Energy storage for long endurance AUVs

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SYNOPSIS

Energy storage is a key issue for long endurance autonomous underwater vehicles. Mission duration, speed through the water and sensor and payload capabilities are constrained by the energy available, which in turn is governed by the characteristics of the energy source or sources and the mass and volume that the vehicle designer can devote to the energy system. Tensioned against these technical issues are those of cost, operational life, ease of use, maintainability, safety, security and continuity of supply of the items forming the energy system. This paper focuses on primary and secondary electrochemical batteries, how existing vehicles have constructed their energy storage systems and seeks to establish whether electrochemical cells alone will be able to provide the necessary energy at an affordable cost for future long endurance AUVs and the missions being considered.

INTRODUCTION

Energy is a key issue for long endurance autonomous underwater vehicles (AUVs). Mission duration, speed through the water and sensor and payload capabilities are constrained by the energy available, which in turn is governed by the characteristics of the energy source or sources, the mass and volume that the vehicle designer can devote to the energy system and the details of how the weight of the energy system is countered with buoyancy. Most AUVs are dependent on stored energy for their operation. The few exceptions, not considered in this paper, use energy from the environment, either directly as in the case of the thermal engine of the Slocum glider [1] or to recharge onboard supplies as in a solar-powered AUV [2].

Authors’ Biography

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James Jamieson is employed as a Principal Engineer in the Remote Technology Group of Subsea7 where he presently leads the AUV engineering team. His background is in underwater systems engineering, with over 15 years experience in ROV, AUV, and tooling control system development.

Scott Mitchell is a specialist in analogue and power management electronics at SEA Ltd. He has over 20 year experience in the design of power management systems for spacecraft, now being applied to unmanned underwater vehicles.

Kieran Rutherford is a student on the Engineering Doctorate program at the University of Southampton. His research subject is the Energy and Efficiency of Underwater Vehicles.
Batteries, either primary or secondary, are by far the most common choice of energy storage for past and present AUVs. In Jane’s Underwater Technology [3] information on the energy source is available for 61 different AUVs. Batteries, either primary or secondary, were used in 53 of these vehicles (3 primary, 42 secondary, 4 primary or secondary, 4 of unspecified type). Aluminium oxygen semi-fuel cells were used in four vehicles; only one vehicle claimed to use a fuel-cell (hydrogen-oxygen); an air-breathing diesel was used by two semi-subs (one an adaptation of the other) and a closed cycle diesel engine was used by one vehicle. Batteries are likely to remain the technology of choice for at least the next five years, despite their limitations. Partly this is because the technical options are tensioned against cost, operational life, ease of use, maintainability, safety, security and continuity of supply of the items forming the energy system.

Given their importance, this paper focuses on primary and secondary electrochemical batteries. A review of the proportion of an AUV’s mass given over to the energy source is followed by a description of how four existing vehicles (REMUS, Autosub Geosub and USS Cutthroat) have constructed their energy storage systems ranging from secondary lead-acid to primary lithium cells. The paper then tries to answer three key questions:

- How does the choice of buoyancy material affect the proportion of the vehicle’s mass that can be assigned to the energy source?
- Will primary or secondary electrochemical cells provide a technical solution to the energy requirements of future long endurance AUVs?
- If so, what will be the likely cost? Given that the relationship between cost of energy and specific energy is shown to be highly non-linear.

The discussion highlights the importance of an iterative design process that can minimise the energy requirement. Alternatives to increasing the stored energy, such as reducing the vehicle drag and reducing the vehicle payload energy requirements are explored in the context of non-linear relationships between battery specific energy and cost.

**FACTORS AFFECTING THE MASS AVAILABLE FOR ENERGY STORAGE IN AN AUV**

The mass and volume of an energy source within an AUV is a major design factor affecting vehicle size and, as a consequence, handling and platform integration. A simple graph, Fig 1, shows on the ordinate axis what mass the energy source would need to be for total mission power requirements of 1, 10, 100 and 1000 kWh as a function of the specific energy of the energy source. Long endurance propeller-driven AUVs are likely to require at least 100 kWh of energy. While this simple approach can be used to estimate the mass of the energy source knowing its specific energy and the mission energy requirements, assessing what the energy source mass means for the overall mass of the AUV is not straightforward. The following section examines this issue and discusses the ratio of energy system mass to overall mass in present and past generation AUVs.

