

**Zinc–Air Battery
All Electric Bus Demonstration Project**

**Executive Summary and Conclusions
from Phase IV Final Report**

Executive Summary

Overview

The Zinc-Air Electric Transit Bus Program was initiated in late 1998 to support the development, demonstration and testing of a full-size, all-electric zero-emission transit bus powered by Electric Fuel Corporation's zinc-air batteries.

By the time the project concluded with the completion of Phase IV in the fall of 2005, project participants Electric Fuel and General Electric demonstrated that the bus, which had been configured to meet all of the FTA's requirements for city bus drive cycles, including grade climbing and acceleration, is capable of full-day operation with all of its accessories including full air conditioning.

During operation, utilization of the bus's three power sources is dynamically optimized by the advanced control system: the ultracapacitors provide peak power for short-term acceleration, the power battery provides extended high power for long grades, and the zinc-air energy battery supplies adequate continuous power for cruising. During braking, the power battery and ultracapacitors combine to recuperate approximately 12% of theoretical dynamic energy.

Two significant achievements of the follow-on phases were the successful deployment of ultracapacitors in the all-electric hybrid propulsion system for peak power and energy storage optimization, and the characterization of an acceptable alternative zinc fuel morphology that can be produced commercially without necessitating the capital facility investment indicated for commercial production of Electric Fuel's proprietary dendritic zinc fuel.

At the conclusion of the Zinc-Air Electric Transit Bus Program, the prototype bus now embodies fourth-generation hybrid propulsion and control technology, having advanced three generations beyond the simple battery-battery configuration of the Phase I bus. Implementation of ultracapacitors, upgrade of the control system and optimization of the control system parameters have together produced an improvement of more than 40% in driving range on the Central Business District (CBD) drive cycle over the initial Phase I design goals.

The All-Electric Hybrid Bus

In addition to testing and demonstrating the ability of Electric Fuel's zinc-air battery to power a full-sized urban transit bus for a full day in real-world transit driving conditions, the Zinc-air Electric Transit Bus Program has yielded the most advanced all-electric hybrid bus in the world.

The vehicle platform employed in all phases of this project is a standard 40-foot transit bus manufactured by NovaBus Corporation, with a capacity of 40 seated and 37 standing passengers. The bus is pictured below:



The Zinc-Air Electric Transit Bus

As currently configured, the bus incorporates three distinct energy storage systems, each of which plays a different role in the operation of the vehicle:

- The zinc-air battery is the main source of energy with specific energy of 200 Wh/kg, and delivers 312 kWh at moderate power levels (up to about 50 kW, although capable of 100 kW).
- The Ni-Cd auxiliary battery, with specific power capability of 350 W/kg, delivers up to 22 kWh of energy at power levels up to 125 kW.
- The ultracapacitor module has specific power capabilities of about 1,000 W/kg, and contributes greatly to system efficiency through high-rate capture of dynamic retarding energy as well as high-rate delivery of peak power.

The following paragraphs describe the other key technology components of the all-electric hybrid bus.

Propulsion System

The bus's propulsion system consists of a commercially available General Electric AC induction motor with a rugged industrial frame, a high power DC-AC traction inverter, and an associated Motor Controller. A direct drive motor was selected to achieve high traction efficiency with a reasonable cost in high volume production. The traction inverter, based on GE's Digital Signal Processor (DSP) technology, converts DC power provided by the batteries, to adjustable frequency, adjustable current 3-Phase AC excitation as required by the traction motor.

Energy Management System

The Energy Management System (EMS) provides the interface between the high-energy zinc-air battery and the traction drive system, and serves to maintain the state-of-charge of the high power Ni-Cd auxiliary battery and ultracapacitors. The EMS also regulates the capture of a portion of the dynamic retarding energy in the auxiliary battery and ultracapacitors during vehicle deceleration. In Phase IV of the program, control software was upgraded in order to increase the amount of energy capture during regenerative braking.

Vehicle System Controller

The Vehicle System Controller (VSC) provides the interface between the driver and the propulsion system, as well as between the traction inverter and associated Motor Controller, Energy Management System, and zinc-air battery controller. The VSC translates the driver commands, including the position of the key switch, forward/neutral/reverse switch, brake transducer, and accelerator pedal position into electrical signals that are sent to the propulsion system. Motor torque, speed, and power are controlled and also limited by the VSC to keep the propulsion system components within their safe operating ranges.

Pulse Width Modulated Auxiliary Drive System

Another innovative system contributing to vehicle efficiency is the advanced Pulse Width Modulated (PWM) auxiliary drive system. The air-cooled advanced PWM drive was designed specifically to supply electrical excitation and control of the transit bus auxiliary loads, including the coolant pump and associated fans for thermal control of the traction motor and power electronics, air compressor (air brakes and vehicle suspension and kneeling system) and power steering hydraulic pump, and also the air conditioning system's freon compressor.

