97210

DEVELOPMENT OF A COMPACT HIGH-POWER ZINC-OXYGEN BATTERY FOR A HEAVYWEIGHT TORPEDO

Binyamin Koretz
Neal Naimer
Electric Fuel Limited
P.O. Box 23073
Jerusalem 91230
Israel
Tel. +972-2-589-0890 Fax +972-2-532-2252
e-mail: info@electric-fuel.com

ABSTRACT

Electric Fuel Limited (EFL) is completing the second year of development of a compact, high-power zinc-oxygen battery for heavyweight torpedoes, under subcontract to STN ATLAS Elektronik GmbH of Hamburg, Germany. STN ATLAS is the prime contractor to the German Federal Office for Defence Technology and Procurement (BWB) for a new generation of heavyweight torpedo.

The program has consisted thus far of a first phase in which the concept of the zinc-oxygen battery stack was evaluated in small (330 cm^2 active area) cells, and a second phase in which the cells were scaled up about fourfold to the final full size of the torpedo battery stack. A general schedule of these two phases of the development program is shown in Figure 1.

	PHASE I				PHASE II			
	3Q 1995	4Q 1995	1Q 1996	2Q 1996	3Q 1996	4Q 1996	1Q 1997	2Q 1997
PHASE I								
Conceptual Design								
Single Evaluation Cell								
5-Cell Evaluation Stacks								
21-Cell Evaluation Stacks								
PHASE II								
Scale-up to Full-Size Cell								
Tooling Fabrication								
5-Cell Full-Size Stacks								
51-Cell Full-Size Stacks								

FIGURE 1. DEVELOPMENT PROGRAM SCHEDULE

EFL, as the battery technology developer, is responsible for the design, construction and testing of the zinc-oxygen cell stack. STN ATLAS, with experience and expertise in the design, integration and manufacture of torpedoes and other underwater systems, is developing the battery's peripheral equipment and interface with the torpedo.

This paper will review the zinc-oxygen technology, cell and stack design, the progress and results of the development program to date, and the directions for future development.

ZINC-OXYGEN TECHNOLOGY

Some of the electrode technologies incorporated in the zinc-oxygen battery are based on zinc-air technology previously developed by EFL for use in electric road vehicles. However, during this project, EFL has introduced significant changes in the structure of the cell and stack, as well as in the design and composition of electrodes and other cell components. EFL has also demonstrated a high degree of safety in a cell stack.

The result today is a zinc-oxygen reserve battery optimized for gravimetric and volumetric power densities within the framework of overall mission requirements for overall energy capacity, weight and volume. As will be discussed in the final section, alternative designs with more emphasis on energy density are also possible, mainly by changing the ratio of zinc mass to oxygen cathode area.

The zinc-oxygen battery stack is built from zinc-oxygen cells arranged in series, in the quantity required. Each cell comprises a static anode bed of electrochemically generated zinc particles compacted onto a current collection plate, opposed by a high-power oxygen reduction cathode.

During discharge, after an aqueous potassium hydroxide electrolyte is introduced, zinc at the anode is consumed by conversion to zinc oxide, and, at the cathode, oxygen is electrochemically reduced to hydroxide ions, as per Table 1.

At the anode:	$Zn + 4\ OH^- = Zn(OH)_4^{2-} + 2e$
	$Zn(OH)_4^{2-} = ZnO + 2\ OH^- + H_2O$
At the cathode:	$O_2 + 2H_2O + 4e = 4\ OH^-$
Overall reaction:	$2Zn + O_2 = 2ZnO$

TABLE 1. REACTION EQUATIONS

CELL STACK DESIGN

The cell stack design today, shown schematically in Figure 2, is similar to that of a fuel cell, wherein each cell consists of a number of plates or leaves separated by gaskets; the gaskets serve to route and compartmentalize cooling fluid, oxygen, and electrolyte.

