Aluminum Energy Semi-Fuel Cell Systems For Underwater Applications: The State Of The Art And The Way Ahead

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Abstract - **Fuel Cell Technologies Ltd. (FCT) is currently developing high endurance Aluminum Energy (AE) semi-fuel cell systems for various underwater applications. One system under development is a novel Aluminum/Hydrogen-Peroxide pressure-compensated semi-fuel cell system that will deliver 80 kWh at 300 W for a deep-sea autonomous underwater vehicle (AUV). This will permit over 11 days of uninterrupted full-power operation without a pressure hull.**

A second system under development is an aluminum energy system for a diver heating application. This underwater co-generation fuel cell system will provide both electrical power and heat to divers while decompressing during their ascent from deep cold-water dives. The proof of concept of this system completed pool trials in March 2001, and FCT is now developing the Advanced Development Model for field trials.

This paper will summarize the principle issues associated with the design and proof of these high performance underwater energy systems and will report on the current status of system evolution as well as the planned way ahead for this technology.

I. INTRODUCTION

Fuel Cell Technologies Ltd. has been developing underwater energy systems for over 13 years, and has logged over 550 hours of underwater operation of their proprietary aluminum energy semi-fuel cell systems.

FCT is currently focussing on increasing the neutrally-buoyant energy density of the AE underwater energy systems to quadruple that available from expensive silver-zinc batteries. FCT has to date put to sea two systems with a neutrally-buoyant gravimetric energy density in excess of 200 Wh/kg. The FCT current target deliverable is a system with an energy density of up to 396 Wh/kg (510 Wh/l), which would provide over 10 times the neutrally-buoyant endurance of an equivalent Lead-Acid or Ni-Cd system, 4 times that of a Silver-Zinc system and 3 times that of a Lithium-Ion system, all in a 21-inch diameter non-pressure-hull AUV, such as the Bluefin Robotics Odyssey AUV.

The FCT AE technology is based on the semi-fuel cell concept, which combines features of both batteries and fuel cells. This technology offers superior energy density, which is paramount for underwater applications.

For underwater applications, fuel cells require the on-board storage of both fuel and oxidant, and require additional complicated systems for water and/or thermal management.

In general, batteries offer a much simpler solution to underwater energy density, but at the cost of reduced endurance and, for higher endurances, significant expense and complex recharging.

AE technology offers much higher energy density than secondary batteries. One reason for this is that the AE technology has much higher theoretical values for energy density. For instance, Silver-Zinc batteries store and release energy using the following reaction:

$$Zn + AgO \Rightarrow ZnO + Ag$$

This releases 2 electrons at a cell voltage of 1.9 V, and equates to a theoretical energy density of

524 Wh/kg.

Similarly, Lithium-Ion uses the following reaction:

$$LiC_6 + CoO_2 \Rightarrow C_6 + LiCoO_2$$

This releases 1 electron at a cell voltage of 4.2 V, and equates to a theoretical energy density of

663 Wh/kg[1]**.**

On the other hand, Aluminum/Oxygen systems use the following reaction:

$$2\,Al + 3/2\,O_2 + 3\,H_2O \Rightarrow 2\,Al(OH)_3$$

This releases 6 electrons at a cell voltage of 2.8 V, and equates to a theoretical energy density of

2,866 Wh/kg.

In addition, the Aluminum/Hydrogen Peroxide system uses the following reaction:

$$2\,Al + 3\,H_2O_2 \Rightarrow 2\,Al(OH)_3$$

This releases 6 electrons at a cell voltage of 3.3 V, and equates to a theoretical energy density of

3,418 Wh/kg.

While it is recognized that practical systems can never achieve this theoretical performance, the above theoretical limits illustrate that the AE technology has much more scope to increase practical energy densities.

To further illustrate the performance advantage of AE systems, the following table compares the gravimetric, volumetric and neutrally-buoyant energy densities of various underwater energy technologies. In addition, the endurance of a representative 40-inch length section of a 21-inch diameter 1kW deep-rated system is shown. It should be noted that the "**Al/H_2O_2 2001**" values are derived from the most recent sea trials in an Odyssey-class AUV in the summer of 2001. The "*Al/H_2O_2 Target*" values are the target goals for the developmental program currently underway at FCT.

[1] **Note:** This is for the most common electrode materials. Research is underway to use exotic electrode materials, which could increase the theoretical energy density to over 1,000 Wh/kg.

