# Aluminum-Hydrogen Peroxide Power System for an Unmanned Underwater Vehicle

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ABSTRACT

**Alupower Canada Limited and the Department of National Defence with CRAD funding and DGMEM engineering support are designing and constructing a fuel cell power system (FCPS) to power small unmanned vehicles (UUV's). The ARCS 1, a DND/DREP owned experimental unmanned submersible has been chosen as the trial vessel.**

**The FCPS will provide sufficient energy to allow the UUV to operate submerged, continuously for 30 hours which is approximately 4 to 6 times the endurance of its existing nickel cadmium system.**

**Unmanned underwater vehicles are attaining increasing importance as "force extenders" for more conventional manned maritime vehicles in times of budgetary constraint. Despite rapid advances in many UUV systems such as navigation and sensor technology, UUV's are now limited by the availability of an advanced power source capable of attaining the desired mission.**

**A steady state power output of 1.7 kW is achieved within a volume of 375 litres and system mass of 315 kg.**

## 1.0 INTRODUCTION

Alcan's aluminum-air fuel cell research began in 1981[1] although as with many electrochemical power sources the technology originated much earlier, in this case with Hulot in 1855. Alcan's program led to the development of a high efficiency aluminum anode alloy which is producible in commercial quantity. Alupower was formed to carry out the development of a range of aluminum power sources exploiting the core technology developed by Alcan.

The objective of the described aluminum-hydrogen peroxide power source is to increase the underwater endurance of unmanned underwater vehicles (UUVs) in this case the ARCS 1 experimental vehicle owned by the Department of Defence, Defence Research Establishment Pacific (DND/DREP). The existing Nickel-Cadmium batteries provide an endurance of 6 to 8 hours, the target for this program was to achieve 30 hours underwater at an average vehicle power consumption of 1.7 kW.

Alupower has also developed and tested an aluminum-gaseous oxygen fuel cell which is currently installed in the

Applied Remote Technology XP-21 UUV and has bench tested a system for the Marconi Underwater Systems Limited 0.53 m diameter UUV.

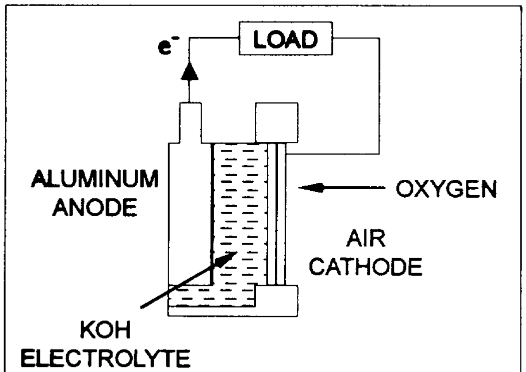
The ARCS 1 vehicle is an extremely sophisticated UUV which has been used to develop a wide range of underwater technologies. It is equipped with an acoustic transmission link and has autonomous onboard navigation and control capability. The vehicle was designed, developed and manufactured by ISE Research Ltd. It is 0.686 m in diameter and in the test configuration is 6.32 m long.

### 2.0 ALUMINUM SEMI-FUEL CELLS

Aluminum fuel cells are more accurately described as semi-fuel cells in which a consumable aluminum anode and a replenishable supply of oxygen are used.

The basic principles of the aluminum-air cell are shown in Figure 1. The cell is composed of an aluminum anode, an aqueous electrolyte, and an air cathode. At the anode, the aluminum is dissolved

**Fig. 1: Aluminum-Air Cell Schematic**




$$Al + \frac{3}{2}O_2 + \frac{3}{2}H_2O + OH^- \longrightarrow Al(OH)_4^-$$

$$Al(OH)_4^- \longrightarrow Al(OH)_3 + OH^-$$

in alkaline elctrolyte. The air cathode is a catalytic membrane which provides a site for three phase contact between a solid catalyst, the liquid electrolyte and oxygen from the air. The oxygen is reduced to $OH^-$ ions. The aluminum combines with the $OH^-$ ions in the reaction to form soluble aluminate ($Al(OH)^-_4$) ions.

