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ScienceDirect
Journal of Power Sources 162 (2006) 935–942
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Power sources for autonomous underwater vehicles

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Received 9 February 2005
Available online 1 September 2005

Abstract

The paper addresses the general requirements for power sources for AUVs, including battery and semi-fuel cell design and safety considerations. The focus is on the last AUV in the HUGIN family: the HUGIN 1000 mine reconnaissance system. For this AUV, FFI recently developed a pressure tolerant lithium ion battery based on commercially available polymer cells. The Royal Norwegian Navy has been operating HUGIN 1000 since February 2004.

Keywords: Underwater; Vehicles; HUGIN family; Battery; Semi-fuel cell; Fuel cell

1. Introduction

FFI has been developing autonomous underwater vehicles (AUV) for more than a decade. During this period we have been using many different power sources: magnesium/dissolved oxygen seawater semi-fuel cell [1,2], valve-regulated lead–acid (VRLA), nickel/cadmium (NiCd), nickel/metal hydride (NiMH), alkaline aluminium/hydrogen peroxide semi-fuel cell (AlHP) [3,4], sealed lithium ion and lithium polymer. Most of this work has taken place in close cooperation with Kongsberg Maritime, which is also the commercial producer of the HUGIN class autonomous underwater vehicles (AUV) [5]. HUGIN is an acronym for High precision Unmanned Geosurvey and INspection system. It is also a name from Norse mythology: Hugin and Munin were the two ravens that daily flew from Odins shoulders down to the earth. After returning, they informed him on what was going on in the world. This was an advanced form of rapid environmental assessment (REA), one of the primary tasks of naval AUVs besides mine counter measures (MCM). A typical HUGIN AUV is equipped with sensors for seabed mapping and imaging, a sub-bottom profiler for subsurface characterization, acoustic links for communication and navigational sensors for accurate positioning. The requirements for civilian and military AUVs are similar, and the HUGIN AUV development is one of the rare cases where non-military industrial interests have financed the initial development. In February 2004, however, the first military AUV, HUGIN 1000, was delivered to the Royal Norwegian Navy for operation from the mine-hunting vessel KNM Karmøy.

2. Alkaline aluminium/hydrogen peroxide semi-fuel cell

The civilian AUV HUGIN 3000 is operated commercially all over the world by different companies. One company, C&C Technologies, has accumulated more than 40,000 km of line survey with their HUGIN 3000 [6]. In a routine seabed mapping operation, HUGIN 3000 follows the seabed at a constant height above the seabed. It operates at 4 knots down to a sea depth of 3000 m and has an endurance of up to 60 h with a typical sensor suite and all sensors operating (side-scan sonar, multi-beam echo sounder, sub-bottom profiler, etc.).

An alkaline aluminium hydrogen peroxide semi-fuel cell developed at FFI [7] powers HUGIN 3000. The cell stack is composed of six serially connected cells and uses circulating electrolyte (7 M KOH). Hydrogen peroxide is added continuously to the electrolyte in order to keep a constant (but low) concentration of hydrogen peroxide and oxygen in the

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doi:10.1016/j.jpowsour.2005.07.021

electrolyte. A DC to DC converter generates a stable system voltage of 30 V. The stack voltage is typically 9 V. This system is under constant development and at present, the energy content is up to 50 kWh per refill of electrolyte (anodes are only changed every second or third dive), giving the vehicle an endurance of typically 60 h at 4 knots and all sensors working [8]. The corresponding energy density is 100 Wh kg^{-1} based on total system weight. This power source has been described in detail in ref. [4]. The basic chemistry of the system is described in [3]. Compared to other power sources for AUVs, the main advantages of the Al/HP power source are high energy density, low weight in water and that it operates at ambient pressure without the weight penalty of a pressure hull. In addition, it allows rapid mechanical recharge, typical deck time is only a few hours and usually determined by the time needed to unload the data from the vehicle and not by the time used to recharge the battery. Fig. 1 shows the Al/HP cell stack and Figs. 2 and 3 typical system data during opera-

Fig. 1. The Al/HP semi-fuel cell stack with gas separation system and connections.

