A MODULAR APPROACH TO UUV PROPULSION USING ALUMINUM/OXYGEN SEMI-FUEL CELLS

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Abstract - A modular approach to UUV power source design and construction is described. A range of output power for near term UUV's from 300 W to 5 kW and a range of energy capacity from 15 to 500 kWh is considered. The different power and energy requirements are all met by use of a modular aluminum-oxygen semi-fuel cell with essentially the same anode area but with a different anode thickness and number of cells. The control system and many other components can also be used for different applications maximising the economical use of resources and reducing development time. The approach is illustrated by several examples including the pre-production prototype design being built with a capacity of 2.0 kW and 100 kWh for the ARCS vehicle. Test results for the cell stack are reported and life cycle costs compared to conventional batteries.

1.0 INTRODUCTION

A wide variety of Unmanned Underwater Vehicles (UUVs) are under construction or in productive use in a number of countries. With very few exceptions it is true to say that the only constant is their intended use underwater, and all other parameters such as diameter, power, and energy capacity vary widely from one design to the next. In many cases the designs have been constrained by availability of components such as 21" diameter hull sections, or the desire to eventually launch a vehicle from a torpedo tube. In other cases the design energy capacity was determined by the availability of off-the-shelf batteries rather than the desirable capacity for the UUV mission.

It would be prohibitively expensive to design and develop to the required levels of reliability, a brand new power source optimised for every vehicle, regardless of the technology selected. In this paper the use of a modular design approach to the application of the aluminum-oxygen power source is considered for a variety of vehicles. This approach is proposed as a means of reducing the life cycle cost of a high energy capacity power source for UUVs.

The application and development of aluminum based power sources for UUVs is widely described in the literature [1,2,3,4,5] and only a brief description will be given here in Section 2.0.

2.0 SYSTEM DESCRIPTION

A simplified schematic of a generic Aluminum-Oxygen power source is shown in Figure 1. Essentially there are six major subsystems to consider. The overall system is comprised of a stack of energy producing cells containing solid aluminum anodes, a volume of potassium hydroxide electrolyte which is pumped through these cells, the means of storing and regulating the supply of oxygen to the cell stack, a hydrogen management system, a thermal control system, and an electronic control system. Each is outlined below.

Cell Stack

The cell stack consists of one or more sets of cells, generally between 12 and 150, wired in series or parallel to achieve the desired combination of power and stack voltage. Each individual cell is equipped with inlet and outlet passages for electrolyte and oxygen.

