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Electrochemical power sources for unmanned underwater vehicles used in deep sea survey operations

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Abstract

A comparison of available energy from different power sources for unmanned underwater vehicles, discharged at atmospheric pressure or at ambient pressure, has been undertaken. The basis for the comparison has been a neutrally buoyant power source with a total volume of 300 l. For deep diving vehicles, the use of batteries that can operate at ambient pressure is advantageous. This advantage increases as the mean density of the battery decreases and as the mean density of the pressure hull increases. A fuel cell using spherical gas containers is also an attractive power source for deep diving survey underwater vehicles. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Applications/underwater vehicles; Semi-fuel cells; Comparisons/battery systems

1. Introduction

In the late 80s, a group at the Norwegian Defence Research Establishment (FFI) began looking at the possibility of demonstrating the use of the magnesium/seawater/dissolved oxygen system [1] as an energy source for an unmanned, untethered underwater vehicle (UUV). This system has a very high specific energy density, but the power output is very low, unless a forced flow of seawater through the battery is employed.

The idea was to use the velocity of the vehicle to force seawater through the battery [2]. Even so, the specific power density was low, forcing us to develop low power solutions for UUV propulsion, communication and manoeuvring. The project, to develop and test a technology demonstrator, was concluded in 1993 after a successful series of sea trials. Then the work began to look for application of this newly learned technology.

We soon found out that near term applications of UUV technology required much more power than available from the seawater battery technology. On the other hand, the very high energy density of the seawater battery was not necessarily required. An endurance in the range of 6 to 48 h was considered sufficient for most applications.

Mine counter measures (MCM) is one area where UUV technology is considered to be very attractive [4]. Effective mine hunting operations with UUVs requires access to high-resolution topography data and the capability of forward detection, classification and precise localisation of manmade objects on the seabed or in the water column.

The submerged endurance should be as long as possible to allow for large area coverage and the turnaround time between missions should be as short as possible, i.e. large energy density and short recharge time from the battery. These technical requirements are very similar to the requirements for a UUV for high-resolution seabed mapping, which could be used by the offshore industry. Thus, a joint team was formed with participation from the Royal Norwegian Navy, Norwegian offshore industry (Statoil), Kongsberg Simrad AS (KS), Norwegian Underwater Interventions AS (NUI), Norwegian Industrial and Regional Development Fund (SND) and FFI for developing UUVs for high precision seabed mapping and military route surveys (HUGIN). The work reported here took place in the mid and late 90s.

2. Underwater vehicles for seabed mapping

Modern seabed mapping is usually done from a surface vessel carrying a multibeam echosounder and cruising at a known speed and course. A typical sounder may have 127 beams covering a swath of 120°. In this way, a three-dimensional picture of the seabed is created along the route of the vessel. Given that the vessel knows its orientation and position along the route, a map can be generated. In shallow

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water, this map can have both a high resolution and a high accuracy, but as the water gets deeper, it is necessary to submerge the sensor to get it closer to the seabed in order to get a high resolution. Traditionally, this has been done with remotely operated vehicles (ROV), which are connected to the mother vessel by an umbilical or by using towed equipment. In all cases, the positioning of the submerged multibeam echosounder relative to the surface vessel is based on acoustic positioning. This positioning equipment is most accurate when the platform is located straight below the surface vessel. Thus, one problem with towed platforms is the uncertainty in global platform position caused by layback, whereas the main problem with ROVs is the drag of the umbilical, reducing the speed of operation to a fraction of a knot at large depths. Both systems suffer from mechanical disturbances caused by the umbilical or towing cable.

The obvious solution to these difficulties was to use a UUV as the platform for the multibeam echosounder. Because the power for propulsion increases with approximately the cube of the vehicle speed, a realistic target speed was 4 knots. Still, it was important to keep power consumption as low as possible on all subsystem of the vehicle. Due to size limitations, total volume of the UUV was set to 1.2 m^3.

The first phase of the HUGIN project was finalised through the commissioning of two UUV systems, the HUGIN I and II. In 1998, the HUGIN II vehicle was transferred to NUI, who has since then operated the system on a commercial basis for high-quality topographic seabed mapping on the Norwegian continental shelf under the name of 'NUI EXPLORER'. These services have provided documentation to be used by the oil companies in support to offshore site and pipeline developments [3]. The system is also used for data acquisition in support to national fishery research and estimation activities and for marine science missions.