The overall mass (and hence size, given that it is usual for AUVs to be near neutral buoyancy) of an AUV can be expressed as an equation whose form depends on the configuration of the vehicle. For an AUV composed of multiple pressure vessels, with the energy source within one or more pressure vessels the mass of the vehicle is given by:

\[ M_{AUV} = M_E + M_{BE} + \sum_{i=1}^{n} M_i + \sum_{j=1}^{n} M_{Bj} \]  

(1)

where \( M_E \) is the mass of the energy source, \( M_{BE} \) is the mass of the pressure vessel(s) containing the energy source, \( M_i \) the overall mass of the \( i^{th} \) pressure vessel or other component and \( M_{Bj} \) is the mass of the \( j^{th} \) weight or added buoyancy to achieve near neutral buoyancy overall. For an AUV with a single pressure vessel this equation can be used, by letting \( M_{BE} \) represent the mass of the single pressure vessel, \( M_i \) the mass of the \( i^{th} \) internal component and \( M_{Bj} \) the mass of the \( j^{th} \) weight (if any) added to achieve near neutral buoyancy overall.
One design objective for a long endurance AUV is to maximise the proportion of the total vehicle mass available for the energy source. That is, the ratio of $M_E$ to $M_{AUV}$ should be as high as possible, subject to other design requirements being met, for example diving depth and payload capacity. While the ratio of $M_E$ to $M_{AUV}$ provides a simple metric, the denominator term contains $m+n+I$ terms, and hence up to $m+n+I$ factors that influence the ratio. Nevertheless, examining the ratio $M_E$ to $M_{AUV}$ for existing vehicles can provide an assessment of the energy-carrying capacity of AUVs that have been built. Fig 2 shows the ratio $M_E$ to $M_{AUV}$ for 30 AUVs using data obtained from [3]. In many cases, $M_E$ was not provided, but has been estimated from the data on energy source capacity and chemistry, hence the error bars on the data in Fig 2. Note that the vehicles are ranked on the abscissa by claimed maximum depth. The most immediate conclusion is that no current vehicle has a $M_E$ to $M_{AUV}$ ratio of greater than 0.5 and that no vehicle capable of diving deeper than 1500 m (Autosub and to the right) has a $M_E$ to $M_{AUV}$ ratio of greater than 0.25.

Other conclusions need to take account of some of the factors within the $m+n+I$ terms in $M_{AUV}$. For example, many of the vehicles with a ratio of below 0.15 are test or demonstrator vehicles, where there may be little need to provide significant energy, at least in their present configurations; examples include the Twin Burger, Sea Squirt and Urashima. Conversely, the vehicle with the highest $M_E$ to $M_{AUV}$ ratio, the Pilot Fish, is a shallow diving test vehicle, comprising a single plastic pressure vessel, built to demonstrate the effectiveness of an oscillating fin thruster, with little in the way of additional payload and instrumentation, and a target to achieve a similar power-to-weight ratio as marine creatures, in the region of 25 W kg$^{-1}$ [4]. For the Theseus AUV, figures for its test configuration (with a 20 kWh NiCd battery) and its operational configuration (with a 360 kWh AgZn battery) are included, showing a significant increase in $M_E$ to $M_{AUV}$ ratio for the operational vehicle.

For those vehicles with their energy source contained within one or more pressure vessels, the mass of the pressure vessel(s) can be a significant proportion of the total vehicle mass. If the size (mass) of the vehicle is constrained, then the performance and choice of the buoyancy material is important to the energy-carrying capability of the vehicle. Stevenson and Graham [5] give indicative graphs and figures for the mass to displacement ratio and densities of pressure vessels and buoyancy foams. Rearranging to give the mass to buoyancy ratio for ring-stiffened cylinders gives:

$$\frac{M_B}{B} = \left( \frac{SP_w}{K - SP_w} \right)$$

where $M_B$ is the mass of the pressure vessel, $B$ the buoyancy provided, $S$ the required safety factor, $P_w$ the maximum working pressure (in MPa) and $K$ a material dependent constant: $\sim 75$ for titanium, 100-120 for carbon fibre reinforced plastic (CFRP) and $\sim 67$ for aluminium. The resulting mass to buoyancy ratio for titanium and CFRP ring-stiffened cylinders are shown in Fig 3 together with those for a number of different buoyancy foams, a ceramic cylinder [6] and two sizes of borosilicate glass buoyancy spheres.
Fig 2 Energy system mass to total vehicle mass for 30 AUVs, ranked by maximum diving depth.

