Aluminum Fuel Cell Power Sources for Long Range Unmanned Underwater Vehicles

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Abstract-Aluminum fuel cell power sources have been developed by Alupower to satisfy a range of UUV configurations and mission requirements. Specifically, for long range, low power missions the fuel cell reaction product, aluminum hydroxide, is allowed to precipitate (solids managed) in order to maximize energy density. In order to meet the requirements for higher power missions, the power source is designed such that the aluminum hydroxide product remains dissolved in the electrolyte (solids free).

To meet the high energy density requirement, a solids managed power source, designed to provide 1.25 kW and 50 kWh, has recently been tested, at sea, in Applied Remote Technology's (ART) XP-21 test platform. Using compressed oxygen the energy density of the total system was 260 Wh/l which would increase to 320 Wh/l using liquid oxygen.

A system using a solids free power source will be tested in the Advanced Research Canadian Submersible (ARCS) built by International Submarine Engineering (ISE). The maximum power of this system will be 1.7 kW and the energy density 120 Wh/l. This system decomposes 50% hydrogen peroxide to provide the oxidant. Variants of this system will be the building block for future higher power density systems.

The key to the success of aluminum fuel cell power sources has been the development and production of an anode alloy which operates with high efficiency at low current density. This means that cell design is simplified and that there is no requirement to mechanically maintain a constant cell gap. The low level of hydrogen produced using this anode alloy is easily recombined to water using a catalytic converter.

Work is now focussed on improving system reliability, reducing operating cost and the development of higher power density systems.

INTRODUCTION

The development of aluminum fuel cell power source systems has been promoted by the US Navy after the system was recommended by a series of power source comparative performance studies for long range UUV missions. The eventual goal is to place a power source into a UUV that can be launched and recovered from a submarine [1-4]. The original ARPA target specified a need for high energy density at low power density. Alupower addressed this technical objective through the development of a power source for ART's XP-21 UUV test platform. With time, the US Navy power source requirements changed in emphasis to higher power density with an energy density sufficient to perform a 24 to 30 hour mission [5,6]. This new target was identified as the volume available for the power source was reduced from the original specification of 105-inches in a 44-inch diameter to a 4-foot length in a 21-inch diameter vehicle. This reduction was required in order to fit a full suite of sonar and other sensors as otherwise the total vehicle length increases to a point where launch and recovery is difficult. This change in emphasis has a significant impact on aluminum fuel cell development. In order to achieve the higher power density, a change in technology is required to the solids free option. This approach has been initiated with the development of the power source for the ARCS experimental vehicle. The initial UUV power source performance target as proposed by ARPA and a more recent target for Submarine Offboard Mine Search System (SOMSS) as identified by the Applied Physics Laboratory of Johns Hopkins University are shown in a Ragone plot in Fig. 1.

The SOMSS requirement of 4 kW and 96 kWh is such a difficult target that a more achievable target requirement has been adopted by Alupower for a power source that can provide 50 kWh at 3 kW in a

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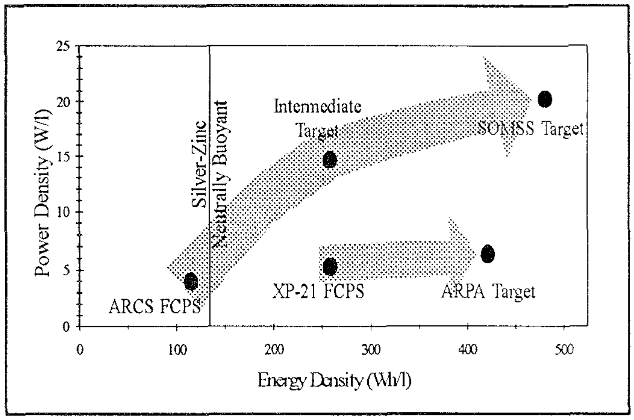

Fig.1. UUV power source performance targets shown as a volumetric Ragone plot.

hull section length of 4 feet and 21 inches in external diameter.