HUGIN I was constructed with Ni/Cd batteries in two cylindrical aluminium pressure containers to allow us time to develop vehicle subsystems and to decide on the high energy density battery chemistry for HUGIN II. The result of that process was the development of the pressure compensated alkaline aluminium hydrogen peroxide semi-fuel cell described at the 21st Power Sources Conference [5]. This paper describes the process ahead of this decision, but it also takes into consideration the more recent technology.

The alkaline aluminium–hydrogen peroxide semi-fuel cell is also used in HUGIN 3000; a UUV produced by KS and FFI and delivered to C&C Technology, Lafayette, USA in July 2000. This vehicle, shown in Figs. 1 and 2, has a displacement of 2.4 m^3 compared to 1.2 m^3 for HUGIN I and II. Depth rating is increased from 600 to 3000 m and the endurance at nominal load (900 W) is 48 h. The increase in performance compared to HUGIN II, is primarily due to an increase in cell numbers from 4 to 6, an increased efficiency of the dc/dc converter (94% at 900 W), an improved propulsion motor and increased size and instrumentation. Some of these improvements will also be implemented on HUGIN I and NUI EXPLORER.

3. Battery systems for UUVs

When designing a UUV, one has to take into consideration that the weight of the vehicle must equal the Archimedes buoyancy force for the vehicle to be neutrally buoyant. This is equivalent to saying that the mean density of the UUV

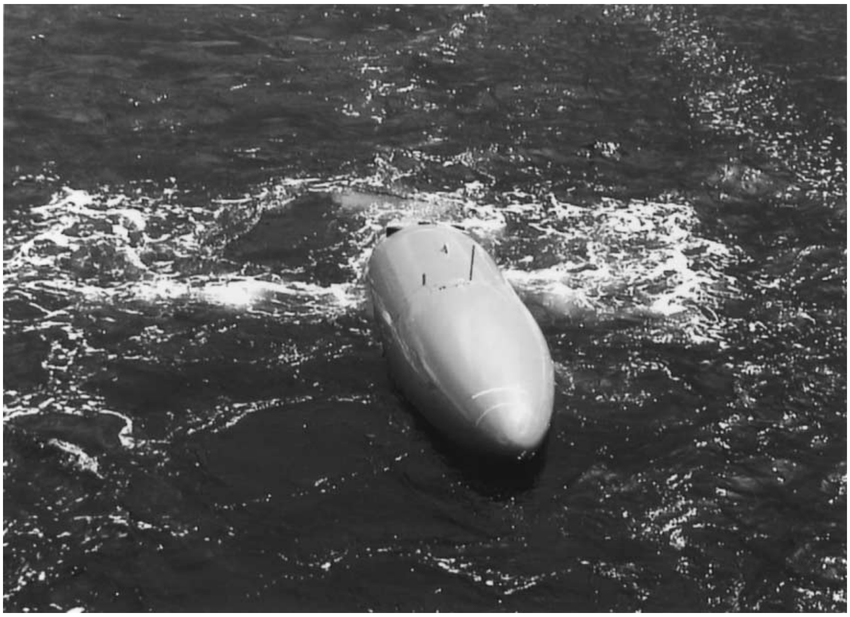

Fig. 1. HUGIN 3000 in the deployment phase.

Fig. 2. HUGIN 3000 during retrieval.

must be equal to the density of the surrounding water. Small deviations from neutrality can be compensated as long as the vehicle is in motion by using dynamic lift, or when still, by using thrusters, but this is costly in terms of power consumption. As the design depth of the vehicle is increased, the mean density of the empty pressure containers (pressure hull) increases, decreasing the ability of the vehicle to carry useful weight such as batteries and instrumentation while remaining neutrally buoyant. A second design consideration is that the centre of gravity must be on the vertical line below the centre of buoyancy.

To compensate for excess weight, flotation materials such as syntactic foam (glass bubbles in a polymer matrix), have been developed. A typical foam material has a density of 550 kg m^{-3} and a working depth rating of 3000 m. The main advantage of using foam (as opposed to, for example, large hollow glass spheres) is that the foam can be machined into any shape and put where required, thus, exploiting the available void space to a maximum.

