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Power Sources for AUVs

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1 Introduction

High energy density power sources is one of the technology areas that needs to be pushed to enable us to exploit the true operational benefits of autonomous underwater vehicles (AUV). Ideally, we want AUVs to be able to operate continuously over many days (weeks even) with a powerful multifunction sensor suite on board, and at the same time limit the overall size of the vehicle body to enable simple operation from vessels of opportunity. Evidently with the current state of art of batteries and fuel cells, this means introducing compromises. Pushing battery and fuel cell technology is therefore one of the areas that will provide most benefit to the operational community.

The various applications of AUVs dictates very different technical requirements for power sources. Therefore in reality there are no single, ultimate power source for AUVs, rather a range of technologies that may be adapted through a detailed customs design effort. Technology driving elements in addition to power and endurance specifications are the constraints introduced by limited volume and form factors allowed for the power source, the operational depth, the safety level that is acceptable, the requirements for turn-around time (e.g. recharging time), the level of logistics support that is available, the technical skill on board the support ship and the cost constraints.

2 Power sources for generic AUVs

When comparing various alternative power sources for AUVs, the intimate relation between the power source and the vehicle itself must be taken into consideration. This means that the quality figures normally stated by the battery manufactors, e.g. energy density, do not apply directly, unless a specified set of assumptions has been made. For instance, we must take into consideration that the weight of the vehicle must be equal to the Archmedes buoyancy force for the vehicle to be neutrally buoyant. In order to be able to compare alternative power sources on equal terms, we must therefore assume that the power source itself is neutrally buoyant. This means that in addition to the plain power source, weight and volume for buoyancy material and pressure containers must be added in order to be able to calculate the true energy density in the AUV. In this buoyancy calculation the operational depth then comes in as a driving parameter. This is both due to the fact that the specific density of available buoyancy material increases with depth rating and that the weight of pressure containers increases with design depth as well. This means that both operational (maximum) depth and the specific materials used for buoyancy and containers (Aluminium, Titanium, Fibre reinforced plastic or glass containers) should be specified in order to do a proper comparison of electrochemical power sources for AUVs.

Some electrochemical power sources (e.g. fuel cells) are highly complex and they therefore need advanced auxiliary systems and fuel storage units to operate. These auxiliary and fuel storage systems do not necessarily scale linearly with energy production. This means that there will be minimum vehicle size (i.e. battery volume) that can accommodate these technologies and that the energy density of these technologies to some extent will be dependent on actual volume.

When ranging power sources in terms of providing AUV endurance, assumption must be made about the size of the vehicle itself, the fraction of the total volume allocated to batteries and the power cycle pattern. Vehicle size itself is an important parameter, since the available energy on board scales with volume, whereas propulsion power in general scales with surface area. This means that endurance requirements are easier to meet in large vehicles than in small. The power load consists of propulsion and hotel load (sensors and other systems except the propulsion motor(s)). Propulsion power is highly sensitive to vehicle speed (in third power), which means that the penalty of designing AUVs with nominal speed beyond the 3-4 knot window is usually too high.

Electrochemical power sources for AUVs may be divided into four different groups:

1. Standard batteries inside a pressure container 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

Examples in the first category are conventional lead or Ni-based rechargeable batteries, silver-zinc rechargeable batteries, primary and rechargeable lithium batteries. In the second category examples are Lithium-polymer ambient pressure batteries and Aluminium-Hydrogen peroxide batteries (semi fuel cells). Seawater batteries makes use of the environment (the sea) itself in the process of generating energy, and therefore fall into a category of its own. Fuel cells are a family of technologies operating on hydrogen fuel and oxygen.

When comparing power sources, a number of factors should be considered in addition to specific energy (and power) capability, typical factors being cost, battery life (both in terms of cycle and calendar life), maintenance requirements and safety.

In Table 1 the technologies that have been used in AUVs to date (or in progress of development in conjunction with a specific AUV program) are listed. 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 depth used in the calculations are 1000m and 3000m. 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.

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

Table 1: Typical performance figures of electrochemical power sources in a generic AUV of a total volume of 1.2 m^3.

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. Alkaline primary batteries are also benign batteries to use, but are slightly more temperature sensitive. Operational cost may also be high if the AUV is to be used on a continuous basis as the cost is more or less proportional to operation time. The silver-zinc technology was mostly used in the early period of AUV history, but due to high initial cost and low cycle and calendar life, this system is not the preferred choice for modern AUVs.

A great leap in performance came with the introduction of rechargeable Lithium Ion batteries. These systems may sustain vehicle operation of one day for small and medium sized AUVs, 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.

