Unmanned Underwater Vehicle Fuel Cell Energy/Power System Technology Assessment

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Abstract

This paper provides a technology assessment for an Unmanned Underwater Vehicle (UUV) fuel cell energy/power system, including design methodology and design concepts. The design concepts are based on the polymer electrolyte membrane fuel cell operating on hydrogen and oxygen. The technology assessment method presented is a holistic approach which combines alternative hydrogen and oxygen storage (and fuel cell system) options to provide the highest specific energy and energy density – within the constraints of the UUV application. Using this method, some surprising combinations appear as the theoretical “winners” for maximum energy storage within the application constraints of the UUV.

Keywords: fuel cell system, hydrogen storage, oxygen storage, UUV.

Introduction

The primary goal of this technology assessment is to provide an initial evaluation and technology screening for the application of a polymer-electrolyte-membrane (PEM) fuel cell energy/power system (FCEPS), operating on H\(_2\) and O\(_2\), to the propulsion of an Unmanned Underwater Vehicle (UUV). The impetus for this evaluation is the expectation that a PEM-FCEPS has the potential to significantly increase the energy storage in an UUV, when compared to other refuelable Air-Independent-Propulsion (AIP) energy/power systems – e.g., such as those based on rechargeable (“secondary”) batteries. If increased energy storage is feasible, the PEM-FCEPS will enable greater mission duration (range), a smaller UUV, and/or higher performance capabilities within a given mission. A secondary goal of this paper is to outline a design process for optimizing a PEM-FCEPS design within the UUV application constraints.

Within this paper the following definitions are used.

- The Fuel Cell System (FCS) within the FCEPS is the systematic combination of: a fuel cell stack and its supporting valves, manifolds, and other components, hybrid/auxiliary battery or other electrical energy storage, and required electric conversion devices (DC/DC converter, inverter, etc.), plus, optionally, a fuel processing system (reformer).
- The Storage System (SS) is defined as the onboard stored fuel, oxidant, and product water.
- The overall FCEPS is the combination of the FCS, SS, ballast or floats, and overhead structure, insulation, etc. – as required for the UUV application and mission profiles.

To provide context, the FCEPS is compared to two benchmark metrics for refuelable AIP energy/power systems – as applied to UUV propulsion. These benchmark metrics are:

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1. A Threshold energy density value (as defined for Navy applications of a refuelable AIP energy/power system). This benchmark is based on a specific U.S. Navy application (Egan).

2. An energy density value for a rechargeable battery energy/power system (RBEPS) based on the use of Lithium Ion (Li-Ion) or Lithium Ion Polymer (Li-Poly) rechargeable batteries implemented for the UUV application – i.e., with density (buoyancy) appropriate to the UUV design and missions. This benchmark is developed within the Design Concepts section of this paper. Certainly comparisons between the FCEPS and other AIP systems, such as combustion energy systems, are possible, but are not included here. In addition, FCEPS designs requiring hydrocarbon fuel reformation are not included.

Following Benchmark 1, a 60 inch Large Displacement Mission Recoverable UUV (60” LD MRUUV) is used as the nominal application for the PEM-FCEPS technology assessment provided in this paper. The general constraints for a UUV application and the more specific nominal constraints of the U.S. Navy application are summarized in the Appendix.

Previous H2/O2 PEM Fuel Cell Stacks, Systems, and Applications
Numerous H2/O2 PEM FC stacks and systems have been designed or are in development for marine and space vehicular applications. Summaries of the most relevant projects are below and in Table 1. More complete and detailed information is available in a report to the Office of Naval Research (ONR) [Davies and Moore].

Lynntech Gen IV Flightweight 5 kW for Helios
Helios was a solar/regenerative FC powered airplane for high altitude operation [Bents, et al.] Hydrogen and oxygen were both stored as compressed gas in composite tanks from Quantum Technology. In operation, the tanks store a net 21 kWh of hydrogen and oxygen\(^2\). The Lynntech Gen 5 kW FC stack is 54% efficient at 3.6 kW and 48% efficient at 4.5 kW [Garcia, et al.].