Pressure resistant containers are typically either spherical or cylindrical with semi-spherical end caps. The sphere is the best in terms of mean density as defined by empty weight divided by external volume, the cylinder is more convenient to use. Thus, shallow diving UUVs are mainly based on cylindrical pressure resistant containers, while deep diving UUVs often use spheres (the outer hull, giving the UUV its shape, is usually not pressure resistant and may be made of thin fibre reinforced plastic).

The selection of a power source for a specific UUV application with a defined energy requirement, is usually done by comparing the performances of completely neutrally buoyant battery sections, given a defined available volume and a design depth.

Electrochemical power sources for underwater applications are classified in four different groups:

1. standard batteries inside a pressure hull and working at normal pressure;
2. pressure compensated batteries working at ambient pressure, but electrically insulated from the seawater;
3. seawater batteries;
4. fuel cells.

Typical examples from the three battery groups are: lead/acid batteries operating at normal pressure in conventional submarines, pressure compensated batteries in the US Navy deep sea rescue vehicle (DSRV) and magnesium/silver chloride seawater batteries in torpedoes such as the UK Stingray lightweight torpedo. In the magnesium/silver chloride battery, seawater is used as the battery electrolyte and the internal pressure of the battery is equal to the external (ambient) pressure, given by the water depth and seawater density. In the DSRV, the battery is based on silver/zinc cells where the voids in the cell is filled with oil and the pressure of the electrolyte is kept equal to the external pressure via a flexible member between the oil and the seawater.

When comparing battery systems, a number of factors should be considered in addition to the specific energy content and power capability, typical factors being cost, battery life (both in terms of cycle and calendar life), maintenance requirements and safety. This also holds for UUV batteries. In addition, pressure compensated batteries may have variation in buoyancy with depth or with degree of discharge. Variation in buoyancy with depth of discharge is always the case for seawater batteries.

For shallow diving UUVs, the net mean density of the pressure vessel is low and the simplest and probably the most efficient battery solution is to use a battery system with a high energy density and put the battery and electronic systems together inside the pressure vessel. In this case, the only concern is to keep a safe atmosphere within the pressure vessel at all times, safe meaning non-explosive, non-combustible and non-corrosive.

As the design depth of the UUV is increased, things get more complex. Below is a comparison of battery systems, given a design depth of 3000 m and an available volume of 0.300 m^3 with neutral buoyancy.

4. Batteries discharged at atmospheric pressure

For this configuration, standard batteries can be used. Of special interest are the high energy density batteries presently being developed for the electric vehicle (EV) industry. In contrast to EV batteries, however, batteries for deep sea survey UUVs are typically discharged at a nearly constant power and over a time of typically 12–36 h. Thus, high rate capability is usually not required for this type of UUV. This simplifies both cell design and inter-cell connections, especially if high rate charging is not required. Thermal control under discharge is also comparatively easy since the seawater temperature is rarely outside the range of -2–26°C.

In the calculations, it has been assumed that the battery container has a depth rating of 3000 m and has the shape of a cylinder with a length of 1.6 m and with semi-spherical endcaps. Wall thickness is 20 mm and the internal diameter is 260 mm. Internal volume is 87 l. The battery container is made from an aluminium alloy with a density of 2700 kg m^{-3}. The battery weight is calculated from cell weight plus an additional 8 kg for interconnections and hardware. During discharge, a diode voltage drop of 0.5 V is assumed. Syntactic foam with a density of 550 kg m^{-3} is used to balance the weight and volume of the system.

Given the constraints above, the calculated battery weight is 125 kg (cell weight 117 kg), the weight of the empty container is 77 kg and the weight of syntactic foam is 103 kg.

Using typical battery data, Table 1 shows the performance to be expected.

For a HUGIN I type of UUV, the load is approximately 550 W. Thus, in the example above, from 8 to 127 h of continuous operation is possible, depending on the type of battery.