A derivate of the Li-ion technology that just recently has been commercialised, is the Litium polymer batteries. These power sources may be operated at ambient pressure, using polymer poach cell technology from the electronics industry (PCs, mobile phones, etc). These poach cells are stacked into cell modules and moulded in a polymer resin, which are then stacked into larger battery modules. Performance are similar to the conventional Li-ion batteries, but they are insensitive to operational water depth, which make them especially attractive for deep water AUVs.

Semi-fuel cells based on Aluminium metal anodes, hydrogen peroxide (oxygen) and alkaline electrolytes have been used by the commercial offshore industry in the HUGIN 3000 AUVs since 1998. These systems operate at ambient pressure and are therefore very attractive in deep water systems (e.g. 3000 m). Recharging is done by replacing consumed anodes and electrolyte between dives. Turn-around time is low (less than four hours) and endurance is high (60 hours 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 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 cost and battery safety is of great concern. This will limit the use of primary Li batteries to applications that are valued important enough to accept the very high risk and cost levels.

Seawater batteries, in particular batteries that exploits the oxygen in the ocean, have also been used in AUVs, however these systems have not been included in table 1. 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 which limits the application to a low power sensor suite.

3 Battery development at FFI

Norwegian Defence Research Establishment (FFI) has since the mid 1970's actively pursued developments of several of the above mentioned technologies. FFI has also worked extensively on Lithuim battery safety research, both to try to establish the safe operational envelope of the various Li-battery systems and also investigate possible failure mechanisms in these batteries. However, in our experience most Li-based rechargeable systems are safe to use as long as the proper safety measures are employed, whereas large primary lithium batteries should only be used with special caution. If the safety precautions fails, Lithium batteries may vent and burn violently if subjected to overcharge, overdischarge, internal shorts or external heating. Some types of primary lithium batteries have been seen to explode violently, causing extensive damage. In addition the fumes from vented and exploded batteries may be toxic to personnel.

Throughout the 1980's FFI pioneered work to develop portable Aluminium-air semi fuel cells for powering communication equipment in the Army. This initial effort founded the basis for the Aluminum-Hydrogen peroxide (Al/HP) semi fuel cell that was developed for the HUGIN AUVs. These systems are currently being used by the offshore survey companies FieldCare, GeoConsult, C&C Technologies and Fugro (2005). The first Al/HP system was developed in the period 1995-98 in order to meet the very demanding requirements of the offshore survey application. The Al/HP battery for HUGIN 3000 now provides 50 kWh of energy and 60 hours of endurance at 4 knots continuous speed with all sensors running (multibeam echosounder, sidescan sonar, subbottom profiler and CTD). The depth rating is 3000 m. With turn-around times of only a few hours for every 60 hours of operation, this technology in effect enables a continuous survey service, which makes the HUGIN vehicles a very cost-effective tool for commercial seabed mapping.

Figure 1: HUGIN 3000 with the battery compartment (right) showing the 50 kWh Al/HP semi fuel cell.

In parallel with the semi fuel cell developments in the 1980s, the same technology basis was used develop seawater batteries for underwater applications. Initially these batteries were designed for powering stationary subsea equipment (subsea monitoring systems, oil production facilities, seismic instrumentation) and light buoys (for ship navigation). These batteries used magnesium in stead of aluminium as anode material, the electrolyte was seawater, and special cathodes were developed to exploit the dissolved oxygen in seawater. Since this battery could make use of the environment for energy production, very high energy densities has been demonstrated, however the power density is limited by the amount of dissolved oxygen in the ocean. Typical discharge times of these batteries are 2-5 years, with the option of physically replacing consumed anodes by the aid of ROVs. The deepest installation of these seawater batteries is off the coast of Japan at 2200 m water depth.

In 1991 FFI started a project to adapt this stationary seawater battery technology to AUVs. The battery operation is dependent on a continuous flow of seawater and this particular AUV (AUV-DEMO) was designed for very high hydrodynamic efficiencies, and at the same time so that the necessary seawater was forced thorough the battery by the vehicle movement through the water in order for the cathodes to access the oxygen and generate power. In 1993 AUV-DEMO was demonstrated in the Skagerrak (between Norway and Denmark) over a distance of 100 nautical miles. The endurance potential of this vehicle was approximately 1200 nautical miles, and a full discharge test of an identical battery under simulated AUV conditions was also performed.