In the current version of the ARCS power system the $Al(OH)^-_4$ remains in solution in the electrolyte once the system is discharged. Ultimately when the electrolyte is removed from a system the aluminum may be recovered from the electrolyte as $Al(OH)_3$ following a precipitation reaction.

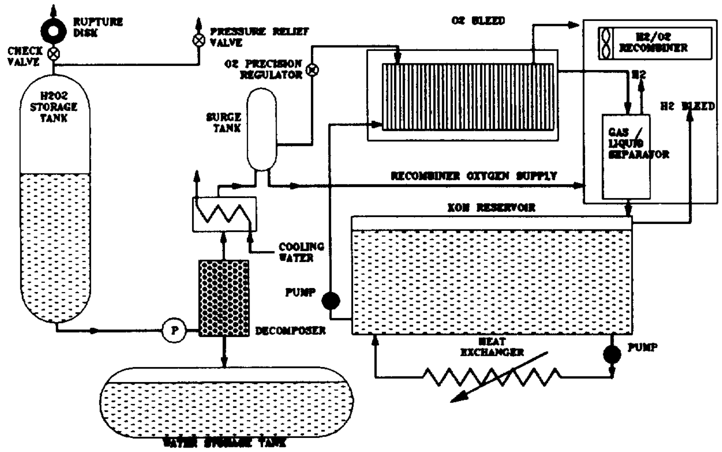
Alcan has developed aluminum anode alloys which exhibit high efficiency, low open circuit corrosion rates and uniform dissolution. These alloys are available in commercial quantities for aluminum-air systems. Alupower has developed a low cost laminated cathode which is presently being manufactured in commercial quantities using a "continuous web" process analogous to paper manufacturing techniques.

Demonstration by Alcan of aluminum-air batteries in vehicles have included a range extended "golf-cart"[2] in 1987 and road going vehicles in 1989 and 1991[3,4]. These projects demonstrated the potential of aluminum air to significantly extend the range of electric vehicles.

### 3.0 SYSTEM DESCRIPTION

A simplified schematic of the aluminum/oxygen Fuel Cell Power System (FCPS) is shown in Figure 2. The system is comprised of a stack of energy producing cells, a volume of electrolyte which is pumped through the cells, a volume of

Fig. 2
ARCS 1 FCPS SYSTEM SCHEMATIC



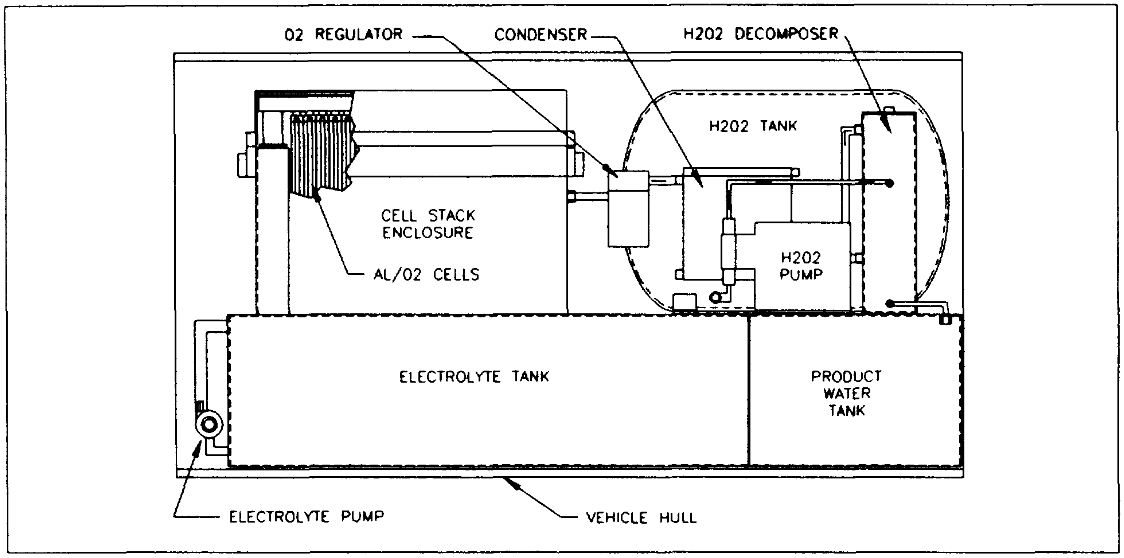

50% hydrogen peroxide which is catalytically decomposed to produce oxygen, a hydrogen management system, a thermal control system, and a control system. Electrolyte, composed of 8 molar KOH solution, is pumped through the cells and returned to a storage tank.