Low rate silver/zinc batteries have traditionally been the preferred rechargeable battery for UUV operation. They have energy densities ranging from 100 to 200 Wh kg^{-1} when new, but short wet life and declining capacity with cycle count have been major problems. However, the silver/zinc battery is still the yardstick to which other systems are compared. In Table 1, we have arbitrarily used the figure 120 Wh kg^{-1} as a typical figure over the lifetime of a silver/zinc battery.

In the future, we expect that Li-ion will be the preferred chemistry over silver/zinc for rechargeable UUV batteries. In contrast to silver/zinc, the Li-ion cell is hermetically sealed and does not evolve gas during charge. Thus, the battery may be charged in the sealed container and may also be charged much faster than silver/zinc batteries. To obtain practical experiences in operation with Li-ion batteries, in 1998. we exchanged the Ni/Cd battery in HUGIN I with a Li-ion battery made from 360 Sony US26650 cells. This also allowed us to remove one of the two battery containers to allow space for a larger sensor suite. The battery was designed with eight blocks connected in series and with 40 cells in a parallel in each block, giving a nominal capacity of 108 Ah. A combination of hardware and software protects the battery at the cell level.

In the future, lithium-ion batteries developed and optimised for low rate, room temperature discharge, should be available with much higher energy density than indicated above. Not least the availability of large EV cells should decrease cost and increase the performance of the Li-ion UUV batteries. In terms of safety, however, the authors prefer many small cells, as it is our experience with lithium batteries that battery incidents mostly start with one cell only. Thus, even though increasing cell number increases the probability of an incident, keeping cell size small may reduce the severity of the incident.

At the present time, FFI do not consider the use of lithium primary batteries, partly due to the high cost of operation and partly due to the safety aspects of the use of multiples of large, high rate batteries. However, given the exceedingly high energy density of some lithium primary batteries, they should be very suitable for specialised operation requiring long range. Given a low rate design, safe use of large lithium batteries designed for UUV applications should be possible (Zolla et al. [6]), provided that special safety considerations are maintained. One measure to increase safety would be to use single cells paralleled via diodes or fuses and connected to a dc/dc converter. Such a design would completely remove failure modes related to serial connections such as over-discharge of failed cells, but at a cost of reduced energy.

Table 1
Batteries operating at atmospheric pressure

Chemistry	Energy density of cell (Wh kg^{-1})	Energy density of neutrally buoyant system (Wh kg^{-1})	System energy (kWh)
Ni/Cd 4.5 Ah D-cell	36	14	4.2
Ni/MH 9 Ah D-cell	60	23	6.9
Ag/Zn	120	46	14
Li-ion MP176065	120	46	14
Li/$SOCl_2$	400–600	153–230	47–70

Table 2
Battery systems operating at ambient pressure

Chemistry	Energy density ($\mathrm{Wh\,kg^{-1}}$)	Energy density of neutrally buoyant system ($\mathrm{Wh\,kg^{-1}}$)	System energy (kWh)
Silver/zinc	90[a]	47	14[b]
$\mathrm{Al/H_2O_2}$[c]	101	83	25
Future Li-ion	120	75	22

[a] Value for Yardney LR700DS single cell. Weight and volume of battery box and gas separation system are not included.

[b] Estimated system value. Value based on the weight of single cells is 16.4 kWh.

[c] Based on the HUGIN 3000 semi fuel-cell, but scaled down to fit within the 300 l neutral volume that is used for system comparisons.

5. Pressure compensated battery designs

Most battery chemistries can be used in pressure compensated designs. The main requirement is that the battery does not contain voids that may be compressed. Typically the cell is composed from solid or liquid phases, with a flexible member between the liquid electrolyte and the outside water. This flexible member compensates for differences in compressibility of the different materials allowing volume change with pressure and also allows for small amounts of compressible gas in the battery. If a larger amount of gas is expected, a gas separation system is mandatory.

Two examples of this technology which are in commercial use are the alkaline aluminium–hydrogen peroxide system ($\mathrm{Al/H_2O_2}$) used in HUGIN II and HUGIN 3000 UUV and the balanced silver/zinc battery used in DSRV.