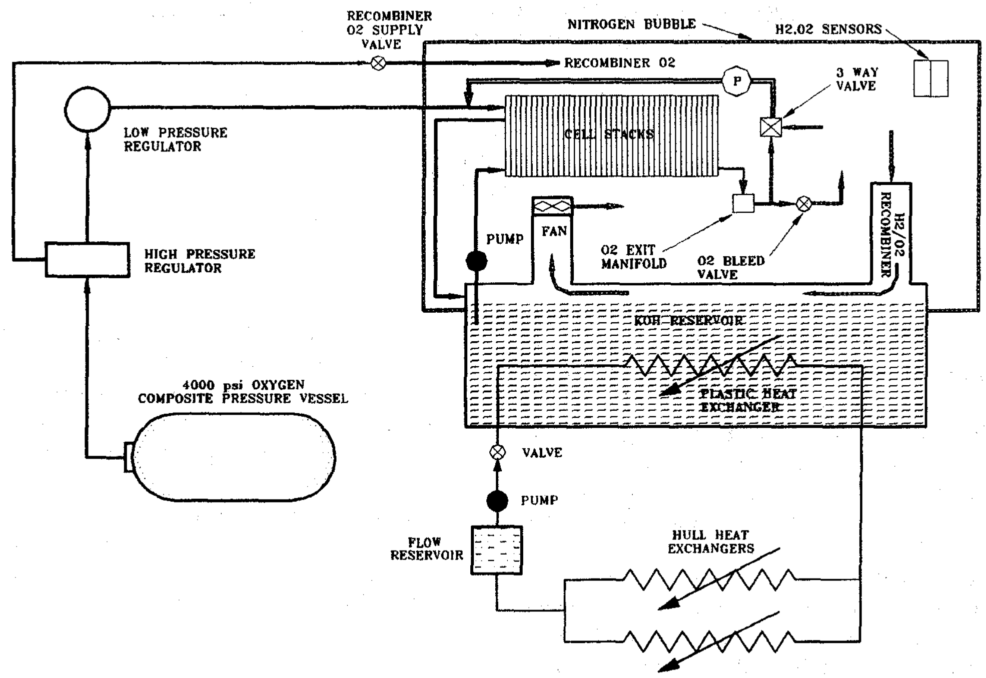

Figure 1 - Simplified Schematic of Aluminum-Oxygen Power Source

Manifolds are formed by openings in the cells, and the whole assembly is sealed with O-rings when clamped between rigid end plates. The anode area in the monopolar configuration used is approximately 600 cm^2, and in all production designs to date has not varied outside the range of 350 to 1000 cm^2. Operating current densities at nominal power output are usually selected to be in the range between 20 and 100 mA/cm^2.

Oxygen Storage and Supply

A detailed trade-off study performed under contract to the Canadian Department of National Defence[6] led to the selection of high pressure oxygen at 4000 psig in a composite wrapped pressure vessel as the means of oxidant storage. A high pressure regulator, followed by an electronically controlled proportioned valve supplies the stack at a constant pressure of a few inches of water. The selected system is extremely mass efficient, comparable in volume to 50% hydrogen peroxide and chlorate candle systems, and much simpler to operate than LOX.

Electrolyte Management System

The electrolyte management system consists of a reservoir, currently stainless steel, to contain the electrolyte, and a circulation pump. This relatively simple system is generally designed to be conformal to the vehicle hull. In general the electrolyte reservoir forms 40% of the volume of the total system, and also provides the mechanical structure integrating the other subsystems.

Hydrogen Management System

A small amount of hydrogen is produced at the anode by a corrosion reaction between the aluminum and the aqueous electrolyte. This is continuously removed by a recombiner system and a recirculating atmosphere of nitrogen. A small amount of oxygen is added to recombine with the hydrogen, forming water that is returned to the electrolyte reservoir. The nitrogen-containing enclosure around the cell stack, recombiner components and circulating loop are generally all designed to be conformal to the vehicle hull, thus increasing packing density.

Thermal Management System

This extremely simple system controls electrolyte temperature, typically at 60°C by means of an electrolyte to coolant heat exchanger, a recirculating loop of water based coolant, and conformal aluminum heat exchanger panels bonded to the inside of the hull.

Electronic Control System

The electronic control system and the software is generic and based on the use of industrial PCs and off-the-shelf electronic components such as power supplies and sensors. Typically up to 48 channels of data and control might be used, but this will be reduced as system control becomes less of an art and more of a science based on several successful sea trials [4].

Summary

The overall approach to making this system modular and reducing development effort is summarised in Table 1. The key elements absorbing the bulk of the development effort for a new application are the **cell stack** and the **oxygen storage system**. All other systems are readily optimised for a given application, are extremely simple in an engineering sense, and have no tooling or long lead time components.

Subsystem	Dependence on Power	Dependence on Energy	Development Required	Tooling/Long Lead Time	Impact on Life Cycle Cost	Comment
Cell Stack	Strong	Strong	Yes	Yes	Large	Key Subsystem for Modular Approach
Oxygen Storage & Supply	Weak	Strong	No	Yes	Small	Key Subsystem for Modular Approach
Electrolyte Mgt. System	Weak	Strong	No	No	Small	Easily Custom Designed to Fit Hull/Energy
Hydrogen Mgt. System	Strong	None	No	No	Small	Easily Reconfigured Recombiners are Modular
Thermal Mgt. System	Strong	None	No	Minor	Small	Easily Reconfigured Panels are Modular
Electronic Control System	None	None	No	No	Small	A Universal ECS is possible

Table 1: Rationale for System Modularity

3.0 APPLICATIONS

In order to examine this approach a broad range of vehicle types was studied, and four selected as being representative in terms of power, energy and size. They are shown below in Table 2. For comparison purposes it was assumed that all of these applications were to use compressed oxygen wherever possible. The use of a DC/DC converter to efficiently match the stack voltage to the vehicle voltage was also examined using FCT's proprietary system modelling program. A cell size of 600 cm^2, as used in the ARCS system currently under construction was selected for this work. The key points for each application are noted below.