In summary, Alupower has undertaken two development programs which were designed to test two different variants of the aluminum fuel cell power source technology based on solids management and solids free versions of the technology. The first of these programs was completed at the end of 1993 with sea trials of a power source system in the XP-21 UUV test platform [7,8]. The second of these programs will be completed in the middle of 1994 with the sea trials of a power source in the ARCS experimental vehicle owned by the Canadian Department of Defence [9]. The present paper will summarize these two development programs and will then discuss development options for both systems against the present performance targets.

CORE TECHNOLOGY

All of Alupower's aluminum fuel cell power sources using alkaline electrolytes use anodes which are cast from super pure aluminum with low level alloying additions of tin and magnesium [10]. These additions together with a low level of tin dissolved as stannate ions in the electrolyte stabilize the aluminum anode such that only a low level of hydrogen is evolved from the power source cell either under load or at open circuit. The efficiency of the aluminum anode is progressively reduced as the level of iron in the metal increases. Iron is present as an impurity in super pure aluminum and the more iron that can be tolerated the lower the grade of superpurity aluminum that can be used which has a significant cost benefit. Recently Alupower has developed an anode fabrication practise that enables the use of superpurity aluminum at $3.1k/tonne rather than the previous cost of $6.7k/tonne which significantly improves the cost effectiveness of aluminum as a fuel. Presently, commercial grade aluminum sells for $1.2k/tonne. Fabrication costs have to be added to these figures, which are for the base metal only.

Alupower's low cost oxygen electrode technology has been established for several years based on the use of silver as an oxygen reduction catalyst [11]. A cobalt catalyzed version of the Alupower cathode has recently been developed which increases cell voltage by 100 mV.

Potassium hydroxide is the preferred electrolyte as it has a higher conductivity and aluminum solubility than sodium hydroxide. The electrolyte concentration used depends on whether the system is run "solids-free" or with solids precipitation. Solids-free systems use 8M KOH (34%) electrolyte which has a discharge capacity of 500 Ah/l as this electrolyte has a high solubility for aluminum. Where solids precipitation is required to increase the electrolyte discharge capacity to 800 or even a 1000 Ah/l, then a 4.5M KOH (22%) electrolyte is used. In both cases, the electrolyte contains an addition of 0.01M sodium stannate which improves anode efficiency, particularly at low operating current densities.

As with most "fuel cell" type power sources the electrolyte discharge capacity is the most significant parameter that determines the overall energy density. The cell stack weight and volume is dominated by the electrolyte weight and volume with cell hardware and the aluminum anode fuel constituting only a relatively minor part of the total.

Alupower has developed two basic cell types that can be used as the power source building blocks. Both designs feature a solid anode opposed by two oxygen cathodes that are secured to the cell walls. In the first design, which was initially used for a land-based reserve power unit, electrolyte is pumped up between the anode and the cathode from the bottom of the cell, leaves the cell via an overflow weir at the top of the cell and is returned to a common electrolyte sump [12]. In the second design, each cell is a separate unit and electrolyte flow is by natural convection. Reaction products are returned to the common sump in the first design whereas in the second design they fall to a sump in the bottom of each cell. Both cell types can be run either solids free or with solids management. The second type of self contained cell has become known as the self-managing cell and was used for the solids managed low power, high energy XP-21 power source development program [7]. The present ARCS power source, under development, uses the pumped, common sump cell design and operates solids free.

OXYGEN SUPPLY

The most compact form of oxygen storage is liquid oxygen, the use of which is widely accepted in Europe for submarine applications. However, in North America, this is not the case and significant effort has been expended on alternative storage technologies like high pressure oxygen gas, hydrogen peroxide and solid oxygen candles that are burnt to release oxygen. Alupower has developed oxygen delivery systems based on the use of either 30 MPa (4000 psig) containment spheres or 50 % hydrogen peroxide which is decomposed to oxygen, water and water vapour [9]. In both cases, the oxygen is regulated to a low pressure to be supplied as required to the cell stack.

Oxygen is also supplied to the hull atmosphere via a bleed port in the cell stack. This oxygen is used to remove hydrogen from the hull atmosphere by catalytic combination to form water.

In addition to an oxygen supply system, the aluminum oxygen fuel cell power source requires a thermal management system to maintain the electrolyte temperature in the range 55-65°C in the cell gap between the anode and the cathode and a control computer to monitor and control system operation. These sub-systems have been described in other publications [7-9].