Siemens BZM 34 and BZM 120
The Siemens BZM 34 and BZM 120 have been or are being installed in at least 16 submarine applications\(^3\). Hydrogen is stored in a maintenance-free metal hydride tank which can be mounted between the outer hull and inner pressure hull. Oxygen is stored as a liquid in double-walled and vacuum-insulated tanks [Hauschildt and Hammerschmidt].

The BZM 34 has an efficiency of 69% at 6.8 kW (20% of the maximum continuous power rating)\(^4\).

The BZM 120 has an efficiency of 68% at 24 kW (20% of the maximum continuous power rating)\(^5\). The BZM 120 module consists of two FC stacks. The information in Table 1 refers to the system with both stacks together as one unit. The BZM 120 is undergoing sea trials. In the Type 214 submarine, the oxygen tank is installed inside the pressure hull [Hauschildt and Hammerschmidt].

\(^2\) Based on hydrogen LHV and 317 moles H2 and 158 moles O2 as specified in [Garcia]
\(^3\) "Fuel cell submarines offer underwater stealth," http://www.gizmag.com/go/3434/, November 7, 2004
\(^4\) Siemens AG product literature, “SINAVYcis Application Potential,” 2004
\(^5\) Siemens AG product literature, “SINAVYcis Application Potential,” 2004
ZSW

ZSW (Centre for Solar Energy & Hydrogen Research) in Germany has developed a series of FC stacks and is developing a FCS for DeepC, an underwater research vehicle.

The DeepC Autonomous Underwater Vehicle (AUV) design is powered by two ZSW stacks, each capable of 1.8 kW net electrical power [Joerissen, et al.]. The information listed in Table 1 refers to both FC stacks as one unit. The FC stack, cooling equipment, storage tanks, and power distribution electronics will be installed inside the pressure hull of the vehicle [Geiger], [Joerissen, et al.]. Hydrogen and oxygen will be compressed in composite tanks [Joerissen, et al.].

MHI for Urashima

The Mitsubishi Heavy Industries (MHI) FCS includes two stacks electrically in series [Hyakudome, et al.]. The information listed in Table 1 refers to the entire system with both stacks. The Japan Marine Science and Technology Center (JAMSTEC) installed the MHI FCS in its Urashima AUV. The entire FCS, including the stack, heat exchanger, and reaction water tank, is mounted inside a titanium alloy pressure vessel having the dimensions listed in Table 1 [Maeda, et al.]. The Urashima FCEPS is hybridized using a Li-Ion rechargeable battery system with a Specific Energy of 0.15 kW/kg [Hyakudome, et al.].

Hydrogen is stored in an AB5 rare earth alloy metal hydride in a pressure vessel which is external to and separate from the FCS pressure vessel [Maeda, et al.]. Oxygen is stored in a compressed oxygen tank of 0.5 m³ volume at 14.7 MPa [Maeda, et al.].

UTC for 44” UUV

International Fuel Cells (IFC) developed a Fuel Cell System for a 44 inch diameter UUV in the early 1990s [Rosenfeld]. The full system was based on four 5 kW stacks, each of which could fit in a 21 inch diameter UUV. A 10 kW system (two stacks of 5 kW) was tested for 2000 hours including 1000 hours at full power [Rosenfeld]. The information in Table 1 references the entire system (four stacks).

<table>
<thead>
<tr>
<th>Description</th>
<th>Stack or System?</th>
<th>Specific Power (kW/ke)</th>
<th>Power Density (kW/L)</th>
<th>Maximum Continuous Power (kW)</th>
<th>Peak Power (kW)</th>
<th>Volume (L)</th>
<th>Mass (kg)</th>
<th>Rated voltage (V)</th>
<th>Rated Current (A)</th>
<th>Efficiency at Maximum Efficiency</th>
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<td>0.26</td>
<td>5</td>
<td>19</td>
<td>20</td>
<td></td>
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<td>54% @ 70A</td>
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<td>0.04</td>
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<td>Power Density (kW/L)</td>
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<td>Peak Power (kW)</td>
<td>Volume (L)</td>
<td>Mass (kg)</td>
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<tr>
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<td>264</td>
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<tr>
<td>ZSW for DeepC</td>
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</table>