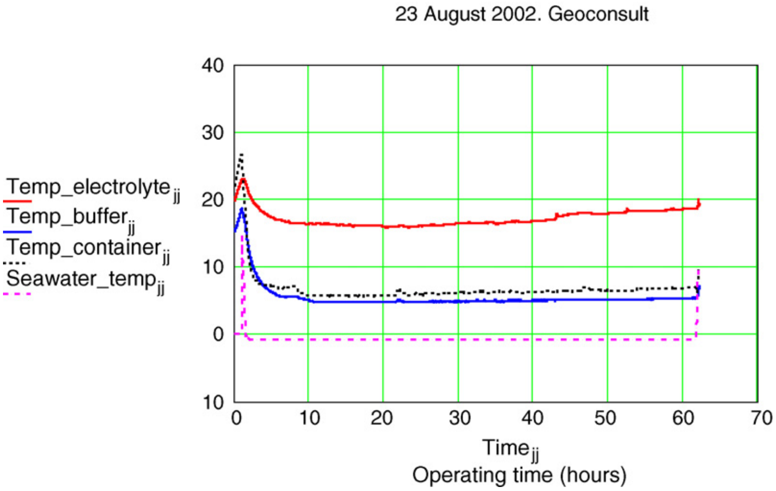

Fig. 2. Temperatures of battery electrolyte, buffer battery, battery control container and seawater during a dive in the Norwegian Sea; sea depth 0–980 m.

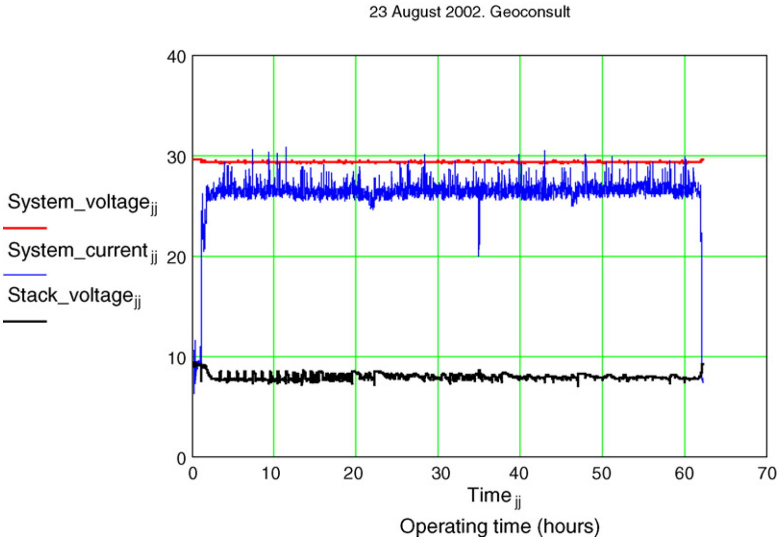

Fig. 3. System voltage, system current and stack voltage vs. time.

Table 1
HUGIN 3000: typical operation is constant velocity (ca. 4 knots) and constant height (typically 40 m) above the seabed

Displacement (m^3)	2.4
Dry weight (kg)	1400
Length (m)	5.35
Diameter (m)	1.00
Maximum operation depth (m)	3000
Endurance	60 h at 4 knots, all sensors operating

Table 2
Weight and performance of the HUGIN 3000 AlHP semi-fuel cell

Aluminium anodes for six cells (kg)	60.8
185 liter 7 M KOH (kg)	238.7
70 liter 50% HP (kg)	84
Sum active components (kg)	383.5
Battery box complete with cathodes (kg)	82.4
Hydrogen peroxide systems (kg)	6
Sum battery weight (kg)	472
Battery weight in water (kg)	148
Nominal system voltage (V)	30
Nominal system energy (clear electrolyte) (kWh)	50
Maximum continuous system power (kW)	1.2

tion. With a net power output of 1 kW, heat production in the cell stack is approximately 2 kW, resulting in a temperature increase of approximately 18 °C above the seawater temperature. In normal operation, HUGIN 3000 operates with clear electrolyte, but if precipitation of aluminium hydroxide is allowed, a major increase in energy output can be achieved. Operation with precipitation does however require disassembly and cleaning of the cell stack after discharge. Table 1 shows some figures for the HUGIN 3000 AUV and Table 2 technical data for the power source.

The main disadvantage of the AlHP semi-fuel cell system is the logistics requirements. The mother vessel must be equipped with systems for safe handling of 7M KOH, 50% HP and for the collection of spent electrolyte. In addition, the crew must be well trained in order to handle the chemicals in a safe manner. Typically, the AUV is operated from two containers that contain systems for launch and recovery, AUV maintenance, handling of chemicals and water purification.