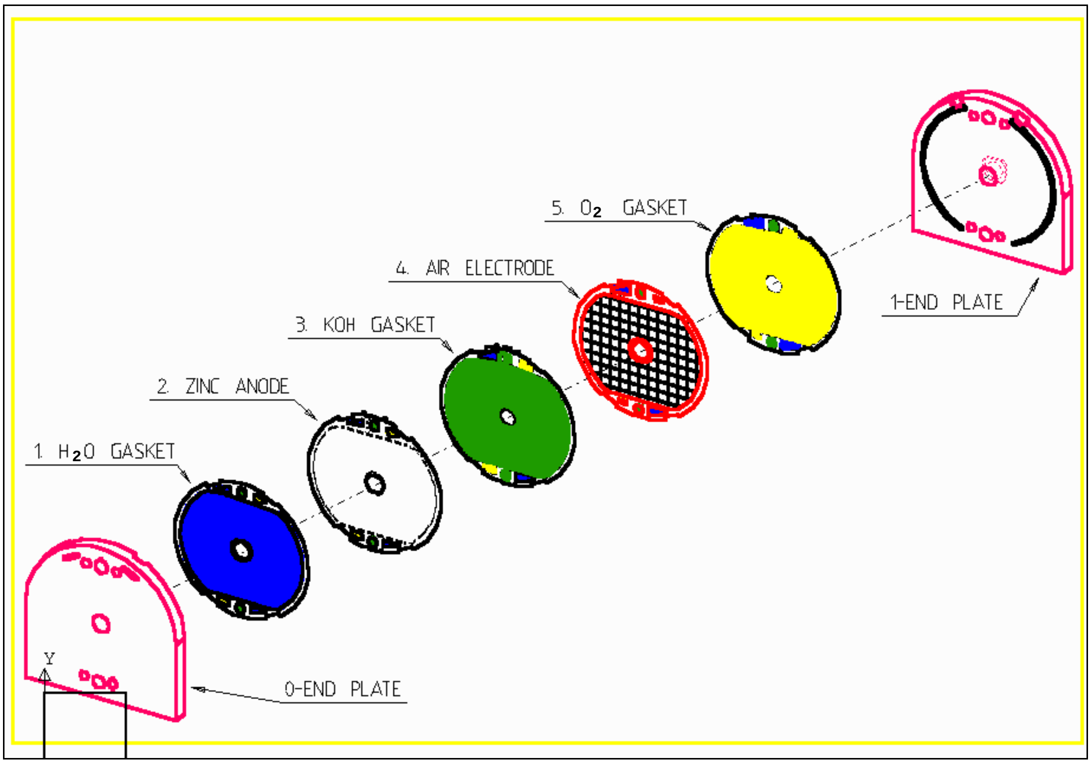

FIGURE 2. SCHEMATIC DRAWING OF CELL STACK

PHASE I

During the first year of development, which ended in June 1996, EFL designed, built and tested 21-cell stacks made up of quarter-size evaluation cells. Each evaluation cell had a square active area measuring about 18.2 cm on each side, for a total active area of 330 cm^2.

This size was chosen primarily because it enabled us to use the electrode fabrication tooling already existing within the company. The active area of 330 cm^2 is similar to that of the zinc-air cells used in EFL's electric vehicle batteries.

Figure 3 shows schematically the relationship between the evaluation cell stack and the target design for the torpedo cell stack.

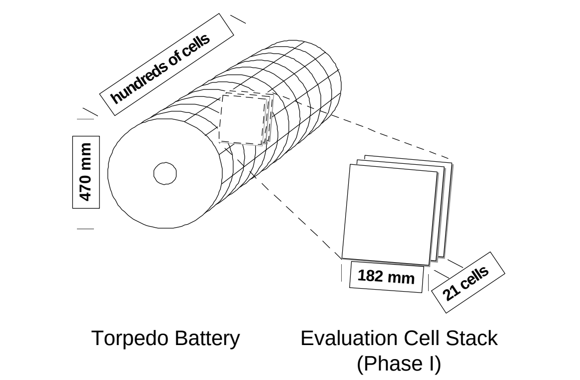

FIGURE 3. EVALUATION CELL STACK CONCEPT

Single-Cell Discharges

In a first step, a number of preliminary experiments (approximately 20) were carried out using EFL's zinc-air vehicle-battery cells. Each of these cells incorporated EFL air electrodes fabricated on metal mesh soldered to a current collector and glued in a plastic half-cell frame.

The very first experiments within this first step were done with EFL vehicle-battery anodes, in order to test the feasibility and baseline performance of the EFL vehicle-battery cell using pressurized O_2 instead of flowing air, as would be provided in the electric vehicle. These anodes consist of an electrochemically produced alkaline zinc slurry cold-pressed on an open wire current collector frame. After these first few tests, we continued with the first version of the new mission-specific anode. This anode consists of electrochemically produced zinc pressed onto a thin plate made from a copper sheet glued to an epoxyglass backing. The copper plate was prepared using a proprietary process to yield a surface that would allow the zinc particles to adhere to it.