Table 1: H2/O2 PEM FC stacks and systems [Davies and Moore]

**Design Tools and Methodology**

*Relationship of Specific Energy, Energy Density, and Buoyancy*

Specific Energy (SE) is energy per unit mass:

\[ SE = \frac{E}{m} \]  

(1)

Energy Density (ED) is energy per unit volume:

\[ ED = \frac{E}{V} \]  

(2)

Both metrics refer to the same quantity of energy, and density is ED divided by SE:

\[ D = \frac{m}{V} = \frac{ED}{SE} \]  

(3)

When ED is plotted as a function of SE, the slope of a line from the axis intercept to any point is the corresponding density at the point. Figure 1 shows this relationship. The dotted line represents the density of seawater, or about 1.03 kg/L. Any point above the line has negative buoyancy and any point below the line has positive buoyancy.
If a given FCEPS design did not have the required buoyancy as represented by the dotted line in Figure 1, then ballast or float material would have to be added to the design in order to meet the buoyancy requirement. Assuming the FCEPS mass and dimensions are limited, this ballast or float would displace mass and volume otherwise available for FCEPS components, particularly energy storage. This interaction is represented by the vectors in Figure 1.

Since the UUV FCEPS must provide Air-Independent Propulsion (AIP), oxygen must be carried onboard as well as hydrogen. Hydrogen and oxygen can both be evaluated in terms of SE and ED based on the stoichiometric ratio of the FC reaction.

It is possible to calculate the overall Storage System (SS) SE from the SE of hydrogen and oxygen storage [Davies and Moore]:

$$SE_{SS} = \frac{SE_{H2}SE_{O2}}{SE_{H2} + SE_{O2}}$$

(4)

In order to maintain constant FCEPS density throughout the mission, a product water storage tank will likely need to be included separately in the SS. Assuming that the empty mass of this tank is negligible, Equation 4 above still holds true. The ED of product water (energy produced divided by mass of product water) is 3.73 kWh/L. If the product water tank wall thickness is negligible, the SS ED is [Davies and Moore]:

$$ED_{SS} = \frac{1}{ED_{H2} + \frac{1}{ED_{O2}} + \frac{1}{3.73 \text{kWh/L}}}$$

(5)

Substituting Power for Energy, the same relationship between Specific Power (SP), Power Density (PD), and density exists as for SE, PE, and density.
**Concept Design Steps**

The following steps provide a method for generating FCEPS design concepts with specific high-level system parameters (such as reactant storage type and size, FCS choice, etc):

1. Determine the mass and volume of overhead FCEPS components (structure, insulation, etc.), based on thermal, pressure, and other requirements.
2. Choose and size the FCS for the power demand.
3. Determine the desired SS density based on the remaining volume and mass available in the FCEPS.
4. Choose the SS concept with the highest SE and ED at the desired SS density.
5. Choose and size any required ballast or floats.
6. Determine the FCEPS SE and ED given the volume and mass available for the SS and the FCS efficiency.
7. Iterate the process with different FCS choices.
8. Choose the FCEPS with the highest SE and ED from the design iterations.

**Storage System**

The general results of an analysis of hydrogen and oxygen storage options are summarized here – for more detailed discussions the reader is referred to the ONR report by Davies and Moore.

**Hydrogen Storage**

This UUV FCEPS assessment considers four types of hydrogen storage: compressed, liquid, metal hydride, and chemical hydride. Figure 2 plots a set of hydrogen storage options grouped by storage type on an SE vs. ED graph (as discussed above). The storage options are individually identified in the report to ONR by Davies and Moore. On the graphs, complete system options include the storage tank and supporting equipment, but ideal options do not. The upper bound of hydrogen storage SE is 33.3 kWh/kg [Davies and Moore].

![Figure 2: SE and ED of hydrogen storage options (complete systems only)]
The maximum pressure of commercial off the shelf (COTS) compressed hydrogen tanks is 10,000 psi (68.9 MPa). The overall density of compressed hydrogen systems is typically less than water, shown by the fact that the systems are generally below the dotted lines in Figure 2. There is also the possibility of storing hydrogen as a cryogenically compressed gas [Powers].