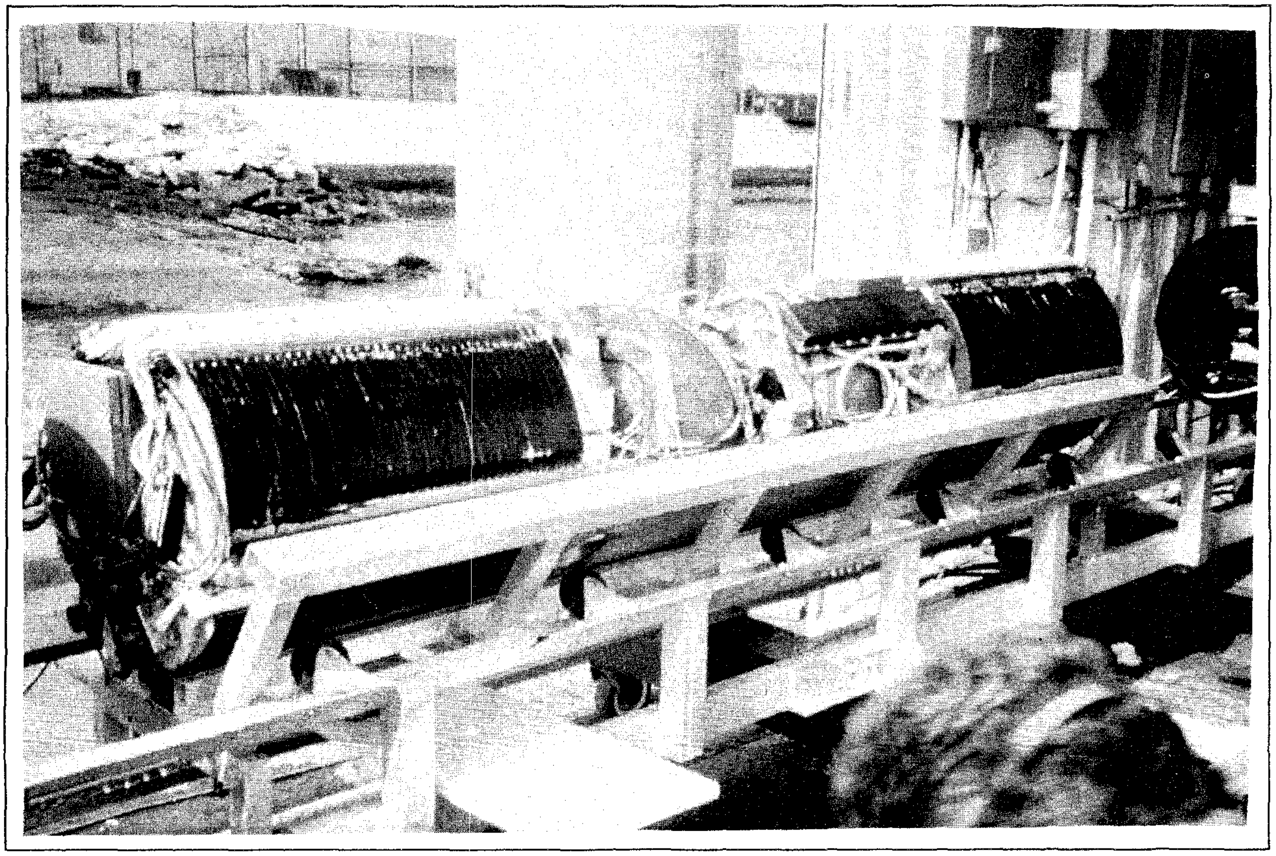

Fig. 2. Photograph of XP-21 FCPS.

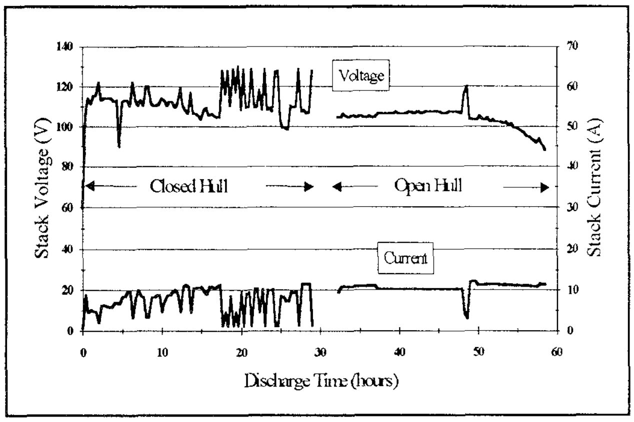

Fig. 3. 76-cell discharge test in the XP-21.