The balance of advantage, in terms of minimising the mass to buoyancy ratio and hence vehicle mass at the required working depth, alters from the ring-stiffened pressure vessels to glass spheres and foam buoyancy above 24-35 MPa (2400-3500m) at a safety factor of 1. More realistically, the cross over point would be at ~ 2000 m for the titanium pressure vessel (at a safety factor of 1.2) and 1750 m for the CFRP if a larger safety factor such as 2 was used.

Fig 3 Mass to buoyancy ratio for buoyancy foams, glass spheres and ring-stiffened cylindrical pressure vessels in titanium and CFRP.
The impact of buoyancy provision on the overall ratio of $M_E$ to $M_{AUV}$ may be seen by considering two examples. First, an AUV with a maximum working depth of 600 m with its energy source in a titanium ring-stiffened pressure vessel with a safety factor of 1.2 (with $M_E/B = 0.10$) leading to a maximum ratio of $M_E$ to $M_{AUV}$ of 0.90. Second, an AUV with a maximum working depth of 5000 m, with its energy source in a titanium ring-stiffened pressure vessel with a safety factor of 1.2 (with $M_E/B = 4.0$) leading to a maximum ratio of $M_E$ to $M_{AUV}$ of 0.20. For this deep diving vehicle, there would be significant advantage in providing the buoyancy using glass spheres (with $M_E/B = 0.7$), leading to a maximum ratio of $M_E$ to $M_{AUV}$ of 0.59 – a three-fold improvement in the energy payload for the same overall weight.

Achieving the endurance gain through increased effective specific energy for deep diving AUVs by the use of foam buoyancy rather than pressure vessels requires that the energy source should be able to operate at ambient pressure. This severely reduces the choice of cell chemistries and cell construction. Lead acid cells have been used in this mode for many years. More recently lithium solid polymer cells have been operated at pressure [7]. It is an open question as to whether cell chemistries such as lithium carbon monofluoride (LiCF) constructed as pock cells could be operated in a pressure-balanced mode. In all of these cases, the mass of the protective housing and any inert pressure compensating fluid would decrease the effective specific energy.

Given these different options, how can they be compared? The concept of specific energy at zero buoyancy as a performance metric has been proposed by Mierlo and others. That is, the energy source and the buoyancy needed (in whatever form) is considered as one unit and the energy available per kg of weight in air is compared. Table I shows this comparison for a range of cell types for a 600 m AUV using batteries within a ring stiffened titanium pressure vessel and a 5000 m AUV with (a) batteries within a ring stiffened titanium pressure vessel, (b) batteries within 17” glass spheres and (c) the cells at ambient pressure with the buoyancy provided by empty glass spheres. At 5000 m (50MPa) the latter option provides the highest specific energy for the low gravimetric density lithium cells.

<table>
<thead>
<tr>
<th>Chemistry and example type</th>
<th>Type</th>
<th>Specific Energy (Wh.kg⁻¹)</th>
<th>SE at $p=1$ Ti PV 6MPa (Wh.kg⁻¹)</th>
<th>SE at $p=1$ Ti PV 50MPa (Wh.kg⁻¹)</th>
<th>SE at $p=1$ Glass Spheres at 50 MPa (Wh.kg⁻¹)</th>
<th>SE cells at pressure, Glass Spheres 50 MPa (Wh.kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>Sec</td>
<td>34</td>
<td>85</td>
<td>31</td>
<td>6.8 (20)</td>
<td>18.5</td>
</tr>
<tr>
<td>Yuasa NPL78-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium polymer</td>
<td>Sec</td>
<td>95</td>
<td>157</td>
<td>86</td>
<td>19</td>
<td>56</td>
</tr>
<tr>
<td>LG Chem Gen III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Manganese alkaline D cell at 20°C 0.2W cell⁻¹</td>
<td>Pri</td>
<td>110</td>
<td>271</td>
<td>100</td>
<td>22</td>
<td>65</td>
</tr>
<tr>
<td>Lithium ion</td>
<td>Sec</td>
<td>160</td>
<td>394</td>
<td>145</td>
<td>32</td>
<td>94</td>
</tr>
<tr>
<td>CGR-18650HG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not suitable</td>
</tr>
<tr>
<td>Lithium thionyl chloride</td>
<td>Pri</td>
<td>420</td>
<td>737</td>
<td>382</td>
<td>84</td>
<td>247</td>
</tr>
<tr>
<td>PT2300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not suitable</td>
</tr>
<tr>
<td>Lithium CF</td>
<td>Pri</td>
<td>709</td>
<td>1095</td>
<td>645</td>
<td>142</td>
<td>417</td>
</tr>
<tr>
<td>LCF111</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>If achievable: 474</td>
</tr>
</tbody>
</table>