3. NiCd, NiMH and lithium ion

Power sources for AUVs typically have a fairly constant load and specific power is moderate. Typical discharge rate is less than C/5 for survey AUVs. Compared to batteries developed for electric vehicles (EV) this rate of discharge rate is modest. The rate of charge however should be high in order to reduce deck time. Historically, EV battery technology development has given the AUVs a free ride. High rate capability and safety are not necessarily compatible, so rate capability above what is needed should be avoided.

The AUV HUGIN 1 was commissioned in 1995 and is still in use for sensor and system development by FFI. It was initially equipped with prismatic valve regulated Hoppecke NiCD FNC 90 Ah cells. The battery was assembled in two tubular aluminium containers with one string in each container (25S 2P configuration). The charge controller for this battery was based on industrial components (Advantech ADAM 3000 series) and PC software. The battery management unit (BMU) contained sensors for current, temperature and voltage measurements, and the string voltage measured directly and in five steps of 6 V nominal (each string was divided in five) in order to detect faulty cells easier. A watchdog terminated the charge in case of computer failures or "hangs".

In 1998, HUGIN 1 was updated with Sony US26600 lithium ion cells in a 40P 8S configuration and the BMU redesigned. The parallel connections were made via polymer fuses (PPTC, polymer positive temperature coefficient resistors). This new battery used only one battery container and the refit made it possible to use the other battery container for sensor electronics. In 2003, the Sony cells were exchanged with AGM ICR34600 D-cells in a 34P8S configuration.

Our experience so far is that hermetically sealed cells in pressure hulls perform well. The US26600 cells were down to 70% of their original capacity after 5 years of use and occasional abuse (discharge below the recommended cutoff). A hardware shut-down device could have avoid this abuse. Given the significant cost of the battery, a low cell voltage hardware disconnect is part of the BMU in later AUV designs. Heat production during charge or discharge is insignificant and the development of differences in the parallel block capacities is very slow, making manual block balancing (once every 2 year) acceptable.

Compared to lithium ion, nickel metal hydride (NiMH) has lower gravimetric energy density, but is much cheaper. During development of HUGIN 3000, we used a 4 kWh 8.4 V NiMH battery (12P7S Sanyo HRD) as a substitute for the Al/HP semi-fuel cell stack. The AUV NUI Explorer (former HUGIN II) was also using NiMH in a pressure vessel.

4. Pressure tolerant batteries

The weight of a pressure hull increases with design depth. As a consequence, the amount of energy that can be contained in a vehicle with neutral buoyancy decreases with design depth. Obviously battery containers should be as light as possible, and design and choice of materials is a science by itself. An alternative, especially for deep diving vehicles is to make a battery that operates at ambient pressure, but is electrically insulated from the seawater.

FFI did some encouraging experiments with polymer lithium ion cells in the late 90 s [9]. Fig. 4 shows that the cell voltage is only marginally affected by pressure during discharge. Others also made similar experiments, such as Bluefin Robotics [10].

For solid (and liquid) materials, the compressibility is very low, thus a large increase in pressure is necessary in order to

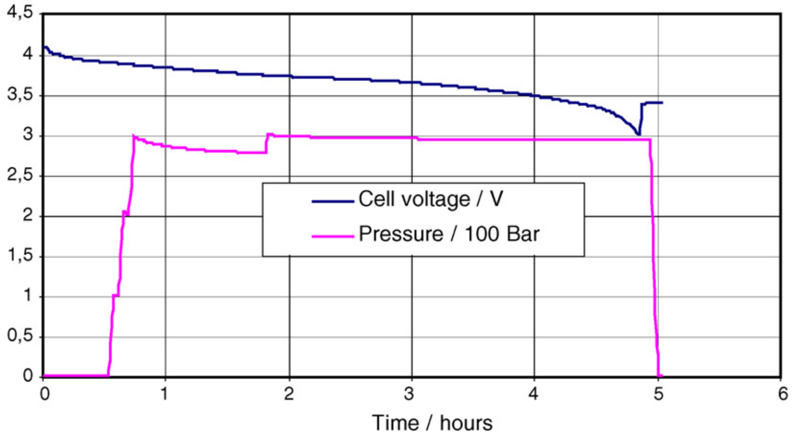

Fig. 4. Discharge of a lithium ion polymer cell moulded in polyurethane and exposed to pressure variations during discharge. Nominal capacity 3.8 Ah, vendor B. Discharge current C/5, room temperature. Upper curve, cell voltage and lower curve pressure (3.0 equals 300 bar or 3000 m sea depth).

achieve a significant change of the dimensions. For a composite material, such as a polymer cell, the result is that the hydrostatic pressure must be very high in order to develop displacements that may destroy the cell. In presence of a void, however, even a low pressure may result in deformations that may lead to a cell failure.