REQUIREMENTS						OUTPUTS		
Vehicle	Typical Application	Power kW	Energy kWh	System Voltage V	Internal Diam. cm	No. of Cells	System Volume L	DC/DC Converter
Aurora	Scientific	0.3	16	120	40.6	12 [1]	67	Yes
Generic 21" Hull	Mine Warfare	2.0	40	120	47.0	32 [2]	212	Yes
ARCS	Bottom Survey Hydrographic	2.0	100	60	65.4	44 [1]	490	No
Theseus	Cable Laying Under Ice	4.0	320	120	83.8	92 [1]	1090	No

Note 1: 10 mm Anode
Note 2: 5 mm Anode

TABLE 2: RANGE OF APPLICATIONS AND MODELLED RESULTS

Aurora

This small and cost effective UUV is under development by ISE Research Ltd. The pressure hull is only 16" in diameter and the vehicle is intended for use in long missions at low power, typically 300 W. In order to build a cost effective system for this application a stack of only 12 cells is required, necessitating the use of a DC to DC converter to generate the required system voltage. An overall energy density of 240 Wh/L is achieved.

21" Mine Warfare

This application is generally intended for torpedo tube launched military applications such as mine warfare. The energy capacity of 40 kWh is adequate, giving 20 hours endurance at an average power of 2 kW. An energy density of 190 Wh/L is achieved. Again the most economical solution uses a DC/DC converter. An anode of approximately 5 mm thickness is used. The other applications would all benefit from a 10 mm anode. One possibility is to use the 10 mm anode in this 21" application and run the cell stack twice, the second time with fresh electrolyte and oxygen. This would generate 80 kWh of energy from a single cell stack

ARCS

This system was the basis for the optimisation and is currently the "lead ship" under construction. Thus the bulk of the development effort will be undergone on this system resulting in sea trials in 1996. As in the previous phase of the work on the ARCS vehicle a cell stack of 44 cells will be used, but the current work will result in an increase in energy density of 60% relative to the unit sea trialed in June 1994[(4)]. No DC to DC converter is needed.

Theseus

This large and sophisticated UUV has the task of laying fibre-optic cable beneath the Arctic ice. Cell stacks based on the ARCS cells can be used. Typically 4 modules of 24 cells may be used, very similar to the 2 modules of 22 cells in ARCS. Three of the high pressure storage vessels used in ARCS will provide the required energy and fit within the Theseus hull.

4.0 IMPLICATIONS FOR CELL STACK DESIGN

This wide range of applications with a 20 to 1 range in energy and 13 to 1 in power is met with essentially only one cell design with a common cell frame and end plate design. All manifolding, inlets and outlets are common. Two anode thicknesses are required of a nominal 5.0 mm and 10.0 mm thickness, the tooling for which is an extrusion die costing less than $1,000. This approach also results in two different cell frame moulds, but these are also simple NC machined steel moulds costing less than $5,000 to fabricate per set.

5.0 IMPLICATIONS FOR OXYGEN STORAGE AND SUPPLY DESIGN

The oxygen flow control system can be common across the spectrum with only a change in proportional control valve size needed for the lowest power (Aurora) application. The composite wrapped pressure vessel with its Inconel 718 liner is common to the ARCS (1 of) and Theseus (3 of) applications. It is 17.5" in diameter and will fit in a 21" hull, but will have an unnecessary high storage capacity. In any event it is likely that a solid chlorate candle approach would be used for the 21" military applications.

The small Aurora vehicle would likely use conventional steel tanks external to the pressure hull.

6.0 TEST RESULTS

The cell stack for ARCS with 600 cm^2 anodes has undergone single cell testing with excellent results, resulting in a detailed design being carried out for the modules and stacks. The end-plates were subjected to finite element analysis to ensure proper stiffness, essential to creating uniform sealing pressure on the O-rings. The moulds for casting the cell frames integral with the semi-porous cathodes have been manufactured and cells produced and tested. Typical 4-cell short stack results are shown in Figure 2. These results from the first run of these cells were achieved with no performance problem areas and zero operator intervention. The cell frames are cast from a 2-part epoxy resin with an inert filler to increase stiffness.