Oxygen is provided by the catalytic decomposition of 50% hydrogen peroxide which produces a mixture of oxygen, water and water vapour. As shown in the figure, this mixture passes through a condenser, where the water vapour is removed. The oxygen is then regulated to low pressure and supplied to the cell stack where it is consumed in the cell reaction. The water produced in the reaction is collected in a separate storage vessel which fills up during discharge of the FCPS.

Parasitic corrosion of the aluminum anode results in the production of a small amount of hydrogen as the FCPS is discharged. The electrolyte flows through a gas/liquid separator, and the hydrogen is swept from this separator and the void space in the electrolyte tank by a recirculating volume of nitrogen. A fan is used to recirculate this volume of nitrogen through an oxygen/hydrogen recombiner, where the two gasses are catalytically recombined to produced water or water vapour. Enough oxygen is regulated into this atmosphere to allow the reaction to take place. This hydrogen management system is currently used on other UUV power systems presently being developed at Alupower.[5]

To achieve the desired power and energy requirement for this project, two stacks of 22 cells are wired in series. The cell is designed in such a way that a stack of cells with the required electrolyte and oxygen manifolds, and supply to individual cells, is achieved by bonding the cells together with adhesive. The electrolyte inlet path to the individual cells is designed to ensure even distribution of the flow of electrolyte through the full range of vehicle pitch and roll angles. Oxygen is fed to the cathode-cathode gap between adjacent cells through the oxygen inlet

FIG. 3 - SIDE VIEW OF SYSTEM




manifold. An outlet manifold is located at the bottom of the cell to collect any water vapour which may condense on the cathode surfaces. A small bleed flow from the cell stack ensures removal of this condensed water.

The stack endplates include fittings for the electrolyte supply and exit piping, and the oxygen supply and bleed piping. The modular nature of the cell stacks enables the cell stack to be replaced after discharge by simply removing quick disconnect fittings for the electrolyte and oxygen piping, removing the spent cell stack, and replacing it with a new cell stack.

The electrolyte tank contains 85 litres of 8 M KOH solution, and provides the main structural support for all the components of the FCPS. The electrolyte tank is conformal to the inner shape of the ARCS 1 hull, which will allow the FCPS to slide into the hull on teflon runners. Figure 3 shows an overall view of the FCPS installed in the hull.

The water compartment of the storage tank is separated from the electrolyte portion, and is used to store the 40 litres of water produced in the decomposition of 44 litres of 50% hydrogen peroxide. The deck supports the cell stack, the hydrogen peroxide storage tank, the hydrogen management system, and the peroxide decomposition system, as shown in the figure. Refuelling the FCPS between missions consists of draining and replacing the electrolyte, draining the peroxide product water and replacing the peroxide, and replacing the spent cell stacks.

The cell reaction produces a peak heat output of 2.5 kW, which must be removed from the electrolyte in order to maintain the electrolyte at 60°C. The thermal control system consists of a polypropylene heat exchanger which is mounted in the electrolyte tank, a pair of aluminum-panel heat exchangers which are bonded to the inner hull of the ARCS 1 vehicle, and a pump and piping to circulate a volume of water through the two heat exchangers. The aluminum-panel heat exchangers were developed at Alupower and produced by an Alcan subsidiary, Algoods Ltd. The development and performance of these cooling panels has been established[5] on other UUV applications. When bonded to the inner hull, they provide excellent heat transfer to the surrounding seawater. The plastic heat exchangers are commercially available and required minimal alteration to mount them in the electrolyte tank and connect to the piping loop.

The use of hydrogen peroxide as an oxidant source gives comparable oxygen storage density to very high pressure (4000 to 5000 psi.) gaseous oxygen systems, without the relatively high capital cost associated with these systems or the complexity of liquid oxygen storage. A suitable catalyst was developed by researchers at Alcan's Kingston Research and Development Centre. This system supplies the oxygen required by the cell stack and the hydrogen hydrogen management system.