The Zinc-Air Battery

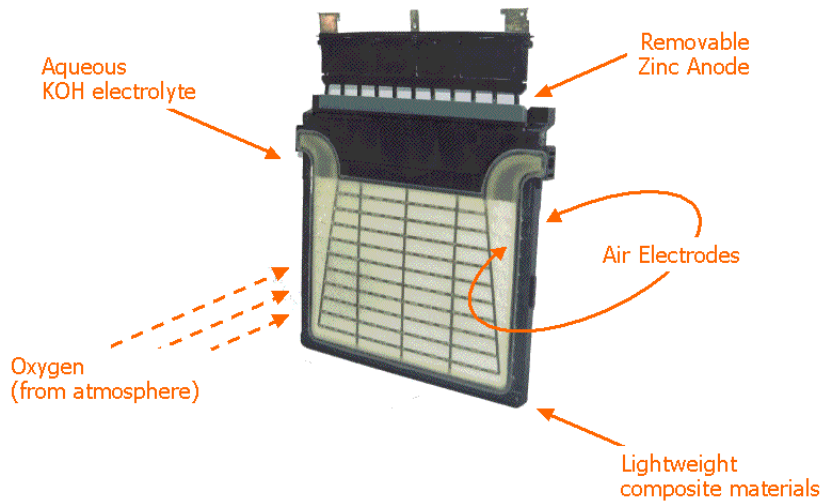
In a zinc-air battery, oxygen from the atmosphere reacts with zinc in an electrochemical cell to release electricity.

A special membrane called an air electrode, conceptually similar to the one deployed in hydrogen fuel cells, is employed to extract the oxygen electrochemically from the air.

The underlying chemical reaction of a zinc-air cell is the same as that of ordinary household alkaline batteries, which are also based on the reaction of oxygen with zinc in an alkaline electrolyte. An important difference is that alkaline batteries store their oxygen inside the cell, in the form of a bulky material called manganese dioxide. The manganese dioxide in an alkaline battery typically accounts for half of its weight and volume, which means that a zinc-air battery, which doesn't have to store oxygen inside the cell, is much lighter and smaller for the same amount of energy storage. An additional advantage over alkaline cells is that the oxygen supply of a zinc-air cell never runs out, and therefore the discharge capacity of a zinc-air battery is limited only by its supply of zinc fuel.

In order to bring the long run-time and low weight of zinc-air batteries to electric vehicles, Electric Fuel developed a battery that allows for easy mechanical replacement of the zinc after every discharge. The discharged zinc, in the form of zinc oxide, is recycled after each use and converted back to zinc metal for reuse in the battery. Both the individual cells and the battery module are designed in such a way as to facilitate the rapid replacement of the zinc anodes. An anode consists of zinc metal particles in a potassium hydroxide solution, compacted onto a current collection frame.

The figure below shows the major elements of a zinc-air cell with partially withdrawn zinc anode:



The table below lists the key top-level specifications of the current generation of zinc-air battery module, which is shown in the photograph alongside.

No. of cells	47
Open Circuit Voltage	67V
Operating Voltage	57-40 V
Capacity	325 Ah
Energy Capacity	17.4 kWh
Peak Power (@80% DOD)	8 kW
Weight	88 kg
Volume	79 liter
Energy Density	200 Wh/kg
Dimensions	726x350x310 mm



Zinc-air battery module, one of 18 installed in the FTA prototype transit bus

Phase IV Summary

The results of Phase IV program tasks and activities are summarized in the following sections.

Performance Testing

The primary objective of the Phase IV performance test was to demonstrate that the zinc-air all-electric transit bus will meet the performance requirements of a typical transit bus, including vehicle range measurements on a Central Business Driving Cycle (CBD) and vehicle acceleration measurements. A second objective was to measure energy consumption while the vehicle was operating at specified conditions. A third objective was to compare the test results with previous tests' results to see the

improvement of the enhanced configuration using prototype ultracapacitors and a novel energy management system. All performance measurements were performed on a smooth and level test track

The official performance tests of the all-electric transit bus were performed on unused runways at the former Griffiss Air Force Base in Rome, NY, where the “energy battery” was comprised of a zinc-air battery.

Following the performance test with the zinc-air battery, a badly worn bearing on the rear (drive) axle of the bus was discovered, and it was determined that this mechanical malfunction had impacted the mechanical performance of the vehicle, and therefore the energy consumption data collected, during the CBD cycle testing. Nonetheless, the tasks objectives were met satisfactorily.