In lithium ion cells, the volume of the active masses varies with the temperature, the pressure and the state of charge. In hermetically sealed cells, a small void inside the cell allows volume changes to occur with only minor change in the internal cell pressure and normally without a significant change in the external dimensions of the cell. In a polymer cell, however, the thickness of the cell increases with state of charge. An obvious consequence of this dimensional change is that cell assemblies must be resilient.

Initially, cells from two vendors (A and B) were purchased, moulded into polyurethane, charged at normal pressure and discharged at 300 bar, corresponding to a sea depth of 3000 m. Cells from vendor A developed gas internally, “ballooned” and further experiments were terminated. This ballooning was not related to the pressure testing. The results with cells from vendor B were encouraging and it was decided to develop a pressure tolerant battery based on these cells (Figs. 5 and 6). Later, we have also been using cells from a third vendor (C) with good results.

5. General requirements for an AUV for MCM and REA

The Norwegian mine counter measure (MCM) fleet is based on surface effect ships (SES). These ships are fast, and as most catamarans they have a large deck area, but their performance is very sensitive to weight. The naval energy carrier is diesel and electricity is generated on-board from diesel. In an AUV with mine reconnaissance and REA as

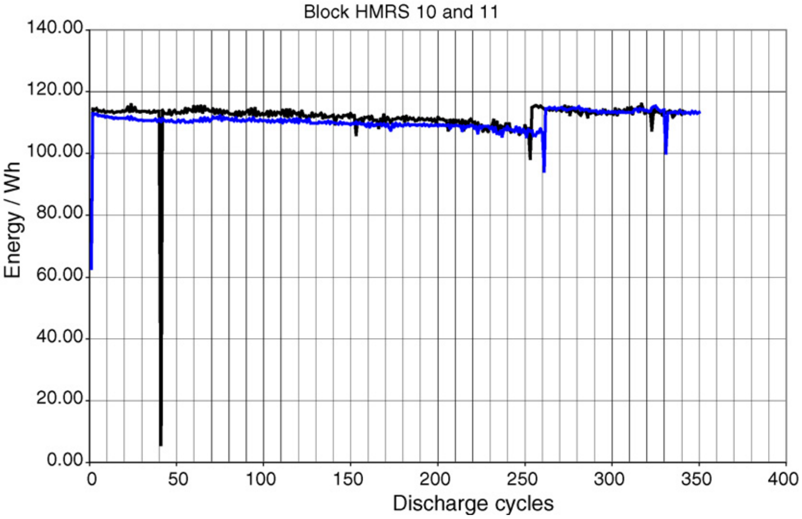

Fig. 5. Discharge energy/Wh vs. cycle number for two blocks made from cells from vendor B. Charge: C/5 to 4.20 V, terminated at C/10. Discharge C/5 terminated at 3.00 V. Equipment: Diagatron BTS 600. The increase in capacity at approximately cycle 250 correlates with a recalibration of the equipment.

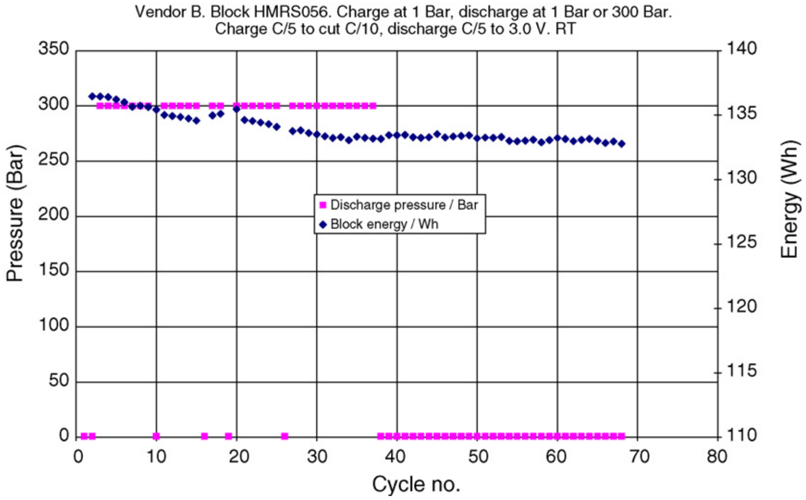

Fig. 6. Block energy vs. cycle number for a polymer block charged at normal pressure and discharged at normal pressure or at 300 bar. Charge and discharge as in Fig. 5. Cells from vendor B.