In the next step, we constructed the first zinc-oxygen evaluation cells on the plate/gasket concept, and made the first tests using wet anodes, i.e., anodes with KOH solution already filling the interparticulate gaps in the zinc structure. The most important new development tested in this set of experiments was the first version of the mission-specific oxygen electrode. This oxygen electrode, unlike the vehicle-battery air electrode, is based on a non-woven mesh with an integral current collector.

Following this, we produced and tested dry anodes for the first time. The dry anodes were a new development required by the project in order to allow extended periods of dry storage without self-discharge due to corrosion and also to facilitate very rapid wetting and voltage activation upon filling the stack with KOH.

More than 60 cells were discharged over a four-month period in single-cell discharge experiments. Cells were discharged to about 40 Ah at current densities ranging from 130 to 375 mA/cm^2. Cell voltage was typically between 1.45 V (open circuit) and 0.9 V (at 375 mA/cm^2 at end of discharge), with very little variance from cell to cell.

5-Cell Discharges

We then decided to undertake a 5-cell experimentation program as an intermediate scale-up development step before going on to the 21-cell evaluation stacks, in order to examine and optimize the key parameters that were specific to multi-cell stack discharges.

These parameters included:

- activation procedures
- automatic KOH filling
- contact resistance
- fabrication and placement of internal contacts
- method of O_2 introduction and overpressure
- optimization of the cooling chamber spacers
- optimization of separators

Some 15 discharge experiments of 5-cell stacks were performed over a three-month period, during which we attained a high degree of reproducibility of performance results. End of discharge voltages were typically 50 mV higher than those of the single-cell discharges, primarily because of the thermal retention properties of the stack.

21-Cell Evaluation Stack Discharges

The final stage in Phase I was the construction and discharge of three 21-cell evaluation stacks. The discharge programs included the most important tests yet of rapid electrolyte filling and stack activation.

The first stack was successfully discharged at EFL's laboratory facility in Jerusalem, Israel, and the other two stacks were subsequently discharged at STN ATLAS's facilities in Wedel, Germany. The discharge regimes were identical to those used for the single-cell discharges, with current densities ranging from 130 to 375 mA/cm^2. With the exception of a small number of cells that encountered electrolyte filling problems, the stack performance met expectations.

At the end of the discharge of the third stack, an additional step of one minute duration at 485 mA/cm^2 current density was added, following the 40 Ah cutoff.

During this additional high-power step, power output of at least 130 W, or 393 mW/cm^2, was measured in 17 out of 21 cells (i.e., all those without filling problems). Three of the cells remained at or above 150 W, or 455 mW/cm^2, for the full minute of the 160 A discharge.

PHASE II

The objective of the second year of development, which is scheduled to end in July 1997, has been to scale-up the cells to full torpedo size, and to test 51-cell stacks built from full-size prototype cells. Each prototype cell will again be discharged at current densities ranging up to 480 mA/ cm^2.

The structure of Phase II was similar to that of Phase I, in that three distinct hardware milestones were planned:

- single-cell discharges
- 5-cell discharges
- large multi-cell stacks (51 cells in Phase II, as opposed to 21-cell stacks in Phase I)

However, the most important element of Phase II was the scale-up to full torpedo size.

The most time-consuming aspect of the scale-up effort was the design and procurement of specialized fabrication tooling for the zinc anode, oxygen cathode, and gaskets. With an active-area diameter of some 470 mm (compared to the 182 mm square active area of the evaluation cells), the new cell components required completely new equipment, including presses, molds, assembly jigs, baths, etc.

At the end of the scale-up effort, single cells were tested that matched the electrochemical performance of the smaller evaluation cells of Phase I. Additional IR losses due to the longer current collection paths proved to be negligible.

Figure 4 is a set of voltage-vs.-current density curves obtained by measuring voltage during a series of high-current polarizations at 3 points during a cell discharge to 100% DOD, or depth of discharge). The current density is calculated as the current per unit of electrode active area.

Single-Cell and 5-Cell Discharges

The issues encountered in the Phase II experimental program were similar to those of Phase I, but made more difficult by the large surface area of the cells and the reduction in parasitic areas, which were previously available for various cell and stack functions. In addition, we had to develop solutions for supporting and separating the large thin fluid chambers, i.e., cooling water, oxygen and KOH electrolyte.