Liquid hydrogen storage has a maximum ED of 2.36 kWh/L [Davies and Moore]. Liquid hydrogen is much less dense than water, and typically, liquid hydrogen tanks have a density slightly less than water as well.

Metal hydride storage systems typically have high ED, but low SE. These systems have a fairly high level of technical maturity, but require thermal management to attain the proper temperatures for absorption and desorption of hydrogen.

Chemical hydrides typically have densities similar to water. Chemical hydride systems promise relatively high SE and ED [McClaine, et al.]. However, most chemical hydride systems are at a lower level of technical maturity than metal hydrides and may require a more complex supporting system.

**Oxygen Storage**

Oxygen storage has been classified into several types: compressed, liquid, chemical, and chlorate candles. The upper bound for oxygen storage SE is 4.20 kWh/kg [Davies and Moore]. Figure 3 plots the set of oxygen storage grouped by storage type. The storage options are individually identified in the ONR report by Davies and Moore.

![Oxygen Storage ED/SE and Density](image)

Figure 3: SE and ED of oxygen storage options

Compressed oxygen storage is a mature technology, and the density advantage of increasing compressed oxygen pressure does not fall off as significantly as does that for hydrogen.

Sierra Lobo, Inc. has designed a complete liquid oxygen (LOX) system for a 21” diameter UUV [Haberbusch]. The boiling point of oxygen is warmer than the hydrogen boiling point, but still imposes difficulties.
Chlorate candles are currently used in submarine and emergency applications, and are technically a type of chemical oxygen storage\textsuperscript{6} and [Reader, et al.]. Once started, a chlorate candle continues producing oxygen until depleted. Chlorate candles are very stable and can produce oxygen under pressure.

Oxygen can also be stored in other chemical compounds such as hydrogen peroxide, nitrogen tetroxide, and sodium superoxide. These systems must be designed and managed properly for safety considerations.

**Integrated Storage System**

The overall SS has a maximum theoretical SE of 3.73 kWh/kg and an ED of 3.73 kWh/L and [Davies and Moore]. Figure 4 plots the combinations of the complete hydrogen and oxygen storage systems above.

![Storage System ED/SE and Density](image)

**Figure 4: SE and ED of SS options**

**Fuel Cell System Design Aspects**

In the UUV application, high cathode, anode, and ambient pressures are available due to the pressure at the operating depth and depending on the method of H2/O2 storage. This presents the possibility to operate the FC stack at a higher PD and efficiency then indicated in Table 2. However, there are tradeoffs that must be considered.

Cold seawater is available to cool the FCEPS. The thermal management of the system must be carefully considered, especially if cryogenic hydrogen and/or oxygen storage is used.

Depending on the power demand profile of the UUV, it may be advantageous to design the FCEPS as a hybrid system. A hybrid power system could be designed based on batteries, ultracapacitors, flywheel(s), or other means of storing electrical energy. Batteries and ultracapacitors are modular and can potentially be integrated into unused FCEPS space. Depending on the density of the FCEPS components, batteries could be used instead of ballast to achieve the desired FCEPS density (batteries are generally denser than water).

Several opportunities may exist within the UUV FCEPS for integration of components and systems. This integration may enhance the FCEPS design beyond what might be expected when assessing its individual components. For instance, the hydrogen and oxygen storage could be thermally integrated with the FCS, providing advantages depending on the choice of SS options. Integration of the product water and reactant storage might also be possible.

Design Concepts

**RBEPS**

In order to provide a “competitive” benchmark for the FCEPS design concepts, lithium based rechargeable batteries have been assessed. The density of a RBEPS must meet UUV constraints, just as for the FCEPS. Typically, battery systems are denser than seawater, so floats or void space must be added at a loss to ED. Li-Ion and Li-Poly batteries are chosen as a comparison because they are being currently considered as alternatives to the Silver-Zinc (Ag-Zn) secondary and Lithium Thionyl Chloride (Li-SOCL₂) primary batteries used in UUVs [Egan]. In this assessment, multiple Li-Ion and Li-Poly cells are used to fill the available volume and mass, and the packaging is considered to be perfect (no unused space).