Note the very poor performance of the cells in the ring stiffened titanium pressure vessel at 50 MPa. In this case the analysis shows that primary manganese alkaline cells would have a similar effective specific energy as lead acid cells within glass spheres. Of course, safety considerations may well rule out the use of lead acid cells in sealed glass spheres, in which case, at a penalty of less than 10% in specific energy, they could be used in pressure balanced mode in conjunction with the glass spheres. Long endurance deep diving vehicles clearly benefit from using pressure tolerant batteries.

**BATTERY USE IN FOUR CONTRASTING VEHICLES**

**REMUS**

REMUS is a small AUV that can be configured for different applications, hence not all versions are the same length and volume and different versions may have different energy sources. The basic vehicle is constructed in
a single pressure vessel 1.6 m in length and 0.19 m diameter, with a weight of 37 kg [8]. The standard depth rating is 100-150 m. In standard form the energy source is a 1 kWh secondary lithium ion battery, estimated to weigh 7 kg, giving a ratio of $M_E$ to $M_{AUV}$ of 0.19. Versions of REMUS have been fitted with primary lithium cells for longer endurance, providing at least double the 22-hour endurance of the lithium ion pack. In such a small vehicle the high cost of these primary cells may not be such an issue.

The REMUS vehicle, given its small size, comes well equipped with sensors (CTD, light backscatter), navigation instruments (acoustic long baseline, acoustic Doppler velocity log) and all of the necessary systems to provide autonomy. This suggests that the sum of the masses of these components forms a significant part of the overall AUV mass, resulting in a relatively low ratio of $M_E$ to $M_{AUV}$ despite the advantages of its single pressure vessel construction and shallow diving depth. As new technology emerges to replace some of the heavier parts of the vehicle’s systems, it is possible that the $M_E$ to $M_{AUV}$ could increase. As an example, the four transducers of the Doppler velocity log can be replaced with a single phased array transducer now under evaluation.

**Autosub**

At 6.8 m long and 0.9 m in diameter Autosub is a large AUV designed for applications in ocean science [9]. Autosub is constructed as an open frame clad with panels, with a free-flooding internal space for the payload and vehicle systems, most within their separate aluminium, stainless steel or titanium pressure vessels. Many of these pressure vessels are rated to over 3000 m. The largest pressure vessel holds the energy source and its working pressure limits the diving depth of the vehicle. In its first form (Autosub-1) the vehicle was fitted with seven 12 V 80 Ah lead acid batteries providing 6.7 kWh of energy within a 500 m rated glass fibre reinforced plastic (GFRP) pressure vessel (mass 160 kg) that was not ring stiffened. The vessel used titanium end domes rated to 6000 m (mass of 45 kg). This combination provided a mass to buoyancy ratio of 1.085 – far higher than a ring stiffened pressure vessel with the same depth rating. A ring stiffened titanium pressure vessel with the same buoyancy and a 500 m rating at a safety factor of 1.5 would weigh 39 kg, reducing the overall mass of the vehicle by at least 166 kg. The energy source in Autosub-1 weighed 300 kg and the overall vehicle weighed 1578 kg, a $M_E$ to $M_{AUV}$ ratio of 0.19.