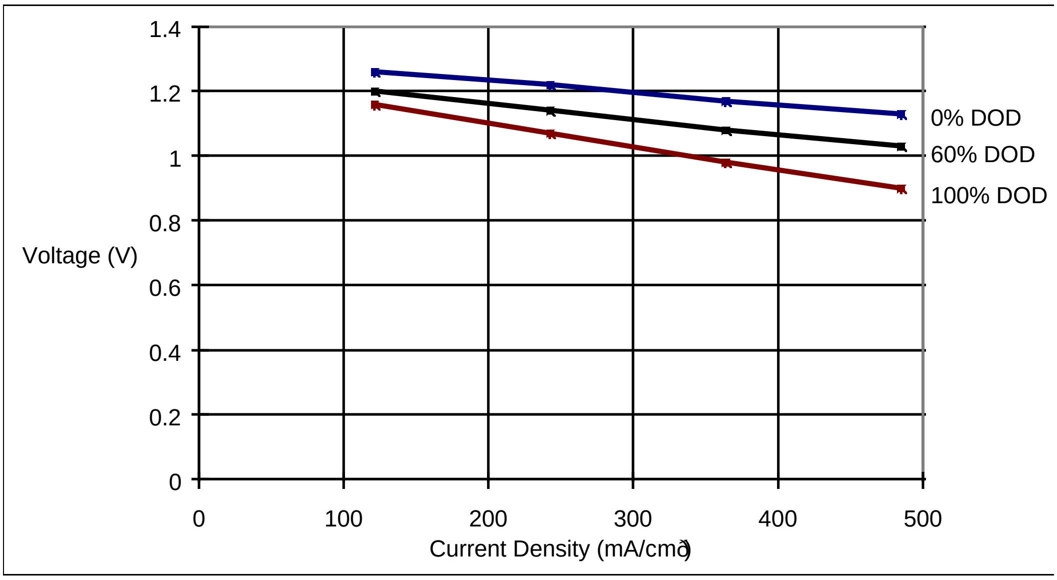

FIGURE 4. VOLTAGE VS. CURRENT DENSITY CURVES

Scale-up

Scale-up of the zinc-oxygen torpedo cell from the evaluation cell of Phase I was completed in the first few months of Phase II. Active cell area was increased fourfold. At the same time, we greatly reduced parasitic area previously used for contacts and stack closure elements.

51-Cell Stacks

As of the time of the writing of this paper, the first of the three 51-cell stacks was to be assembled in Jerusalem and shipped to STN ATLAS in Wedel for discharge, as the discharge requirements of over 600 A and over 70 V (at open circuit) precluded using EFL’s existing battery testing equipment.

CONCLUSIONS

It is anticipated that a decision will be made later in 1997 as to whether development of this version of the zinc-oxygen torpedo battery will continue. If so, then pre-production prototypes of the battery could be ready within about 3 years.

Long-term development targets for the heavyweight torpedo cell stack include:

- power densities of up to 500 W/kg and 1000 W/liter continuous power at end of discharge (not including peripherals)
- energy densities of 175 Wh/kg and 350 Wh/liter (not including peripherals)
- cell stack activation within three seconds
- ten-year shelf life (dry)

High Energy Applications

The zinc-oxygen battery developed by EFL appears to be easily applicable to number of similar applications. In addition to long shelf life as a dry, reserve battery, the technology boasts high energy and/or power densities.

As we stated earlier, this zinc-oxygen cell stack design, as developed for the heavyweight torpedo, is optimized for high power. Other underwater propulsion applications for zinc-oxygen batteries will require more energy and less power.

The zinc-oxygen technology allows for a trade-off between power and energy densities by changing the relative values of the zinc mass and the oxygen cathode area. For example, employing thicker zinc anodes, i.e., anodes with greater zinc mass per plate, will result in higher energy densities but lower power densities for the overall stack.

Table 2 shows projections for energy and power densities for both a high-power version and a high-energy version of the zinc-oxygen battery system.

	Specific Energy (Wh/kg)	**Energy Density (Wh/l)**	**Continuous power to 100% DOD (W/l)**
High-Power Cell Stack ***(status today)***	150	260	710
High-Power Cell Stack ***(projected)***	175	350	1,000
High-Power Total System ***(projected)***	135	300	850
High-Energy Total System ***(estimate)***	180	400	600

TABLE 2. ENERGY AND POWER DENSITY PROJECTIONS