The control system developed for the FCPS is designed to eliminate complication to the end user of the FCPS, while providing the system with safe and reliable control over all active components in the FCPS. The design of all subsystems aimed at reducing the number of components which must be controlled in order to maximize system reliability, and minimize the complexity of the overall system, and hence the control system. The hardware used consists of an industrial computer and interface modules standard to UUV applications, with software written by Alupower.

The FCPS is designed to provide 1.7 kW of net output power over a voltage range of 52.5 volts to 63.5 volts for a 30 hour period. A backup lead acid battery pack is housed in an adjacent battery section, and provides emergency power in the event of failure of the engineering prototype FCPS. The FCPS is designed to fail safe under all conditions, such that the FCPS failure is transparent to the vehicle. All instrumentation and components in the FCPS run off a DC voltage bus common to both power sources, such that the lead acid battery pack provides the power required to activate the FCPS. During normal operation, the FCPS powers its own auxiliaries.

Redundancy is built into all safety-critical components of the electrical system.

## 4.0 HYDROGEN PEROXIDE STORAGE AND DECOMPOSITION

The decomposition of hydrogen peroxide liberates oxygen, water and heat. The stoichiometric relationship for this reaction is described by the following equation.

$$2\ H_2O_2 \rightarrow O_2 + 2\ H_2O + \text{heat} \qquad (1)$$

In the case of 50% hydrogen peroxide, the heat of reaction is sufficiently high to maintain the reaction chamber temperature at approximately 100°C, but does not provide enough heat to varourise all of the water contained in the hydrogen peroxide. A very high energy density is achievable by combining the hydrogen peroxide and product water storage as the volumes of both are very similar. This requires use of a "flip flop" tank. This issue has not been addressed in the current program and the water is stored in a separate tank.

Development of the hydrogen peroxide decomposition system began with an investigation into suitable catalysts for the decomposition of 50% hydrogen peroxide. Catalysts were evaluated in terms of longevity, rate of decomposition, and decomposition efficiency. The most promising catalyst was optimised in terms of catalyst volume and peroxide flowrate. One-tenth scale tests performed with this catalyst resulted in decomposition efficiencies of over 99% during a period of weeks of intermittent operation for periods of up to 30 hours.

The one-tenth scale tests formed the basis for the design of the full scale decomposition vessel. The volume of catalyst required for the full scale system was determined to be approximately 1 ℓ. A metering pump is used to supply the hydrogen peroxide to the decomposer. Testing of the full scale decomposer, as a stand alone component, under conditions which were representative of the FCPS oxygen requirements resulted in similar decomposition efficiencies as those that were achieved during the one-tenth scale testing.

Materials and equipment required for the storage and handling of hydrogen peroxide are well documented by peroxide manufacturers and industrial users. The 50% hydrogen peroxide for the FCPS oxygen supply is stored in a 44ℓ, 304L stainless steel, welded tank which has been passivated. The tank has been provided with ports for pressure relief, pressure and temperature monitoring, filling and emptying. A one-way valve at the tank exit prevents backflow into the tank which could lead to hydrogen peroxide contamination. A shut off valve has been provided between the tank and the metering pump. Pressure relief valves are provided in all sections of piping where hydrogen peroxide decomposition could result in a dangerous increase in pressure.

Integration testing of the hydrogen peroxide storage, oxygen conditioning equipment, and sub-system control constituted the final stages of sub-system development. Because of the high temperature and high water vapour content of the oxygen produced by decomposition of 50% hydrogen peroxide, the oxygen conditioning equipment constitutes a significant portion of the hydrogen peroxide decomposition sub-system. The oxygen first passes through a water cooled condenser followed by a coalescing filter to remove aerosol. A pressure regulator is used to reduce the oxygen pressure before it's introduction into the oxygen manifold.

Preliminary testing of the hydrogen peroxide storage and decomposition system has been completed and the cell stack operated successfully using this oxygen supply.