Some approximations and assumptions were made in order to make a first cut among the numerous battery models available. The stored energy was assumed to be the published nominal voltage (V) times the nominal capacity (Ah). Supplier specified energy storage values were not used because of the inconsistent methods of determining these values. Only the batteries with sufficient available data (nominal voltage, capacity, mass, dimensions, and discharge curves) were considered. Among the models of the same type (Li-Ion cylindrical, Li-Ion prismatic, or Li-Poly prismatic) from a single supplier, the batteries with significantly worse SE and ED at neutral buoyancy (1.03 kg/L) were excluded. Battery capacity data was taken from the published nominal capacity. The published capacity values were generally measured between C/5 and C/5.75 discharge rates. The SE and ED values of the cells are plotted in Figure 5, classified by type. The individual batteries are detailed in the ONR report by Davies and Moore.
Using the approximated SE and ED values described above, the batteries with the best ED at required density values over the range of 0.3 kg/L to 3.5 kg/L were chosen. The Ultralife Batteries model UBC641730 battery (symbol V) has the highest ED at required densities below approximately 1.20 kg/L, and the Panasonic model CGR18650D battery (symbol O) has the highest ED at required densities above that value.

These two battery models, Ultralife Batteries UBC641730 and Panasonic CGR18650D, were more closely evaluated by considering the energy available from the batteries at the required discharge rate. In order to fairly compare the RBEPS to the FCEPS using the Siemens BZM 34 FCS, a continuous power demand of 34 kW was considered. This power demand was divided by the number of cells in the RBEPS concept at each required density value. The resulting cell power was divided by the discharge cutoff voltage for the battery model of interest, giving a discharge current value. The most appropriate published discharge curve graph was numerically integrated to find the final energy value for comparison to the FCEPS.

One notable characteristic of Li-Ion and Li-Poly batteries is capacity fade over the life of the battery. As the battery ages, the electrical storage capacity decreases. The Ultralife Batteries model UBC641730, is specified to retain a minimum of 80% of its capacity after 300 charge-discharge cycles, which appears fairly typical. The usage profile of a UUV RBEPS would likely require nearly full charge/discharge cycles, and full charge/discharge cycles have a more significant impact on capacity fade than partial charge/discharge cycles [Davies and Moore].

Li-Poly cells can operate at up to 60 MPa with 90% of the rated capacity as at atmospheric pressure. This corresponds to a depth of about 6000 m in seawater. This may be desirable in a RBEPS design; however, the Li-Poly cells must be maintained at a suitable operating temperature [Rutherford].

FCEPS
This initial assessment has been done under the assumption that there is no overhead UUV volume and mass – since information is not yet available to determine overhead volume and mass contributions such as insulation, structure, and pressure vessel(s). The 60” LD MRUUV objective volume and mass values (Table 3) are used to find the target FCEPS density, 1.11 kg/L. The Siemens BZM 34 is chosen for all of the design concepts because it is the only FCS option with all of the necessary data and of the proper power level. The FCS volume and mass are a small portion of the total FCEPS volume and mass, 9.1% and 15.9%, respectively.

Table 2 shows the seven FCEPS design concepts with the highest net energy storage using confirmed SE and ED values, as well as:

6K6: Sierra Lobo Advanced LOX system with the most optimal liquid H2 storage (Magna Steyr Liquid H2)
6X6: The most optimal SS using metal hydride hydrogen storage (Ovonic Onboard Solid H2 and Sierra Lobo Advanced LOX system)
6N15: The most optimal compressed hydrogen and compressed oxygen SS (TUFFSHELL 118L, SCI 604)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design Description</th>
<th>Net Energy (kWh)</th>
<th>SE (kWhe/kg)</th>
<th>ED (kWhe/L)</th>
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<tr>
<td>6F18</td>
<td>FCS: Siemens BZM 34 H2: Safe Hydrogen lithium hydride (60%) slurry system O2: Molecular Products CAN 33</td>
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### Table 2: FCEPS design concepts

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### RBEPS and FCEPS Comparison

A particular UUV design may be optimal with an energy/power system that has a density higher or lower than seawater density or that required by the 60” LD MRUUV – i.e., 'banking' the net buoyancy of the FCEPS to offset opposite buoyancy elsewhere in the UUV. In order to see the effect of required energy/power system density on the FCEPS and RBEPS designs, a range of required densities over an order-of-magnitude variation (from 0.3 kg/L to 3.5 kg/L) is summarized below.