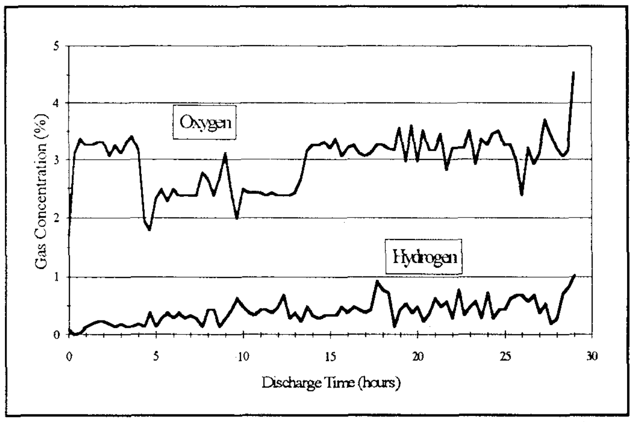

Fig. 5. Gas concentration in hull during XP-21 FCPS sea trials.

IN-VEHICLE TESTING

The complete aluminum fuel cell power source, constructed using self-managing cells, is shown in Fig. 2 prior to insertion in the XP-21 test platform for sea trials. Two 76-cell stacks each with its own oxygen sphere were loaded and were tested sequentially. This was because the system was initially designed to provide 2.5 kW and 100 kWh in an 88-inch long power source section. With the changing requirements, the opportunity was taken, with support funding from ARPA, to test the power source in two halves with each half being more representative of a future complete system. Thus, the power and energy objectives of this work were 1.25 kW and 50 kWh, respectively, in a 44-inch long section.

The stack voltage and current trace for the first stack, which was filled with 4.5M KOH and run at a nominal 1.25 kW load, are shown in Fig. 3 which shows 30 hours of closed hull operation, followed by 30 hours of open hull testing with the vehicle out of the water. The average cell gap electrolyte temperature for the complete run is shown in Fig. 4. Periods when the temperature drops below 60°C are when the power source was either delivering low power or was at open circuit and there was not sufficient heat being generated to maintain electrolyte temperature. The oxygen and hydrogen concentration variations in the hull atmosphere during the closed hull part of the discharge are shown in Fig. 5, showing capability to control the composition of the atmosphere in a closed hull. Approximately 22 kWh of discharge was achieved with the vehicle operating in the water and a further 28 kWh with the vehicle out of the water yielding a total of 50 kWh. The average power level of operation was 0.86 kW which gives a system energy density of 260 Wh/l at a power density of 4.4 W/l. This is the XP-21 performance plotted in Fig. 1.

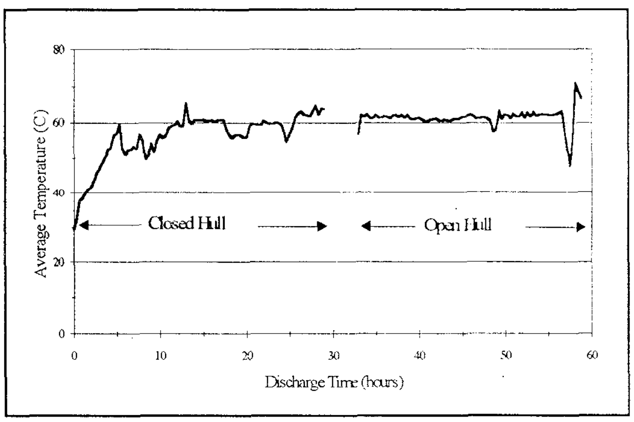

Fig. 4. Average electrolyte temperature in cell gap during XP-21 FCPS discharge.