In 1997 the energy source was upgraded to primary manganese alkaline cells to provide increased energy for the same overall weight. A battery comprising 30 strings of 72 ‘D’ cells in series provided some 30 kWh of energy at 25°C and at a power drain of 500 W typical at that time, sufficient for a 253 km mission [10].

In 2000 the vehicle was further upgraded by exchanging the single GFRP pressure vessel centre section for seven ring stiffened CFRP pressure vessels with a working depth of 1600 m (collapse depth of 3300 m) together with added foam buoyancy segments. The mass to buoyancy ratio of the CFRP tubes was 0.78 (total mass 602 kg) and 1.58 for the foam buoyancy (total mass 294 kg). Seven tubes were used, rather than a single large diameter tube because of the difficulty in manufacturing a single thick-walled CFRP tube and because of uncertainty in the as-built strength. A single ring stiffened CFRP tube with the same displacement as the sum of the seven CFRP tubes in the vehicle and the foam buoyancy, assuming the same mass to buoyancy ratio as that of the smaller tubes, would provide an additional buoyancy of 82 kg; that is, its mass would be 82 kg less.

In practice, Autosub is mass not volume limited. Four of the seven CFRP tubes could be filled with manganese alkaline cells, the other three providing buoyancy and dry space for instrumentation and other vehicle systems. In this configuration the maximum battery weight was increased to 700 kg, while the overall vehicle weight increased to 3500 kg, a $M_E$ to $M_{AUV}$ ratio of 0.20. For recent missions, the battery pack was formed of 58 strings of 75 ‘D’ cells in series, 4350 cells in all, weighing 610 kg and providing about 61 kWh of energy at 20°C and the typical Autosub-2 power consumption of 1 kW. Additional instrument payload meant that the battery weight had to be reduced. As described in [11] the use of primary cells proves cost effective for an AUV such as Autosub used in science research campaigns in areas of high risk of loss, such as under sea ice or under ice shelves.

Autosub has a relatively low ratio of $M_E$ to $M_{AUV}$ partly because, as a research vehicle, the design is optimised for flexibility in payload and systems configuration. The use of multiple pressure vessels, many rated to depths exceeding the overall vehicle specification inevitably adds to the overall weight, as does the use of multiple...
small diameter CFRP pressure vessels. The high safety factor allowed for the CFRP pressure vessels is also a factor.

**Geosub**

Although derived from Autosub, Geosub has been optimised for routine use in the offshore Oil and Gas industry. As in Autosub, Geosub currently uses CFRP pressure vessels for the batteries, with a depth rating of 2000m but with the ability to upgrade to 3000 m. One of the modifications was to move from primary manganese alkaline cells to a battery of secondary lithium ion cells to suit the day-in, day-out operation of the vehicle. The development of lithium ion batteries for use in the commercial arena presented some significant technical and operational issues. They included:

- Operational safety
- Environmental impact
- Wide temperature performance
- Packaging
- Weight
- Rapid charging systems.

The final solution was developed by a specialist battery contractor with close attention to the safety and environmental issues. There are four batteries and one charger system. Each battery fits into one of the seven CFRP pressure vessels and comprises a string of 28 sets in series of 33 parallel lithium ion cells. The delivered battery specification is:

<table>
<thead>
<tr>
<th>Battery Voltage</th>
<th>100 V (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity</td>
<td>165 Ah</td>
</tr>
<tr>
<td>Total vehicle Capacity</td>
<td>660 Ah (four batteries)</td>
</tr>
<tr>
<td>Battery Weight</td>
<td>150 kg</td>
</tr>
<tr>
<td>Total Weight</td>
<td>600 kg (four batteries)</td>
</tr>
<tr>
<td>Charge time</td>
<td>6 hours from empty</td>
</tr>
</tbody>
</table>

Battery protection system

- Over / under voltage
- Over current (charge / discharge)
- Over temperature

The Geosub vehicle fitted with four battery packs has a weight of 2400 kg. This gives the Geosub vehicle a \( M_e \) to \( M_{M AUV} \) ratio of 0.25. This gives a vehicle total of 3696 cells, and provides about 66kWh of energy across a wide temperature range.