The FCEPS and RBEPS design concepts are compared in terms of ED at the required density. At each required density in the set, the FCEPS design steps were followed (limiting the FCS choice to the Siemens BZM 34 and assuming zero overhead mass and volume). Likewise, the best battery option was chosen at each required density, and ballast or floats were added as necessary within the RBEPS. The resulting SE and ED are plotted separately as a function of required density in Figure 6. The FCEPS and RBEPS concepts are labeled with the symbol of the corresponding design (H2 storage, and O2 storage, or battery). As a result of the Li-Ion and Li-Poly cell density, RBEPS designs become more desirable at higher required densities (i.e., above ca. 2.2 kg/L).
Conclusions and Summary

The FCEPS design concept method presented in this paper used a holistic approach to combine alternative hydrogen and oxygen storage and fuel cell system options and provide the highest specific energy (SE) and energy density (ED) within the UUV constraints – including the FCEPS mass, volume, and required power. Using this method, some surprising combinations appear as the theoretical “winners” – when used in an FCEPS with the BZM 34 (Siemens) fuel cell system. Of course, a complete prototype design and application simulation would have to be carried out using each of the alternative fuel cell system and H2-O2 storage combinations to determine the precise SE and ED values for each FCEPS design concept – but the screening methodology used in this assessment is quantitatively useful in reducing the number of different storage combinations and fuel cell system alternatives which will eventually need to be evaluated in a more complex and resource intensive fashion.
Keeping in mind the limits to the precision of these results, the technology assessment presented in the main body of this paper leads to the conclusion that a combination of the 60% lithium hydride slurry system (Safe Hydrogen, LLC) with CAN 33 chlorate candles (Molecular Products) provides the best energy storage option – with SE and ED for the 60” UUV application at 0.44 kWh/kg and 0.48 kWh/L, respectively.

In contrast, an FCEPS using a very conservative H2-O2 storage combination of compressed hydrogen and compressed oxygen provides less than half of these values – with SE and ED at 0.19 kWh/kg and 0.21 kWh/L, respectively.

These bounding values of SE and ED for an FCEPS provided a range of energy storage options that can be compared with the Threshold and RBEPS values of SE and ED at 0.29 kWh/kg and 0.25 kWh/L, and 0.17 kWh/kg and 0.19 kWh/L, respectively – in order to provide perspective for the PEM-FCEPS in a UUV application.

This comparison indicates that the SE and ED range (from the best to the very conservative H2-O2 storage options combined with the BZW fuel cell system) compares extremely favorably with the Navy Threshold and the RBEPS benchmark metrics. Based on these SE and ED values for the PEM-FCEPS, this initial technology assessment supports the expectation that a PEM-FCEPS has the potential to significantly increase the energy storage in an UUV – when compared to currently available refuelable Air-Independent Propulsion (AIP) energy/power systems and, in addition, indicates a high probability that a FCEPS can achieve the Threshold value for energy storage of the 60” LD MRUUV.

However, to balance this very positive conclusion, this technology assessment also shows that there is no reasonable expectation that the Navy’s Objective energy storage value (SE and ED at 3.18 kWh/kg and 2.20 kWh/L) can be achieved from the energy storage and PEM-FCEPS technologies assessed in this paper. Achieving the Objective energy storage will require a breakthrough in either H2-O2 storage technology or in enabling a FCS which can convert high energy fuels within the design constraints of an AIP designed for the UUV application.

One final caveat on these results is that the SE and ED values obtained for the best combination of H2-O2 storage considered here (the 60% lithium hydride slurry plus CAN 33 chlorate candle H2-O2 system) is that this option can perhaps be most fairly compared to a primary battery based EPS rather than a RBEPS – unless these storage media can be implemented as a truly “refuelable” technology. But, even using this combination, the Objective energy storage value set by the Navy for the 60” LD MRUUV is not attainable.