As in Table 1, the performance data are calculated for a neutrally buoyant system with a volume of 300 l and syntactic foam as buoyancy material. The data for the Al battery is calculated from the performance in HUGIN 3000 on its second discharge of aluminium anodes (HUGIN II is equipped with aluminium for three discharges [5], HUGIN 3000 for two discharges. After each discharge, the electrolyte is exchanged and hydrogen peroxide refilled). The $\mathrm{Wh\,kg^{-1}}$ system data is based on clear electrolyte. In a system designed for precipitation of aluminium hydroxide, the energy density can be approximately doubled, but at the expense of the ability of a rapid recharge.

A third battery system, called future Li-ion, is also included in the table. This battery is, for the calculation, assumed to be inside a sealed box made from 1 mm titanium and filled with oil, the volume of the battery box being 12% larger than the cell volume. Titanium weight is assumed to be 20% larger than that corresponding to the weight of the walls of the battery box in order to allow for stiffening members. The oil is assumed to have a density of $870\ \mathrm{kg\,m^{-3}}$. The cell used for this calculation is the Ultralife UBC6034148 with a nominal capacity of 6.3 Wh and a nominal weight of 52 g. This is a polymer electrolyte, lithium ion — manganese oxide type, of a pouch cell construction. The cell is prismatic and the cell container is a thin metallised plastic foil envelope.

We did a discharge test of one cell under a pressure of 300 bar in an oil-filled container. The cell behaved normally during this discharge, in fact, we saw no measurable effect of the pressure on the cell voltage. After the test, however, the cell weight was increased by 3% and subsequent cycles at atmospheric pressure showed a decrease in capacity. Thus, this particular cell design is not suitable for this application, primarily because it contains voids, but it is an example of what can be achieved in the future, given cells that are designed for this application. One change in design may be to let the cell contain a small excess of liquid electrolyte, so that a pressure differential cannot develop over the cell container.

Table 2 gives some data on these three systems.

6. Seawater batteries

Because these batteries use seawater as electrolyte, a significant increase in energy density compared to other batteries is observed. A further increase is possible if the battery is using oxygen dissolved in the seawater as oxidant. Table 3 gives calculated figures on a low rate silver chloride battery and a magnesium-dissolved oxygen battery.

The figures in Table 3 are uncertain. The published nominal energy density for a silver chloride pile type of torpedo battery is $107\ \mathrm{Wh\,kg^{-1}}$, based on dry weight (Yardney MK 44/MK61 MOD 0). For the energy calculation, we used a cell voltage of 1.4 V and assumed nearly 100%

Table 3
Battery systems with seawater as electrolyte

Chemistry	Energy density ($\mathrm{Wh\,kg^{-1}}$)	Energy density of neutrally buoyant system ($\mathrm{Wh\,kg^{-1}}$)	System energy (kWh)
Mg/AgCl	200	100	30
$\mathrm{Mg/O_2}$	600	167	50

Table 4
Fuel cell system based on spherical aluminium containers

System weight (kg)	System volume (l)	System energy density (Wh kg^{-1})	System energy (kWh)
246	300	130	32

Faradaic efficiency for the silver chloride reduction and a Faradaic efficiency of the magnesium anode alloy of 50%. A further reduction in specific energy caused by the use of a dc/dc converter may be necessary for a battery based on discrete cells. In any case, this battery system is attractive as it is very compact, the battery volume being only 72 l, the rest being syntactic foam and buoyancy compensation hardware.

The figures for the magnesium/dissolved oxygen battery are based on a dc/dc converter efficiency of 80% and a power loss of 20% in order to pump the seawater through the battery [2]. Compared to the other battery chemistries, the low specific power for this system makes it less suitable for missions of short duration. Typical applications being missions with a duration of one or a few weeks. Thus, it is not directly comparable to the other systems.

Other seawater battery systems such as CuCl, $PbCl_2$ and MnO_2 with magnesium anodes have been evaluated, but found inferior to those described.

7. Fuel cells

Small fuel cells with kW outputs are interesting sources of power for UUVs. The energy density of the system based on the weight of the reactants, a cell voltage of 0.70 V and a Faradaic efficiency of 0.95 is approximately 2 kWh kg^{-1}. Space application over many years has shown that the fuel cell technology is maturing. In spite of that the use of hydrogen/oxygen fuel cells in small UUVs has not yet been reported.