primary requirements, AlHP was considered unpractical and primary lithium too expensive for routine use. This left us with two high energy density options: lithium ion batteries in a pressure hull or lithium polymer batteries working at ambient pressure. The design depth is only 1000 m, but for a MCM AUV, robustness to shock and vibration is mandatory and the requirements severe. The moulded blocks have excellent resistance to shock and vibration and it was decided to develop a pressure tolerant polymer battery for HUGIN 1000.

6. HUGIN 1000 battery module

The battery module was to be built from blocks of parallel-connected polymer cells. Block size was ca 40 Ah. To reduce or eliminate the danger of electric shock, the battery voltage should be less than 50 V in order to be "non-hazardous" and two men should be able to carry the battery module. Thus, each battery module was composed of 36 blocks in a 3P12S configuration. Assuming polymer cells with 4.2 V charge voltage and 3.0 V end of discharge, the battery voltage range was from 50.4 V down to 36.0 V. The AUV should be able to operate from one battery module only.

Fig. 7. The last AUV in the HUGIN family: the HUGIN 1000 mine reconnaissance system. The Royal Norwegian Navy has been operating HUGIN 1000 with polymer batteries since February 2004.

Typical load is 700 W at a speed of 4 knots, peak load ca. 2 kW at 6 knots. HUGIN 1000 shown in Fig. 7 may be operated with up to three lithium polymer batteries, each of approximately 5 kWh at C/5, giving ca. 20 h at 700 W. Each battery measures 1540 mm × 248 mm × 140 mm and weights ca. 83 kg. An optional primary battery in a pressure hull may give a significant increase in endurance.

7. Battery safety

Even though some polymer cells passed the UN test [11] with respect to short circuit and overcharge, this was no longer the case for the parallel-connected cells in a block. This may simply be because of the reduced surface to volume ratio in the block. In blocks, short circuit tolerance was achieved through the use of polymer fuses on each cell, but this did not prevent an intensive fire resulting from overcharge. Thus, the BMU is a very important piece of safety equipment. Some requirements to the battery were:

- Internal short in one polymer cell should be tolerated—polymer fuses.
- Fire in one block should not spread through the battery—firewalls.
- Cables should not short if heated—glass insulation on power leads.
- Efficient heat transfer to the surroundings—silicone oil.
- Rigid battery case even if the battery is burning—titanium battery box.

Firewalls were made from syntactic foam integrated in the blocks and from thin stainless steel sheets. Silicone oil has a flash point above 320 °C, is very difficult to ignite and is non-toxic. As long as the AUV is in the water, fire is not a safety issue, but during storage and charge a battery fire may have severe consequences. The smoke is poisonous, containing HF and other decomposition products from the battery and the polyurethane plastics used for moulding. A fire is ideally best avoided, but possible to fight with a trained crew using standard fire fighting (water) and protective equipment.

A new BMU based on a micro-controller was developed for the battery. The BMU measures all cell voltages, the battery temperature and the battery current. It also keeps track of charge in and out of the battery, cycle count, production number, etc. During charge the BMU reports these values to the charge PC that controls the charger current and voltage. Normal charge is constant current until a cell voltage of 4.20 V is reached, then constant voltage until the charge current goes below a set value. If any cell voltage, temperature or current is outside the allowed range (3.00–4.25 V) the BMU disconnects the battery. If the charge PC measures any fault condition, the charge will be terminated. A separate set of analogue circuits also senses the cell voltages and disconnects the battery if a voltage reading outside the allowed window is read. The analogue circuits have larger allowable voltage windows (2.70–4.30 V) and should only operate if the digital circuit fails. The analogue circuit is connected to the battery at all time. The BMU also contained circuits for battery balancing by bypassing part of the charge current from those cells that had the highest voltage reading during charge.

During operation of the BMU, current, cell voltages and battery temperatures were transferred to the charge PC during charge and to the AUV control processor (CP) during discharge. The data were stored.