According to the measurements taken during the test itself, which entailed a total of 497 CBD sub-cycles for a cumulative measured range of 80.11 miles, a total of 182,022 Wh of energy (570.6 Ah) was consumed during the operation on the CBD cycles, with energy consumption on the CBD cycle calculated at 2,331 Wh/mile, only slightly less than that measured in Phase III. The projected driving range on CBD cycles of the all-electric transit bus was computed to be 128.4 miles, a 9.2% improvement over the 117.6 mile projected range in Phase III of the program. However, in light of comparative measurements taken after the mechanical problem had been repaired, it became clear that energy consumption in this test would have been about 2,309 Wh/mile, a more substantial improvement over Phase III and a range increase of 42% over the original design of Phase I, based on an assumed deliverable energy of 312 kWh from the zinc-air batteries.

Total energy from the Zinc-Air batteries, Ni-Cd Auxiliary battery, and ultracapacitors for the overall 142-mile performance test was 299,354 Wh (939.2 Ah), which translated to overall average energy consumption of 2,108 Wh/mile.

In addition, a second set of tests was conducted using an electrically rechargeable Na-NiCl₂ (sodium-nickel chloride) or “Zebra” battery, initially in the laboratory and later mounted in the all-electric transit bus as the “energy battery,” on a test track at the former NovaBus facility in Schenectady, NY.

Complete details of Phase IV performance testing may be found in the Appendix, “Ultracapacitor Enhanced All-Electric Transit Bus Performance and Auxiliary Battery Test Summary Report.”

Performance Evaluation of Alternative Zinc

The purpose of evaluating and introducing an alternative zinc morphology, i.e., one that can be made available from existing commercial production, is to enable the introduction of zinc-air buses in the transit industry, without the necessity to provide, in parallel, large infrastructure facilities dedicated to producing and recycling (regenerating) Electric Fuel’s proprietary dendritic zinc.

Various forms of alternative zinc were tested at Electric Fuel’s laboratory, and a final selection was made of the alternative zinc most suitable for the introduction to the

existing zinc-air battery, based on receiving satisfactory performance results in comparison with the previous zinc.

In order to test the performance capabilities of the selected alternative zinc morphology, an additional systemic performance test was conducted wherein 3 out of the 18 modules in the zinc-air transit bus were loaded with anodes made from alternative zinc. One alternative zinc module was placed on each of the 3 6-module trays in order to balance any changes in performance across the trays. The remaining 15 modules were loaded with anodes made from the Electric Fuel dendritic zinc, which had been used in all previous performance tests in all phases of the program. The systemic performance test was completed satisfactorily with 300kWh battery consumption, less than 5% below the design energy capacity of 312 kWh for the zinc-air battery. However, the anodes produced from the alternative zinc had 5% lower density than the dendritic zinc anodes usually employed, and therefore, in light of the physical constraints of the existing zinc-air cell design, the weight of the alternative zinc introduced for the test was 5% less than for the dendritic zinc. Accordingly, the alternative zinc was proven to be fully equivalent to the dendritic zinc when operating under the discharge requirements of the hybrid electric bus.

Results of this test are presented in the “Performance Test Report - Zinc-air Battery Appendix.”

Alternative Zinc Feasibility Analysis

In addition to evaluating the discharge performance of the alternative zinc, a techno-economic feasibility study was performed by program subcontractor Alabama Productivity Center (APC), a nonprofit organization at the University of Alabama in Tuscaloosa, Ala.

The APC study focused on methods of producing the alternative zinc, and on projected costs and constraints associated with the various methods. The study found that one of the three methods studied was substantially cheaper and had only moderate capital investment requirements for adapting the method to the specific needs of the zinc-air battery for the electric transit bus application. Furthermore, as opposed to the case of Electric Fuel’s proprietary dendritic zinc, the study authors found the cost of producing and recycling zinc anodes comprising the alternative zinc to be moderate even for small and medium-sized bus fleets.

A redacted summary of the APC report appears in the Appendix “Alternative Zinc Feasibility Analysis.”

Summary of Earlier Program Phases

Phase I

The Zinc-Air Battery Bus Demonstration Program was initiated in 1998 through a Cooperative Agreement among FTA, CST, EFC and RTC. The stated 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 a

fifty-percent cost-share provided by the project partners. GE-CRD and NovaBus also participated in Phase I as subcontractors.

During the course of the initial program phase, a propulsion system utilizing a proprietary zinc-air battery technology developed by EFC was installed in 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. The effort was supported by a parallel effort by EFC and GE-CRD, funded in part by a BIRD grant, to enhance a basic electric bus propulsion system by including dynamic retarding capabilities, improving the energy management system and demonstrating efficient battery exchange and refueling systems for the bus.