## 5.0 CONTROL SYSTEM

The aluminum-hydrogen peroxide fuel cell control system is designed to operate as a distinct sub-system with little or no encumbrance to the UUV's high level controller. The control system fully administers fuel cell operation and allows the UUV to operate as if the FCPS was a conventional battery. To this end, the fuel cell controller handles all faults automatically, reverting to backup battery supply when required with no power interruptions. All safety-critical instrumentation equipment is duplicated to ensure accurate assessment of the system's operating state.

Since the fuel cell power system is still in its final development stages the control system supports a serial communication link that provides surface operators with complete monitoring and override control capabilities down to the input/output (I/O) point level. The ARCS vehicle control system acts as a messenger for surface communications, preserving the existing control hierarchies.

The fuel cell control system employs standard proven industrial equipment extensively. The control computer, based on a VME bus descendant popular in the UUV industry, runs application software developed by Alupower. Like many embedded control systems the FCPS must operate amidst nuisance (and sometimes dangerous) electrical problems that arise when the 'real world' is instrumented with computers. Problems typical in the fuel cell are ground loops and equipment failure resulting from spills of highly-conductive electrolyte that infect connectors and terminations. To address the nuisance of ground loops, all I/O channels are fully electrically isolated, including those carrying analog-type information. The contamination of instrumentation equipment with seawater during refuelling on-deck is avoided by firstly locating all sensitive equipment in sealed enclosures, and secondly by using only fully-sealed chemical-resistant connectors when interfacing those enclosures.

Application software for the FCPS, developed in the 'C' language, handles all automatic control of the system processes including fuel cell start-up, normal operation and orderly shutdown. All operational data is logged to mass-storage during operation for post-mission analysis. During a discharge all system information is also available via the serial link provided, giving operators or supervisory computers complete status and health data when desired.

The majority of the FCPS control system is fully developed and ready for use in sea trials in the winter of 1993/1994. Work underway at this time includes final electrical system design refinements, re-packaging at the enclosure level and ARCS vehicle detailed integration. Alupower is also developing a surface-console interface for the FCPS which will offer operators insightful system operational data during discharges.

## 6.0 SUMMARY

The aluminum-hydrogen peroxide power source development for the ARCS 1 vehicle is a step in the direction of improving underwater vehicles and will enable full exploitation of previous and ongoing developments in vehicle, sensor and intelligent autonomous control systems. The energy capacity of 51 kWh is achieved with a mass of 315 kg and is packaged within a hull of internal volume 418 $\ell$. When allowance is made for the required vehicle interfaces and vehicle cabling through the section, the actual volume available is of order 375 $\ell$. The system is packaged into this space and achieves neutral buoyancy for the battery section taking into account the battery hull mass.

Future systems currently under development are expected to improve on the 162 Wh/kg gravimetric energy density by more than 60% to values of order 275 Wh/kg while still being neutrally buoyant.

Sea trials of the aluminum-hydrogen peroxide system in the ARCS 1 vehicle are planned for early 1994.

REFERENCES

[1] W.B. O'Callaghan, "A High Energy-Density Caustic Aluminum-Air Battery for Standby Reserve Duty" Paper presented at Society of Chemical Industry Conference, London, England, October 1989..

[2] N.P. Fitzpatrick, D.S. Strong, "Aluminum-Air, A Battery/Battery Hybrid for an Off-Road Vehicle", Paper presented at the 9th Electric Vehicle Symposium, Toronto, Canada, November 1988.

[3] D. Paris, N.P. Fitzpatrick, W.B. O'Callaghan and W. Anderson, "Demonstration of Aluminum-Air Fuel Cells in a Road Vehicle" Future Transportation Technology Conference and Exposition, Vancouver, British Columbia, Canada, August 1989 (SAE Paper #891690).

[4] S. Lapp and J. Dawson, "Testing Results and Running Cost Projections for an Aluminum-Air Lead-Acid Battery Hybrid Electric Van" Paper presented at EVS-11 Conference, Florence, Italy, September 1992.

[5] K. Collins, J. Stannard, R. Dubois and G. Scamans, "An Aluminum-Oxygen Fuel Cell Power System (FCPS) for Underwater Vehicles" Paper presented at Underwater Intervention '93 Conference, New Orleans, U.S.A., January 1993.