There may be two main reasons for this. One is the cost of the cell, the other is the problems associated with weight and space efficient storage of the reactants.

Traditionally, compressed gas has been the preferred method of storage. Thus, the energy density achievable is primarily determined by the performance of the gas containers in terms of wt.% of hydrogen or oxygen, keeping in mind that the containers should be rated for external pressure as well as internal pressure.

The figures in Table 4 have been calculated assuming spherical containers made from an aluminium alloy with an allowable working stress of 130 MPa. Two large containers, one for hydrogen and one for the fuel cell, and one smaller container for oxygen make up the system. The external volume of the three spheres is 300 l. Fill pressure is 300 bar and they contain 16 kg of reactants. The weight of the fuel cell and its auxiliary equipment has been set to 20 kg. The external diameter of the large spheres is 612 mm and the wall thickness is 30 mm, internal volume is 88 l. The small sphere has an internal volume of 44 l, an external diameter of 485 mm and a wall thickness of 24 mm.

In contrast to the other systems described, this system has a net positive buoyancy of 55 kg. This is primarily because of the low weight of the spherical containers. A change to cylindrical containers would increase the gas container weight by a factor of two, but as cylindrical containers are easier to place within a hull, this may still be preferred.

In a real system, power used for auxiliary systems will reduce the figure for available system energy. An increase in weight caused by an auxiliary battery for start-up, inert gas system for flushing of the container etc. must also be taken into consideration. However, in spite of that the resulting figures should still be attractive.

An increase in gas pressure from 300 to 450 bar has been evaluated, but the large deviation from ideal gas behaviour [9], especially for hydrogen, makes higher pressure less attractive.

An alternative to the use of compressed gas is to produce hydrogen and oxygen chemically. For hydrogen, one of the more weight efficient method being the reaction of boron hydride with water, whereas oxygen can be produced by decomposition of hydrogen peroxide, 1 kg of pure hydrogen peroxide giving 0.471 kg of pure oxygen. Again, assuming a Faradaic efficiency of 0.95 and a cell voltage of 0.7, the specific energy based on the weight of water, boron hydride and hydrogen peroxide according to:

$$2BH_3 + 3H_2O_2 = 2B(OH)_3 + 3H_2O$$

is 865 Wh kg^{-1}. This figure is based on the use of pure hydrogen peroxide and that the water formed by decomposition of hydrogen peroxide can be used in the reaction with boron hydride, forming boric acid and hydrogen. Even after reduction of this figure by a factor of three–five, to allow for a practical system, the performance would still be quite good.

Given the high activity on fuel cell development [8], both for portable power and for electric vehicles (EV), one would expect to see fuel cells as a major power source for UUVs in the future.

8. Conclusion

From this work, we conclude that for a design depth of 3000 m, an increase in energy density by approximately 50% may be obtained through the use of pressure compensated batteries. This is especially advantageous for power sources with a low mean density such as the Al/H_2O_2 battery. At larger depths, the pressure compensated designs will be even more advantageous because the mean density of the pressure containers increases.

The numerical results are based on a certain set of assumptions, the most important being the shape of the pressure containers and the density, strength and stiffness of the materials used for its construction. If these assumptions are changed, different results will be obtained. Thus, the exact numbers are not the main point, but the method of selecting the power source, given that system energy is the main criterion.

Still, it is probably safe to say that for the deep diving survey UUV's, the Al/H_2O_2 semi-fuel cell operating at ambient pressure is the rechargeable system that gives the user most endurance at present and in the near future. Compared to silver/zinc, it gives a nearly 50% improvement of the endurance.

For many applications, Li-ion batteries operating at atmospheric or ambient pressure may become the system of choice. Being electrically rechargeable, the logistics is simpler and in the future, comparable endurance to the Al/H_2O_2 system may be achieved. We have used a value of $120\,\mathrm{Wh\,kg^{-1}}$ for the Li-ion cell in our calculations, whereas values as high as $240\,\mathrm{Wh\,kg^{-1}}$ [7] have been postulated with this chemistry.

The fuel cell is a very attractive future power source for UUVs for underwater survey operation. Based on compressed gas, it has light weight, is rapid to refill and the nearly constant load makes it possible to optimise the system for maximum efficiency, allowing a long endurance.

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