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TABLE 1 Comparison of representative AUV				
Representative Technologies	Energy Density 40 kWh, 1kW, 4500m depth rating, 21-inch diameter			Endurance of 40" length section
	Wh/kg	Wh/l	Neutrally Buoyant	hrs
Lead-Acid/Ni-Cd	35	100	23	5
Silver-Zinc	120	185	80	19
Lithium-Ion	115	270	95	17
Al/H_2O_2 2001	**245**	**294**	**208**	**42**
Al/H_2O_2 Target	*396*	*510*	*290*	*53*

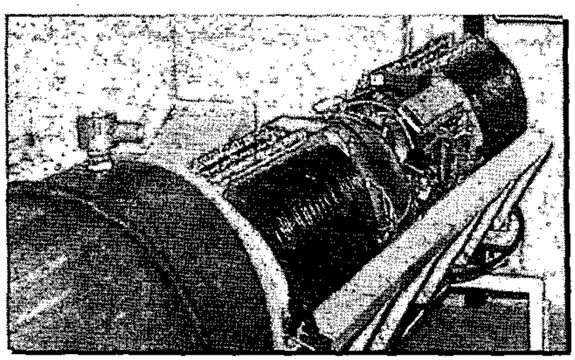
II. AUV ENERGY SYSTEMS

To date, Fuel Cell Technologies has put to sea four aluminum energy systems, all using variations of oxygen supply, wet or dry hulls and electrolyte management systems.

A. *Existing AUV Systems*

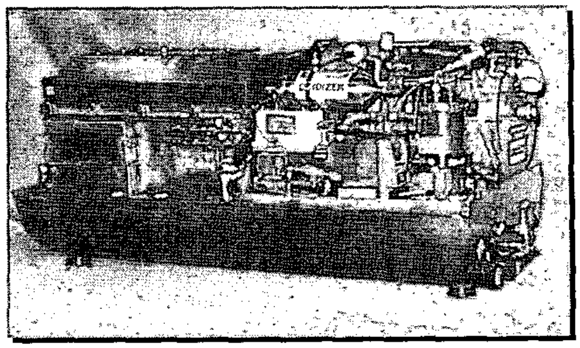
- **XP-21**

The US Navy XP-21 AUV was the first AUV worldwide to complete sea trials (1993) of an Aluminum Energy system. This 21 inch AUV was fitted with a 100 kWh @ 2.5kW aluminum energy system that used high pressure oxygen (4,000 psig) and an un-pumped solids-managed electrolyte[1,2]. Although designed for an energy density of 200 Wh/litre, this early system did not achieve the desired energy density due to thermal control problems with the un-pumped cells.



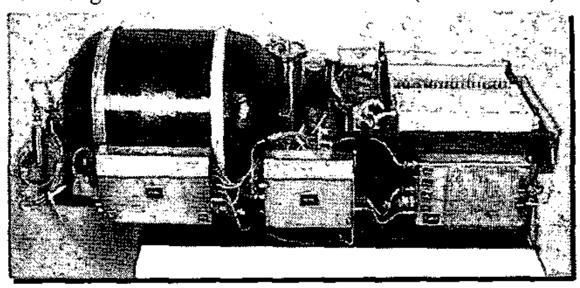
- **ARCS-3**

The Canadian Navy Autonomous Remote Controlled Submersible (ARCS) AUV underwent sea trials in June 1994 with an FCT Aluminum Energy system. This 27 inch AUV was fitted with a 50 kWh @ 1.7kW system that used decomposed 50% hydrogen peroxide as the oxidant and a pumped solids-free electrolyte[3]. It achieved a neutral energy density of 140 Wh/kg and a run duration of 27 hours. (compared to 6 hours on Ni-Cd batteries).



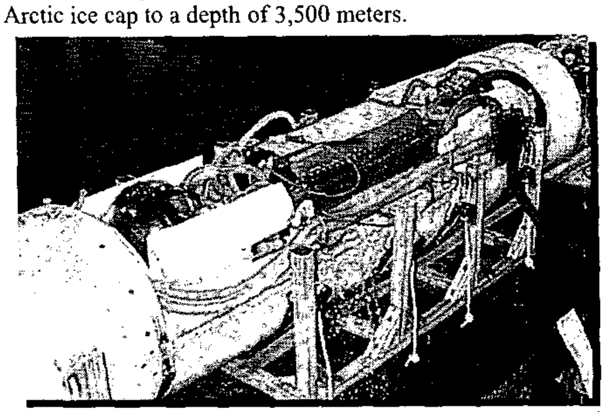
- **ARCS-4**

An upgraded system was developed for the ARCS AUV. This system underwent sea trials March 1997. The AUV was fitted with a 100 kWh @ 2.3kW system that used high pressure oxygen (4,000 psig) and a pumped solids-managed electrolyte. It achieved a neutrally-buoyant energy density of 210 Wh/kg and a run duration of 56 hours (final sea trial).