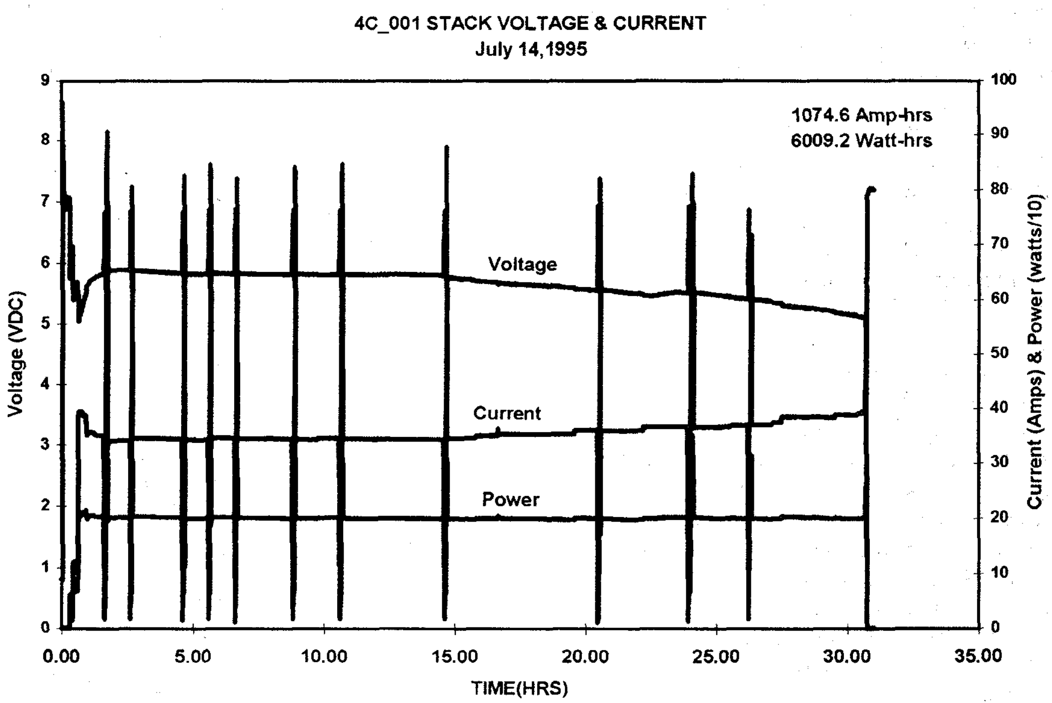

Figure 2 - Test Results from First Modular Cell Stack

7.0 LIFE CYCLE COSTS

The objective of this work is to reduce life cycle cost by means of:

- Reducing development cost and time,
- Reducing non-recurring engineering,
- Reducing parts inventory,
- Reducing parts cost by quantity procurement,
- Improving reliability by means of increased history of testing for each component.

The current specific design is for a 100 kWh, 2.0 kW system for ARCS. Each mission will result in costs for consumables (cells, oxygen, electrolyte, waste disposal) of approximately $5,000 for an energy capacity of 100 kWh or 50 $/kWh. This is for a first-off system built at very modest production rates of only 1 or 2 cell stacks per month. Higher production rates and minor improvements to the process will result in achieving 50% of this cost within a few years, considerably lower than comparable lithium or silver-zinc battery costs which can range from 100 to 500 $/kWh.

The other components of life-cycle cost are the amortisation of the capital cost and the repair and maintenance of the entire energy producing system. Current projections indicate that the production cost in modest quantities of a few units per year will be approximately 1000 $/kWh, with all components being of a robust, high quality nature. For example, the high pressure oxygen storage vessel is designed to comply with MIL Std 1522A and is rated for 1000 cycles. This will probably outlast the average UUV. At a very high usage rate of 4 high endurance missions per month, only 480 cycles are built up on most components in 10 years of operational life. It is anticipated that the ARCS design can easily reach this life with regular maintenance and refurbishment of some components such as the recombiner core. This will result in adding approximately 10% to the consumable cost to amortise capital and maintenance costs, resulting in an overall 56 $/kWh life cycle cost.

8.0 SUMMARY

The Aluminum-Oxygen system lends itself to a modular approach for power source design that will allow a wide range of requirements to be met with relatively few standard components. The first system using this approach will be installed in ARCS and sea trialled in 1996. This approach will result in operating costs less than half of silver-zinc batteries with an improvement in gravimetric energy density of 2 to 3 times.

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