The zinc-air battery technology, previously developed by EFC, is a high specific-energy battery system that generates electricity through the controlled oxidation of zinc in an alkaline electrolyte by oxygen extracted electrochemically from the atmosphere. This system is not recharged electrically in situ, but rather is characterized by the mechanical removal and replacement of spent battery packs from the vehicle for refurbishment of the battery modules and recycling of the zinc anodes.

The zinc-air battery deployed in the demonstration bus consists of 18 modules, each containing 47 cells. It has a specific energy of 200Wh/kg and can provide 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.

By the end of what was to be only the first phase of the program, the zinc-air battery technology was integrated into the demonstration bus, a standard 40-foot RTS transit bus produced by NovaBus. The battery-battery hybrid propulsion system was configured to meet standard bus performance specifications, including grade climbing and acceleration for city urban bus drive cycles. 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. Both batteries were capable of supplying propulsion power for the 200hp traction motor via a DC-AC inverter.

Phase II

In Phase II, the partners in the project were EFL, GE-CRD and RTC. The aim of this first follow-up phase was to enhance and optimize the all-electric propulsion system and evaluate system performance. In addition, Phase II included the incorporation of ultracapacitors fast charge hardware in the propulsion system.

All functions of the bus were tested to verify proper operation, including the zinc-air PLC battery controller, vehicle system controller (VSC), proprietary energy management system (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 a public demonstration in Las Vegas was completed.

During the first formal performance test, 378 CBD cycles were run with a measured range of 59.16 miles. A total of 152,051 watt-hours (Wh) of energy or 477.2 ampere-hours (Ah) were consumed. The total energy from both zinc-air batteries and NiCd auxiliary battery for the complete performance tests was 241,718 Wh and the total capacity used was 762 Ah; energy consumption, therefore, was 2,570 Wh per mile and capacity consumption was 8.07 Ah/mile. Based on these measurements, a total CBD-cycle driving range of 94 miles was projected for the all-electric transit bus. When allowance was made for loading and unloading and unnecessary idling time for data recovery, it could be seen that the design range goal of 95 miles was easily exceeded.

Effective energy available from the zinc-air battery modules was 242kWh. Acceleration of the bus exceeded standard bus performance parameters (based on standard bus procurement guidelines) and even the more stringent requirements of New York City Transit. Further, the most economical speed matched the design goal of 20mph.

Next, a modified propulsion system was developed, installed and tested, and fast charge hardware was tested and implemented. A repeat performance test provided direct performance comparisons. In this case, 487 CBD cycles were run with a measured range of 75.61 miles. A total of 202,877.1 Wh of energy or 615.15 Ah of capacity was consumed. The total energy from both the zinc-air batteries and the NiCd auxiliary battery for the complete performance tests was 315,003 W-Hr and a total of 952.2 Amp-Hr was used. The computed energy consumption was 2,683 Wh/mile or 8.14 Ah/mile. Therefore, based on these track tests, the projected driving range on CBD cycles of the all-electric transit bus was now expanded to 117 miles. When allowance was made for loading and unloading and unnecessary idling time for data recovery the design range of 95 miles was exceeded by more than 25%.

Effective energy available from Zinc–Air was 315kWh, more than the design goal of 312kWh, and acceleration results even further exceeded both FTA and NYCT performance requirements.

Phase III

In Phase III, the partners were the same as for Phase II, with GE-CRD's name changed to GE Global Research (GE-GRC). The Phase III effort focused on the installation and demonstration of a pre-commercialized advanced ultracapacitor/battery energy storage system (ESS) and energy management system (EMS). In addition, Phase III included incorporation of an advanced pulse width modulated (PWM) auxiliary drive system, environmental and mechanical tests, and investigation of the potential for zinc-air bus acceptance by transit operators.

In addition, further public demonstration drives in Washington, DC, and Albany, New York, were completed.

In the performance tests in the Phase III configuration (including the ultracapacitors), fuel consumption on the CBD cycle averaged 2,383 Whr/mile. The projected total driving range on CBD-only testing was 117.6 miles, while total energy from the zinc-

air battery was reduced by 10%. When allowance was made for loading and unloading and unnecessary idling time for data recovery, the design range of 95 miles was again exceeded by more than 25%.

Effective energy available from zinc-air was 282kWh, 90% of the total. Acceleration results even further exceeded both FTA and NYC performance requirements. The advanced PWM auxiliary drive gave 3-4% higher efficiencies than the previous configuration, and the auxiliary system's share of energy was 17%.

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

Studies of the potential for acceptance of zinc-air buses acceptance by transit operators led to the suggestion of introducing an alternative zinc morphology, from existing commercial zinc production capacity, instead of depending upon Electric Fuel's proprietary dendritic zinc morphology. It was also learned that the unique refueling of the zinc-air bus can be made acceptable to the transit bus operators by using battery exchange vehicles that are currently used for this purpose for battery-powered forklifts.