8. Hydrogen fuel cells

A fuel cell based on compressed hydrogen in composite cylinders and pure oxygen is an interesting alternative for underwater vehicles. The system as such is bulky, but the low weight of composite cylinders can make the total performance of a deep diving AUV very high as the hydrogen storage can have the additional function of buoyancy compensation [9]. A typical AUV for deep-sea survey operation may contain 300–600 l of syntactic foam in order to achieve neutral buoyancy. Foam density is approximately 500 kg m^{-3}, increasing with design depth. This density is comparable to a state of the art carbon fibre composite gas bottle filled with hydrogen with a working pressure of 450 bar. Although it should be recognized that the rating for external pressure is significantly less than the rating for internal pressure, carbon fibre composites is an excellent material for pressure vessels. The land-based interest in fuel cells has resulted in a number of commercially available and officially approved composite cylinders for hydrogen storage. This is not the case for compressed oxygen, but here the option of using hydrogen peroxide as an oxygen carrier may be used as an alternative.

Off-base operation of fuel cell powered survey AUVs also requires a minimum size of the mother vessel as the weight and volume of the on-board systems (electrolyser or hydrogen bottles and high pressure pump for hydrogen production) may be fairly high.

There is at present a large interest in hydrogen/oxygen fuel cells for underwater use. The German AUV DeepC [12] as well as the Japanese AUV Urashima [13] are designed with hydrogen/oxygen fuel cells. The technology is mature for large submarines and space application and a miniaturization of the systems for commercial application in AUVs is expected.

9. Discussion

In Table 3, some power sources that have been used in AUVs to date (or in progress of development in conjunction with a specific AUV program) are compared. The following assumptions have been made in the performance calculations.

AUV volume is 1.2 m^3, with 25% of the total volume allocated to the power source. It is assumed that this volume is kept neutrally buoyant by using syntactic foam with a density of 550 kg m^{-3} and aluminium (Al 6082 T6) as the pressure container material. Maximum design depths used in the calculations are 1000 and 3000 m. For the endurance calculations, a propulsion power of 350 W (corresponding to constant velocity of approximately 4 knots) and a hotel load of 400 W have been used.

In the low performance end, we find the conventional lead–acid and Ni-based rechargeable technologies, which are simple, benign and low-cost systems, often used on AUVs for testing and experimentation. A great leap in performance came with the introduction of rechargeable lithium ion batteries. They are simple to use and have good cycle life, thereby providing acceptable overall life cycle cost. Safety is acceptable, if the proper best practices in battery design and operation are employed. Today, they are replacing silver zinc as the workhorse of the AUV community.

Semi-fuel cells based on aluminium metal anodes, hydrogen peroxide and alkaline electrolytes have been used by commercial offshore industries AUVs since 1998. These systems operate at ambient pressure and are therefore very attractive in deep-water systems (e.g. 3000 m). Turn-around time is low (less than four hours) and endurance is high (60 h in HUGIN 3000, which is a larger vehicle than the one used in the calculations above). The system is fairly complex and involves onboard infrastructure and logistics that requires skilled personnel for operation.

Hydrogen–oxygen fuel cells are now approaching maturity in other applications (e.g. air independent propulsion for

Table 3
Typical performance figures of electrochemical power sources in a generic AUV of a total volume of 1.2 m^3

Technology	Type	Energy density (Wh/dm^3)	Endurance (h)	Cost	Logistics/maintenance
Lead–acid	Rechargeable	10–20	4–8	Low	Low
NiCd/NiMH	Rechargeable	10–30	4–12	Low	Low
Alkaline batteries (heated to +45 °C)	Primary	10–30	4–12	Low/high	Medium
Silver–zinc	Rechargeable	30–50	12–20	High	Medium
Lithium ion (D-cells)	Rechargeable	40–70	16–28	Medium	Low
Lithium polymer (poach)	Rechargeable	50–75	23–30	Medium	Low
Aluminium–oxygen	Semi-fuel cell	80–90	32–36	Medium	High
Hydrogen–oxygen	Fuel cell	100+	40+	Medium	High
Lithium batteries	Primary	100–150	40–60	High	Low

conventional submarines), but are only in its infancy when it comes to AUVs. Fuel cells have a fair potential in the future, in particular in the larger AUVs.

Primary lithium batteries provide very high energy density and endurance, but operating costs and battery safety are of great concern. This will limit the use of primary Li batteries to applications that are valued important enough to accept the high risk and cost levels [14].