In the late 1990s FFI started a collaboration with the hydrodynamic research laboratory Bassin des Carènes d'Essais in Val de Reuil, France. The purpose of this collaboration was to further develop the seawater battery concept for AUVs, both in order to extend the endurance capability through a more optimised vehicle body design and by introducing internal pumping devices for battery flow. A common test vehicle, CLIPPER, was built and tested at the Val de Reuil facility where the French team provided the vehicle body and propulsion system, and FFI delivered the internal pressure housing and the seawater battery. A scale battery was also built and tested in a simulated set up outside Bergen, Norway. The results from these tests indicates a potential endurance capability of the CLIPPER vehicle in the order of 1600 nautical miles over 2-3 weeks. This corresponds to the distance between Svalbard and Alaska crossing the North pole. However only low power sensors may be operated from the seawater battery, and we still need developments on other areas of AUV technology to sustain such long missions.

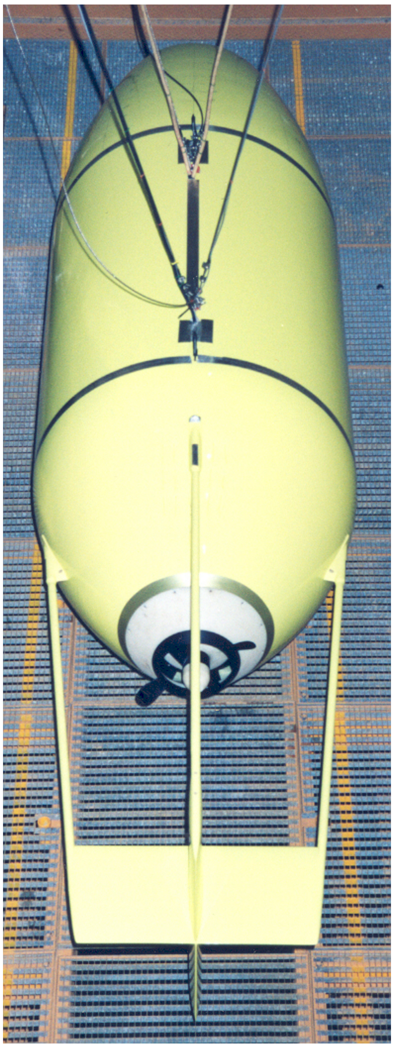

Figure 2: AUVs with seawater batteies: AUV-DEMO (left) and CLIPPER (right)

FFI has also developed ambient pressure Lithium polymer batteries for the HUGIN 1000 vehicle series. The HUGIN 1000 is developed primarily with military applications in mind. The first vehicle in this series was delivered to the Royal Norwegian Navy (RNoN) in January 2004 and a second vehicle is scheduled for delivery in late 2005. The Lithium polymer battery comes in modules of approximately 5 kWh, and two or three of these modules are used in the HUGIN 1000 system, providing 10 or 15 kWh respectively.

4 The HUGIN AUV program

As indicated above, Norway has over the last decade invested heavily in AUV technology for both civilian and military applications. The HUGIN AUV system is a market leader in the offshore survey business and has to date accumulated more than 5000 hours of commercial seabed mapping surveys world wide. The HUGIN 3000 systems, delivered by Kongsberg Maritime, acquires detailed seabed information to be used by the oil companies in the planning of their subsea site and pipeline developments. The three operational systems have operated from the Barents sea in the north to Gulf of Mexico, Brazil and West Africa in the south in water depths down to 2900 m. The AUV technology has created a paradigm shift in this marked niche by making the deep water survey business more effective.

In parallel the Royal Norwegian Navy (RNoN) is now in process of establishing a military AUV capability as well. The military AUV development program benefited from the vast amounts of operational experience gathered by the civilian AUVs, and merged this with the advanced technologies necessary for a full-capability military AUV system. This includes accurate, autonomous navigation and control, highly developed sustainability and robustness, and very high resolution sensors. The end result is the HUGIN Mine Reconnaissance System, an AUV particularly suited for forward minehunting and Rapid Environmental Assessment (REA) operations. Throughout the program an extensive trials and experimentation effort have been performed including the participation in the NATO Northern Light exercise in Scotland and in a Finnish Navy exercise in September 2003 using the FFI test and demonstration system, HUGIN I. In January this year FFI and Kongsberg Maritime delivered the first operational system to the Navy, based of the new generation of HUGIN vehicles, the HUGIN 1000.

Figure 3: The RNoN minehunter KNM Karmøy with the HUGIN I (left), and HUGIN 1000 on the aft deck (right)

After delivery this system underwent a series of training missions and informal acceptance tests. Shortly after the initial tests had been completed, The minehunting vessel KNM Karmøy and HUGIN 1000 participated in the two NATO exercises *Joint Winter* in Northern Norway and in the *Blue Game* exercise in the Southern parts of Norway. The KNM Karmøy with HUGIN 1000 are from October being deployed in one of the standing NATO MW commands, the MCMFORNORTH.

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