The use of lithium ion cells has provided Geosub with a \( M_e \) to \( M_{M AUV} \) ratio and total available power slightly greater to that of Autosub and at a depth rating of 2000 m compared to 1600 m. In addition, the move to secondary cell technology has successfully and safely added the day-in, day-out operations capability demanded in the commercial market.

**USS Cutthroat**

USS *Cutthroat* is the world’s largest AUV at 34 m long, 3 m diameter and weighing 196 tons. She was built as a 0.294 scale model of a US *Virginia* class submarine and contains in her single pressure vessel an energy system weighing some 38 tons, a \( M_e \) to \( M_{M AUV} \) ratio of 0.19. The primary propulsion energy system comprises 1680 Valve Regulated Lead Acid (VRLA) cells arranged as four parallel stacks of 420 cells in series giving an operational voltage of 742-900 [12]. An auxiliary battery for instrumentation comprises a single stack of 186 cells. Power density rather than specific energy is the most pressing specification for *Cutthroat’s* energy supply. The main propulsion motor is rated at 3000 hp (2.2 MW), requiring 1300 W per cell during discharge. The installed energy is sufficient for two runs at flank speed (about 20 minutes at >10 m s\(^{-1}\)), three at 75% power and

* AEA Technology Ltd.
seven at 50% power. *Cutthroat* is also fitted with a 15 hp loiter motor; loiter speed and duration are not available, but are estimated at 1.5 m s\(^{-1}\) and up to 95 hours. The performance of *Cutthroat* underlines the energy required for high speed in a large vehicle, with the corollary that a large vehicle is needed to house the energy source when it is a battery that is economic, but of low specific energy. Indeed, low specific energy is an advantage in this case, as the shallow diving AUV with its large single pressure hull would need to have lead ballast added to achieve near neutral buoyancy.

**DISCUSSION**

Lithium ion secondary cells as in REMUS and Geosub are the state of the art for the modern AUV. Although their specific energy is lower than silver zinc cells, their better cycle life and lower cost of ownership make them the cell of choice where the capital cost can be offset against a large number of missions. However, it would take over 6000 kg of lithium ion cells to provide 1000 kWh for a long endurance AUV. Converting that energy source mass to a vehicle mass at the ratio of 0.2 found in a number of current generation vehicles implies an AUV weighing over 30 tonnes. For most purposes such a vehicle would be impractical, except, perhaps, when shore-based.

Battery chemistries with higher specific energy than lithium ion are available. Commercial lithium carbon monofluoride cells have a specific energy of over 700 Wh kg\(^{-1}\) (Table I), over four times that of lithium ion. However, they are single use primary cells. Moreover, they are very costly. Whilst a Watt-hour of energy from a primary manganese alkaline cell costs £0.07, a Watt-hour from Li CF cells costs over £7. The increase in specific energy is at an enormous monetary cost. Therefore, while there are technically feasible battery solutions for providing an AUV with 1000 kWh of energy at a mass of less than 1500 kg (overall AUV mass of 7000 kg) such a vehicle would not be economic.

What are the realistic options for long endurance AUVs? There are several, many of which have been, and remain, topics of research. They include:

- Improve the energy efficiency of the onboard systems and instruments;
- Improve the efficiency of propulsion;
- Reduce the vehicle drag, and maintain low drag throughout missions;

and, following the arguments made in this paper, increase the ratio of \( \frac{M_a}{M_{AUV}} \) by:

- Rigorous control of the mass of each component at the design stage;
- Appropriate choice of materials;
- Not over specifying the depth rating of the vehicle or its components;
- Choosing the optimum form of buoyancy for the working depth of the vehicle;
- Further research into reducing the uncertainty of the actual collapse pressure of FRP cylinders;
- Further research into affordable high specific energy electrochemical cells capable of operating at ambient pressure (for deep-diving vehicles) and
- Research into hybrid energy sources, combining the simplicity and reliability of electrochemical batteries with the high specific energy of other sources such as combustion-based systems.

**ACKNOWLEDGEMENTS**

This work forms part of the Energy and Propulsion topic within the Battlespace Access UUV programme sponsored by the Capability Manager (Manoeuvre) of the UK Ministry of Defence and was carried out under Contract No. RT/COM/2/013. We gratefully acknowledge their support. The views in this paper are those of the authors and do not necessarily reflect those of the Ministry.

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