- **ALTEX**

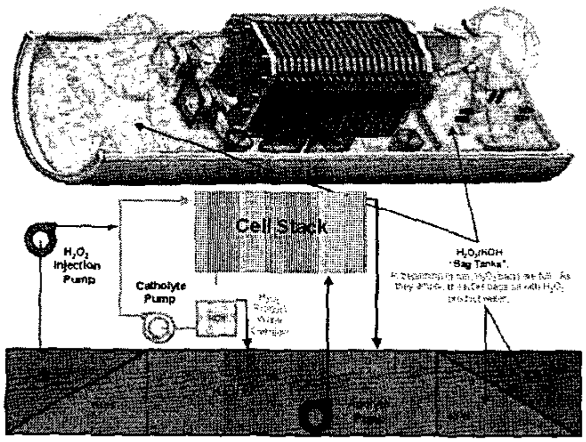
The fourth AUV energy system that FCT has developed is a Very-High Endurance Energy System for the Atlantic Layer Tracking Experiment (ALTEX) AUV. This project, coordinated by the Monterey Bay Aquarium Research Institute, is part of the National Ocean Partnership Program that measures the effects of global warming. The ALTEX AUV is designed to navigate 1,500 kilometres under the Arctic ice cap to a depth of 3,500 meters.



To meet the extreme energy requirements for this application, FCT has designed a novel Aluminum/Hydrogen-Peroxide system to deliver 80 kWhrs at 300 W. This will permit over 11 days of uninterrupted full-power operation of the AUV, independent of operational depth.

The ALTEX Energy System is based on FCT's aluminum/hydrogen-peroxide pressure-compensated technology. As such, it utilizes the dual KOH electrolyte loop (catholyte and anolyte) and 50% hydrogen-peroxide as the oxygen source for the semi-fuel cell.

The image below illustrates the layout of the ALTEX Energy System. The 21-cell stack is centrally located over a hard centre-tank. At each end of the section, a pair of bag-tanks are fitted. At the beginning of the mission, the H_2O_2 bags are filled and the KOH bags are empty. As the system provides power, the H_2O_2 is consumed and the resultant product water from the catholyte is returned to the centre tank, which is connected to the KOH bag tanks on both ends.



The system currently is housed within a 66-inch section of the 21-inch diameter AUV. In addition to the stack and tanks, there are two 10-inch Benthos spheres that house start-up/recovery batteries and all computer controls.

B. *Experience To Date*

To date, FCT has logged over 550 hours of underwater operation of its AUV energy systems, with 190 hours sea trials with the ARCS AUV, 290 hours pool trials of the ALTEX Energy System and 85 hours sea trials with the ALTEX AUV.

An unavoidable part of the development process of high energy-dense systems is that mission interruptions during sea trials do occur. However, one factor that has consistently impacted on sea trials is that the AUVs themselves were not yet designed to run for such extended periods. For instance, the final ARCS sea trial had 7 mission interruptions, of which only 2 were caused by the energy system[4]. Conversely, the FCT ALTEX Pool trials ran for 170 and 120 hours with much fewer interruptions[5]. This problem will diminish as AUV designs mature for longer duration missions, which will be enabled by the high energy density AE Systems.

C. *System Evolution*

Fig. 1 illustrates the evolution of the underwater AE technology. The original ARCS 4 system was an oxygen-based pressure-hull system which had a gravimetric effectiveness[2] of 5.4 kg per Wh. In the evolution of the ALTEX system from a gaseous oxygen, pressure hull system to a hydrogen-peroxide, pressure compensated system, one can see that the Auxiliary[3] and Electrolyte Gravimetric Effectiveness improves significantly, at the cost of a reduction in Oxidant Gravimetric Effectiveness. This results in an overall improvement in system Gravimetric Effectiveness (down to 4.8 kg per Wh), with added capability (i.e. deep depth capability). The planned evolution to next generation systems (SF-40 and SM-80[4]) illustrate the way ahead for overall system improvement to the goal of 3.7 kg per Wh, which equates to 4 times that of an equivalent silver-zinc system.