The second 76-cell stack was filled with 8M KOH and discharged at a higher power level (2.5 kW nominal) with the vehicle out of the water and the hull open. This open hull configuration was used because at the high power level the hull mounted heat exchangers could not accommodate the higher thermal load. This stack delivered 31 kWh of energy at an average power level of 1.0 kW which translates to a system energy density of 160 Wh/l at a power density of 5.3 W/l. The rated capacity of 50 kWh was not achieved due to long periods of open circuit operation during the test.

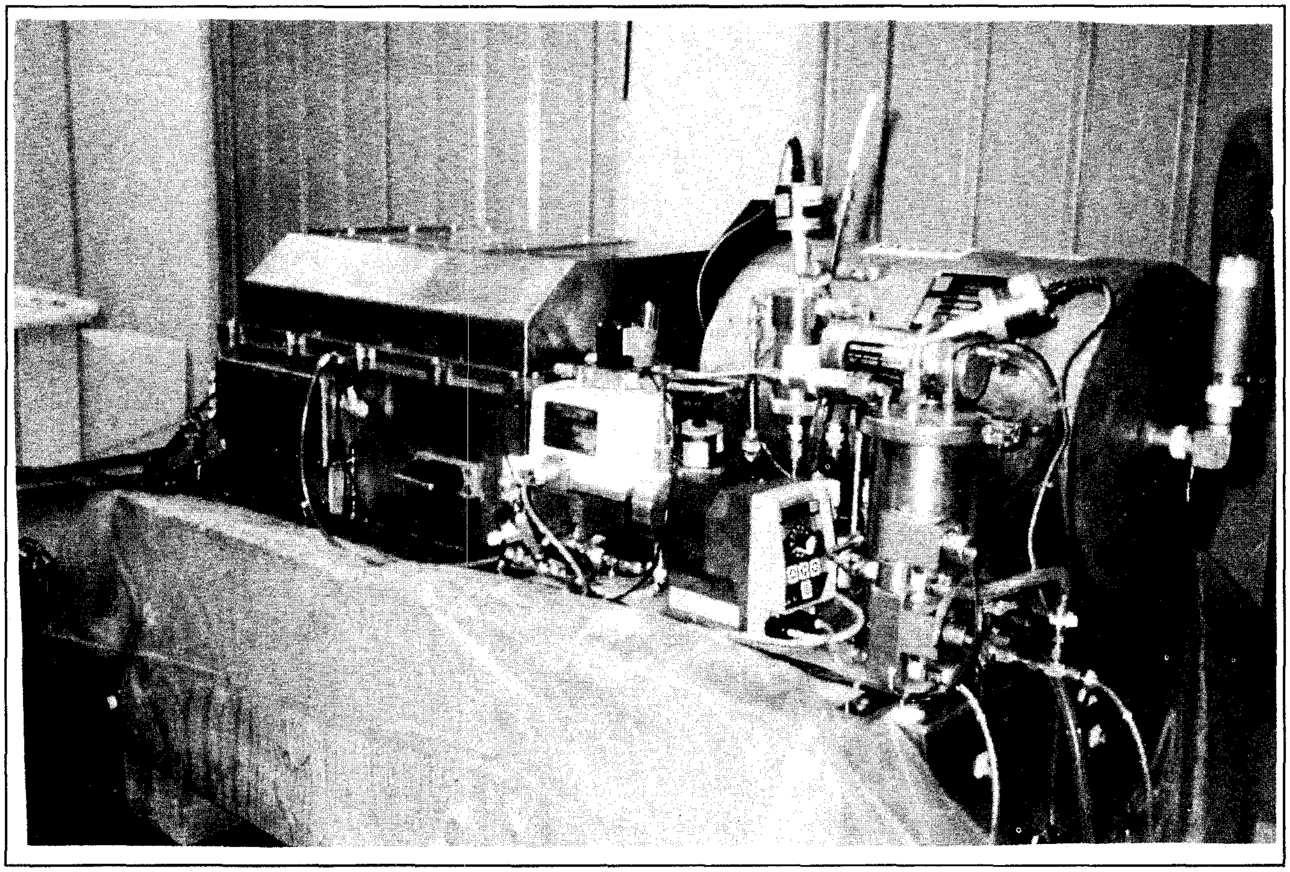

Fig. 6. Photograph of ARCS power source.