References


Tadahiro Hyakudome, et al., "Key Technologies for AUV URASHIMA,” IEEE, 0-7803-7534-3, 2002


Appendix:

The general constraints for any UUV power system application are:

Below is a list of general requirements for the FCEPS design.
Electrical (net energy available, maximum power, average power, nominal voltage, voltage response under transient loads, etc.)
Physical dimensions (diameter, length, volume)
Mass
Buoyancy (density at start of mission, density change throughout mission, center of mass, center of buoyancy)
Safety (Failure Modes and Effect Analysis risk levels, etc.)
Cost (unit cost and recurring cost)
Operation (fueling procedure, startup time, shutdown time, fueled and defueled shelf life)
Maintenance and repair (repair procedures and intervals; Mean Time Between Failures (MTBF); lifetime in terms of time, start/stop cycles, kWh; etc.)
Noise and vibration (maximum levels)
The general environmental conditions experienced by the FCEPS include those below.
Operating pressure (minimum and maximum).
Temperature (minimum and maximum)
Orientation (pitch and roll)
Relative humidity
Corrosion
Vibration
Electromagnetic radiation

For the U.S. Navy 60” Large Displacement Mission Recoverable UUV (LD MRUUV), which is used as the “strawman” application for the FCEPS assessment presented here there are additional considerations. The U.S. Navy has set both “threshold” and “objective” requirements for the 60” LD MRUUV. The objective values are more stringent than the threshold values, and they are included as the target requirements for the assessment. Table 3 lists the objective requirements for the 60” LD MRUUV.

The 60” LD MRUUV objective volume and mass values in Table 3 equate to a FCEPS density of 1.11 kg/L. This density is included as the target FCEPS density for the purpose of this assessment.

<table>
<thead>
<tr>
<th>Power</th>
<th>Energy</th>
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<tbody>
<tr>
<td>70 kW peak</td>
<td>11,500 kWh</td>
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<table>
<thead>
<tr>
<th>Volume</th>
<th>Power Density</th>
<th>Energy Density</th>
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<tbody>
<tr>
<td>3681 L</td>
<td>0.026 kW/L</td>
<td>3.178 kWh/L</td>
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<table>
<thead>
<tr>
<th>Mass</th>
<th>Specific Power</th>
<th>Specific Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>4082 kg</td>
<td>0.018 kW/kg</td>
<td>2.200 kWh/kg</td>
</tr>
</tbody>
</table>

Table 3: Navy LD MRUUV FCEPS objective requirements [Egan]

The nominal configuration of the 60” LD MRUUV provides a power section with available dimensions for the FCEPS of 1.40 m\(^7\) diameter and 2.40 m length. The voltage output of the FCEPS must be

\[ \text{Maria Medeiros, email communication, 21-Jul-2005} \]

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between 100 and 400 VDC. The maximum fixed cost of the FCEPS is $10,000 per kWh of capacity. The maximum recurring cost is $100 per kWh used [Egan]. The UUV must be capable of being fueled and refueled onboard a ship or submarine.

The UUV may be transported by air, truck, rail, or ship, which imposes environmental conditions that must be considered in addition to those imposed in the underwater environment\(^8\). The UUV is expected to experience a minimum temperature of \(-7\) °C during transport and storage to a maximum of \(54\) °C while deployed on a submarine. The UUV will experience a minimum pressure of \(10\) kPa during transport by airplane and a maximum pressure during underwater operation\(^9\). Seawater pressure will increase by about \(10\) kPa per meter of seawater depth. However, the expected operating depth of the LD MRUUV is unknown, and it is also unknown whether the FCEPS will be installed inside an existing UUV pressure hull or be subjected to seawater pressure itself.

\(^{8}\)“Table 3.2.5-1. BLQ-11 Environmental Conditions,” received by email from Maria Medeiros, 21-Jul-2005

\(^{9}\)“Table 3.2.5-1. BLQ-11 Environmental Conditions,” received by email from Maria Medeiros, 21-Jul-2005