Seawater batteries, in particular, batteries that exploit the oxygen in the ocean, have also been used in AUVs, however these systems have not been included in Table 3. The reason for this is that the design of the battery is so tightly integrated with the vehicle itself that it is not possible to comply directly with the initial assumptions. However, the general performance attributes of seawater batteries are a very long endurance capability, but a low power (load) capability that limits the application to a low power sensor suite [2].

Compared to commercially available pressure tolerating polymer batteries, the energy density of the HUGIN 1000 battery module is modest (ca. 60 Wh kg^{-1}). This is partly caused by the use of syntactic foam firewalls and partly by the use of a metal battery container that keeps its shape in a fire. Firewalls made from buoyancy materials do not however decrease the system energy, as they contribute to the buoyancy of the vehicle. Until we have more experience with these batteries, the penalty of using heat and corrosion resistant materials in the battery box will be accepted. The same is the cause for using silicone oil: compared to mineral oil, the density is higher and it is more compressible, increasing the difficulties with buoyancy control of the vehicle. With increased courage based on more experience, lighter and more flammable materials may be used in the future.

The safety considerations with aluminium semi-fuel cell are related to the handling of the chemicals, and to the small amounts of hydrogen and oxygen present in the gas separation system of the AUV. The energy in this volume of explosive gas is too small to be a threat to a properly equipped crew or to the mother vessel.

Similar considerations may be applied to a fuel cell system where an explosion or fire may take place in the fuel cell pressure vessel, releasing a moderate amount of energy. The fuel as such, should not be a problem for a surface ship with well-ventilated AUV handling facilities.

Primary lithium batteries are expensive and their behavior under abuse conditions is a safety concern. For some applications, however, the high range capability associated with their high specific energy outweighs other factors, such as cost, and the unpleasant behavior under abusive conditions.

10. Conclusion

The power source is an important performance-determining component of any AUV and its choice should be done early in the design phase. Depending on the size and use of the AUV, different power sources should be used. For small AUVs with shallow design depth, primary lithium and lithium ion working at normal pressure are preferred. As the design depth is increased, pressure tolerant lithium ion gets an edge. For larger AUVs designed for deep-water operation, pressure tolerant semi-fuel cells and hydrogen/oxygen fuel cells that can use their gas storage as part of the AUV flotation gives the best performance.

References

[1] Ø. Hasvold, A magnesium-seawater power source for autonomous underwater vehicles, in: A. Attewell, T. Keyly (Eds.), Power Sources, vol. 14, 1993, pp. 243–255.

[2] Ø. Hasvold, T. Lian, E. Haakaas, N. Størkersen, O. Perelman, S. Cordier, CLIPPER: a long-range, autonomous underwater vehicle using magnesium fuel and oxygen from the sea, J. Power Sources 136 (2004) 232–239.

[3] Ø. Hasvold, K.H. Johansen, O. Mollestad, N. Størkersen, The alkaline aluminium/hydrogen peroxide power source in the HUGIN II unmanned underwater vehicle, J. Power Sources 80 (1999) 254–260.

[4] Ø. Hasvold, K.H. Johansen, K. Vestgaard, The alkaline aluminium hydrogen peroxide semi-fuel cell for the HUGIN 3000 autonomous underwater vehicle, in: Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, San Antonio, TX, June 20–21, 2002, pp. 89–94.

[5] Kongsberg Maritime, www.km.kongsberg.com.

[6] C&C Technology, www.cctechnol.com.

[7] Ø. Hasvold, US Patent US 6,573,008 B1.

[8] Geoconsult, www.geoconsult.com.

[9] Ø. Hasvold, N. Størkersen, Electrochemical power sources for unmanned underwater vehicles used in deep sea survey operations, J. Power Sources 96 (2001) 252–258.

[10] K. Streitlien, J. Scott Willcox, Pressure-Tolerant Batteries for Autonomous Undersea Application, see: www.bluefinrobotics.com.
[11] Recommendations on the TRANSPORT OF DANGEREOUS GOODS, Manual of Tests and Criteria, ST/SG/AC.10/11/Rev3, Amendment 1, United Nations, Geneva, New York, 2002.
[12] www.deepc-auv.de.
[13] www.jamstec.go.jp/jamstec-e/rov/auv_ex1.html.
[14] N. Størkersen, Ø. Hasvold, Power sources for AUVs, in: Proceedings of the Science and Defence Conference, Brest, France, October 19, 2004.