BENCH TESTING

The aluminum fuel cell power source based on the pumped cell is shown in Fig. 6 prior to insertion in the ARCS power source section and bench testing. The cell stack is comprised of two stacks of 22 cells that are connected in series. The system is designed to provide 1.7 kW of power for 30 hours (50 kWh) with a voltage range of 52.5 to 63.5 V. This translates to a projected energy density of 122 Wh/l at a power density of 4.1 W/l as the volume available in the 27-inch external diameter power source section is 418 litres. A series of bench tests will be required to achieve system optimization.

DEVELOPMENT OPTIONS

The two aluminum fuel cell underwater vehicle power sources under development have both been of low power density. Since the power density requirement has significantly increased, a series of development options have been examined ranging from modest improvements of the current power source types through to more radical solutions involving sequential mixing of electrolyte with seawater and the expulsion of reaction products back into the sea. The range of development options is shown in Table I together with an approximate time schedule which would be required to complete the developments.

Improvements to the system tested on the XP-21 vehicle to improve energy density significantly can be achieved through improved cell design, use of the cobalt catalyzed cathode and the use of liquid oxygen storage. These improvements offer the potential to increase endurance to more than three times that of a silver-zinc battery in a neutrally buoyant power source section, however, they will not significantly improve power density.

TABLE I

ALUMINUM FUEL CELL POWER SOURCE DEVELOPMENT OPTIONS

Option	Schedule (Months)	Power (kW)	Energy (kWh)
Improved SMC[a]	8	1.25	50
Pumped Solids Free[b]	12	3.0	60
Pumped Solids Managed[c]	24	2.0	80
Pumped Open-Cycle[d]	36	4.0	96
Pumped Open-cycle Solids[e]	48	4.0	96

[a] XP-21 aluminum FCPS with improved cell design.
[b] ARCS aluminum FCPS in 21-inch vehicle with 50 MPa (7000 psig) oxygen.
[c] ARCS aluminum FCPS with solids management and 50 MPa (7000 psig) oxygen.
[d] Solids-free open cycle system.
[e] Open cycle system with waste neutralisation.

A much more interesting approach is to take the aluminum power source technology under development for the ARCS vehicle and to modify it for a 21-inch diameter vehicle. Using our system performance computer model [13], the voltage performance of such

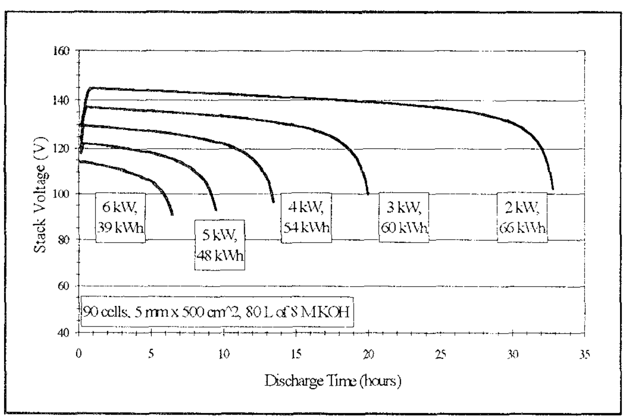

Fig. 7. Modelled performance of solids free power source in a 48-inch long, 21-inch diameter section.

a system as a function of discharge power level can be estimated, as shown in Fig. 7. The oxygen supply used for this exercise was a 16-inch diameter composite sphere capable of operating at pressures up to 50 MPa (7000 psig). This system comes closer to the intermediate power and energy density targets and is easier to operate and refuel than the unpumped individual cell system.

The development of a pumped system with solids management is already being funded by ARPA who have a contract with Eltech/Loral to demonstrate a brass board power source for a 44-inch diameter vehicle in the second half of 1994 [14]. This program is then scheduled to have a power source at sea in 1995-1996 in ARPA's 44-inch diameter UUV built by Draper Labs. The Canadian DND are funding Alupower to add solids management to the solids-free ARCS power source although their long term aim is to have an aluminum fuel cell power source technology to compete with a hydrogen fuel cell power source for the air-independent propulsion of conventional diesel electric submarines [15]. However the combination of increased power density and effective solids management is difficult to achieve as this is always controlled by the solid reaction product growth kinetics [16].

