requirements of New York City.
- The most economical speed matched the design goal of 20mph.

2 Phase II modified propulsion system including the provisory ultracapacitor introduction.

- The projected distance in CBDs driven by the zinc-air bus was 117 miles.
- The fuel consumption, energy efficiency on CBD cycle, averaged 2,683 Whr/mile.
- Effective energy available from Zinc–Air was 315kWh, more than the designed 312kWh.
- Acceleration results even further exceeded both FTA and NYC performance requirements.

3 Phase III incorporation of a pre-commercialized advanced Ultracapacitor/Battery ESS and EMS.

- The projected distance in CBDs driven by the zinc-air bus was 117.6 miles while total energy from the zinc-air battery was reduced by 10%. When allowance is made for loading and unloading and unnecessary idling time for data recovery the design range of 95 miles was exceeded by more than 25%.
- The fuel consumption, energy efficiency on CBD cycle, averaged 2,383 Whr/mile.
- Effective energy available from Zinc–Air was 282kWh, 90% of the designed 312kWh.
- Acceleration results even further exceeded both FTA and NYC performance requirements.
- Advanced PWM auxiliary drive gave 3-4% higher efficiencies than the previous phases configuration, since auxiliary energy portion is 17%, the attribution in range amount to 0.6%.

The results of thermal tests show that the Phase III ultracapacitor hybrid energy storage system hardware and design is sufficient for the pre-commercialized hybrid transit bus application. Likewise, the mechanical shock and vibration tests also show that the custom designed hardware is sufficient to meet the robustness of the transit bus application.

The studies of the zinc-air bus acceptance by Transit Operators, lead to the conclusion to introduce an alternative zinc, from existing zinc production capacity. The unique refueling of the zinc-air bus can be made acceptable by the transit bus operators by using battery exchange vehicles that are currently available for the similar application in forklift operation.

Conclusions

The advanced ultracapacitor system and control installation demonstrated additional capture of energy during the regenerative braking mode of operation, reduction in the traction portion of the energy consumption, effective load-leveling of the batteries in the All-Electric Transit bus and substantially increased the vehicle's energy utilization and zero-emissions range. Recent ultracapacitor technology research and product development is increasing the specific power density (W/kg), and improving thermal and system packaging design. As additional transportation and stationary applications are identified and tested, it is expected that the production volume will increase to a level where the cost of the ultracapacitor system on a life cycle basis is competitive with batteries for the next generation hybrid and electric propulsion systems for use in automobiles and heavy duty buses and trucks.

Durability testing of the advanced PWM drive showed other significant benefits, including; a robust hardware design to meet the demanding transit bus environmental requirements (temperature plus shock/vibration), and the ability to operate over an increased DC voltage range as compared to the AF300 drives. Operation of the auxiliary drives down to lower DC voltage levels may allow modification to the low voltage control shutdown algorithm, thus further extending the range of the All-Electric Transit Bus.

The results of thermal tests described above show that the Phase III ultracapacitor hybrid energy storage system hardware and design is sufficient for the pre-commercialized hybrid transit bus application. Likewise, the mechanical shock and vibration tests described above also show that the custom designed hardware is sufficient to meet the robustness of the transit bus application. Based on the results of thermal and mechanical tests described in this report, no design upgrades are required to meet the Phase III transit bus operational and environmental requirements.

The conclusions of the studies of the zinc-air bus impact on Transit Operators: The zinc-air all-electric bus can be introduced commercially, and can be economically comparable to diesel-hybrid buses that are economically accepted by several transit agencies. The bus, all its electrical components including the battery energy storage is expected to be accepted by Transit agencies, with advantages to this zinc-air all-electric bus. This includes, operation, maintenance and guarantee. The refueling of the bus, which consists of replacing the zinc-air battery modules after every daily cycle, is very different from diesel bus refueling. Available systems are expected to be introduced which can perform the exchange of the battery modules in an acceptable way. Additional space is required for the refueling and the level of automation defines the level of operators required for the refueling. The current unique proprietary zinc developed by Electric Fuel cannot serve as fuel for the introduction of the buses in transit operation within the currently foreseen business environment. It will be necessary to use alternative zinc that is available in the market for the phase of commercial introduction. Promising indication of such alternative zinc resolves the issue of the fuel supply.

Phase III of the project to demonstrate an All-Electric Transit bus powered by Electric Fuel's Zinc–Air battery was completed successfully. The performance of the bus exceeded the design projections.