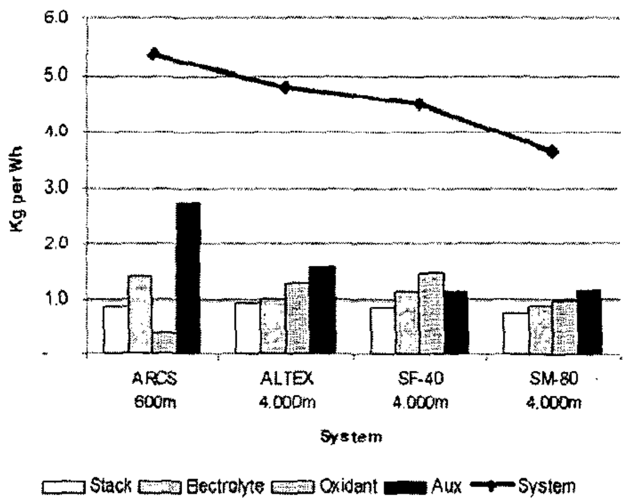


Fig.1. Gravimetric Effectiveness Progression

It should be noted that the above energy densities do NOT include hull structures. The ARCS system used a pressure hull, rated to 600 meters. The ALTEX, SF-40 and SM-80 systems require only a flooded non-pressure-hull.

Fig. 2 illustrates the impact on neutrally buoyant energy density and depth rating for pressure compensated systems. It shows that, due to the increasing density of floatation foam as depth rating increases, more foam is required the deeper the AUV must operate, which increases the weight and volume of the energy section, thus reducing its energy density.

2 Gravimetric Effectiveness being defined as the weight of a particular sub-system required to generate 1 kilowatt-hour.

3 Auxiliary includes reactant containment (such as pressure bottles or peroxide tanks), pumps, electronics, floatation foam (as required) and all other support systems.

4 SF-40 is a 40 kWh solids free system, and the SM-80 is a 80 kWh solids managed system.

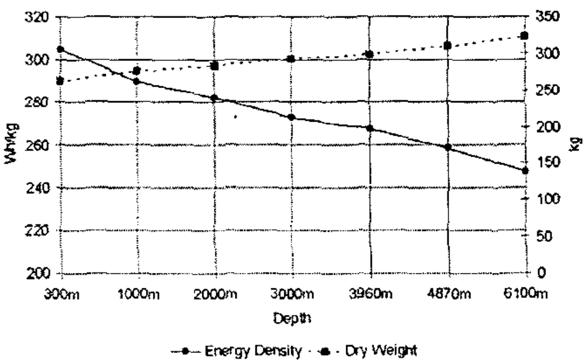


Fig. 2. Neutrally Buoyant Energy Density

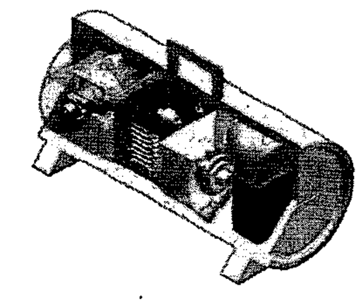
III. DIVER HEATING

The other underwater energy system that FCT is actively developing is based on the aluminum-oxygen technology. It is a co-generation system that delivers both electricity and heat to divers while they decompress in cold waters.

Military diving missions, such as clearing anti-ship mines, often have to be done in cold, icy waters like the North Atlantic. These dives are frequently done at depths that require divers to be exposed to long phases of decompression throughout the ascent following the main mission activities. During decompression, which can last for hours, stationary divers produce minimal body heat. Divers can experience at best, discomfort, and at worst, hypothermia.

The Canadian Department of National Defence has contracted the development of the world's first dry suit diver supplemental heating system. Utilizing a compact heater and efficient closed-circuit technology, the Diver Heating System produces enough heat to keep a completely stationary diver warm, dry and productive even in the coldest water. The electrical power is originally supplied from the surface from 4 automotive 12 V Lead-Acid batteries and power cables. The current system can provide power to the diver for 3 hours.

FCT has been contracted to develop a submerged energy system that will eliminate the requirement for surface batteries and will deliver a compact submersible energy system that will be positioned with the diver at their compression depths and provide both heat and power to the diver(s) for up to 6 hours.



The system is 12 inches in diameter, 24 inches in length and will provide 3 kWh (1.5 kWh_e and 1.5 kWh_{th}) to diver(s) for up to 6 hours cumulatively (12 hours at a 50% duty cycle). It is being designed for ease of use, rapid recharge (10 minutes), hands-off neutralization of the electrolyte and cost effective life cycle costs. Field Trials are scheduled for Q4 2002.

IV. WAY AHEAD

As identified in the "Experience To Date" section, interruptions during sea trials have a detrimental effect on energy section performance. To address this problem, the current phase of system refinement will be undertaken at the FCT facilities, utilizing the FCT Test Pool. The latest program has scheduled 4 progressive pool tests of up to 12 days each to improve the reliability of the energy section so that when the next sea trials are scheduled with an AUV, the FCT system will be shown to be ready for commercialization.

With respect to the Diver Heating system, the production phase of the system is already being developed to utilize the results of the field trials and finalize the production design of the system for commercialization in 2003.

ACKNOWLEDGEMENT

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