The sequential electrolyte formulation option involving mixing of seawater with solid NaOH to produce electrolyte as required has the potential to achieve the required energy and power density target for the SOMSS mission in a 48-inch long power source section. In the cases modelled, the oxygen was provided from a 50 MPa (7000 psig) sphere rather than from liquid oxygen. Discharging used electrolyte overboard results in only marginally increased aluminum concentrations of 1.2×10^{-5} mg/l against a 0.01-1 mg/l background aluminum concentration in seawater. It is also possible to develop an open system of this type with solids management and waste product neutralization, as shown in Table I.

The most straightforward and lowest risk development route to achieve the required power source performance objectives is through a pumped solids free system followed by the open cycle version of this same technology, as shown in Fig. 8. This development route builds on the ARCS power source development and is synergistic with work at NUWC where aluminum silver oxide batteries have been developed

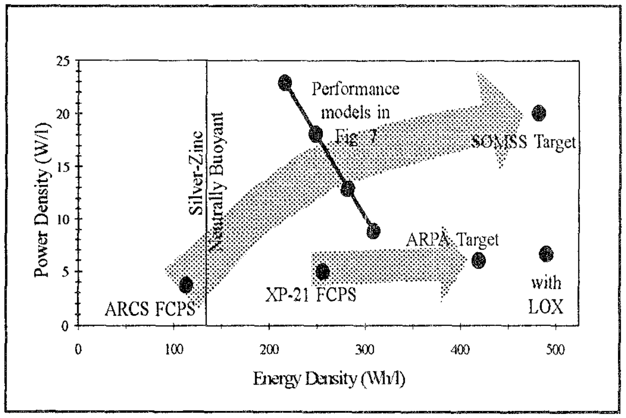

Fig. 8. UUV power source projected power shown as a volumetric Ragone plot.

with a similar electrolyte mixing system [17]. Fig. 8 also shows how the XP-21 power source can be developed to exceed the original ARPA target with the use of an improved cell design and liquid oxygen storage.

Operating Costs

The following table (Table II) compares the operating cost of various power source systems fitted in a 48-inch long, 21-inch external diameter vehicle section. Costs have been arbitrarily averaged over a hundred missions which is seen as the likely maximum service life of an individual vehicle/power source combination. The main competition is between the aluminum fuel cell power source, silver zinc batteries and lithium thionyl chloride batteries. Cost and operational safety factors mitigate against the use of lithium thionyl chloride batteries and the operating costs of silver zinc batteries are very dependent on the cycle life obtained. Hydrogen fuel cell power sources are seen as a very unlikely option for underwater vehicles of 21-inch or even 26-inch in diameter due to the difficulty in providing compact oxygen and hydrogen reactant storage. In the future, silver-metal hydride batteries, zinc-oxygen power sources and secondary lithium batteries may also be competitive options [18,19]. However, these systems are still under development as potential UUV power sources and it is not yet possible to estimate operating costs. In terms of stored energy, they will all be in

TABLE II

Power Source Cost Comparison

System	Stored Energy[a] (kWh)	Cycle Life[b]	Cost/kWh ($)
Lithium-Thionyl Chloride	80	Primary System	450
Aluminum-Oxygen	50-96[c]	Mechanically Refuelled	70
Silver-Zinc	25	20	100
Nickel-Cadmium	8	100	10
Lead-Acid	8	100	3

[a] Within the volume and mass constraints of a 48-inch long, 21-inch diameter power source section.
[b] For a maximum of one hundred vehicle missions.
[c] Depends on the aluminum power source option (see Table I).

the same range as silver zinc batteries but should offer increased cycle life and therefore operational cost reduction.

Summary

Two aluminum fuel cell power sources have been developed by Alupower for unmanned underwater vehicle propulsion based on solids management and solids free variants of the technology. The solids managed aluminum fuel cell power source will exceed the ARPA defined requirements in terms of energy and power density if liquid oxygen is used as the oxidant supply. For higher power density applications, the solids free aluminum fuel cell power source can provide 60 kWh at 3 kW from a 4-foot long section of a 21-inch diameter vehicle. Higher power density and energy density versions of both the solids managed and solids free aluminum fuel cell power source requires the development of open cycle systems. The life cycle costs of an aluminum fuel cell power source are lower than those of a silver-zinc battery averaged over 100 vehicle missions.

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