

MODELING HYBRID ENERGY SYSTEMS FOR USE IN AUVS

G Griffiths¹, D. Reece², P. Blackmore², M. Lain², S. Mitchell³, J. Jamieson⁴

¹National Oceanography Centre, Southampton

²AEA Battery Systems

³Systems Engineering and Assessment

⁴Subsea7

Corresponding author: G Griffiths, National Oceanography Centre, Southampton, Empress Dock, Southampton
SO14 3ZH UK

T: +44 (0) 2380 596004 E: gxxg@noc.soton.ac.uk

Abstract

Specifying an energy source for an AUV is usually a compromise between performance and cost. For most vehicles and most missions, high specific energy primary lithium batteries are not a practical option due to cost. One solution that shows promise and affordable cost is to use a hybrid approach that combines low cost secondary batteries with a fuel cell or combustion energy source. Exploring the design space for these more complex energy systems requires suitable tools for modelling and assessment. One such tool is Virtual Test Bed. To build confidence in the tool, its simulations have been assessed against experimental data for 18650 lithium ion cells and a Ballard fuel cell, with encouraging results. Subsequently, a conceptual design for a lithium ion battery and fuel cell hybrid energy source was modelled and the performance of two variants assessed for two different 7-day mission scenarios. In both cases, the hybrid system exhibited a specific energy comparable to primary lithium manganese dioxide batteries, with full account taken for the mass overhead of realistic reactant storage for the fuel cell.

1. Introduction

When designing a long endurance AUV the specific energy of the power source, expressed as Wh.kg^{-1} , is a key design parameter. So often the ability to carry limited energy on board an AUV is considered a major limitation or technology gap (e.g. Stevenson et al., 2002; Griffiths et al., 2004). Less frequently, the issue may be limited specific power, expressed as W.kg^{-1} , which may determine performance of a sprinting AUV in particular. Cost per Wh is also an important parameter: one with a complex relationship to specific

energy and specific power (Griffiths, 2005). In actuality, the real issue may be the affordability of energy from a source with high specific energy. For example, while primary batteries with specific energies of 300 to over 600 Wh.kg^{-1} are available, cost often rules them out except for small vehicles with low energy demands, or for use in special purpose vehicles where the cost is justified by the mission outcomes.

One solution to breaking the cost-performance trade-off is to use secondary batteries, where the capital cost can be amortised over many charge-recharge cycles. Significant progress has been made in the specific energy of secondary lithium batteries over the last five years, and cells with over 190 Wh.kg^{-1} are readily available for purchase (Russel, 2004). Decreasing prices and increased specification for these cells make them attractive for use in UUVs. However, where the technical goal may be for specific energy in excess of 500 Wh.kg^{-1} , secondary lithium batteries alone will not meet that requirement for many years, if ever (Russel, 2004) described the AEA Technology roadmap for AGM lithium ion 'D' cells out to 2020, with an improvement from $\sim 7\text{Ah}$ in 2005 to $\sim 17\text{Ah}$ in 2020 (equivalent to $\sim 400 \text{ Wh.kg}^{-1}$). This improvement is expected through the use of Stabilised Lector Max Powder (SLMP) together with new anode materials and partial or non-lithiated cathode materials, e.g. based on vanadium *n*-oxides.

An alternative approach to using a single energy storage technology is to combine two or more technologies within a hybrid system (Gao, 2004). In such a hybrid system the goals of high specific energy, high reliability and affordable cost, for initial purchase and for operation, can be decoupled to some extent. The purpose of this paper is to examine how such hybrid systems may be designed and their

performance modelled. Other considerations with hybrid systems, such as radiated noise, substance emissions, maintenance requirements and end-of-life issues are not covered here.

Secondary lithium batteries are a practical solution for one component of a hybrid system. To meet our overall goals, the other part(s) must have the attributes of affordable cost and higher specific energy. While it is desirable to have high reliability, it may not be necessary for the second energy source to match the reliability of the batteries. Reliability aspects should be studied as part of the overall *system* performance.

Candidates for the high specific energy role are fuel cells or combustion-based generators. Fuel cell stacks with the *potential* to be used within UUVs are becoming commercially available. Although data on the performance of modules such as Proton Exchange Membrane fuel cell stacks is readily obtainable from the literature and from independent testing, the systems arrangement and the test and operating conditions are unlikely to reflect those within an UUV. While Urashima has pioneered the use of a PEM fuel cell within an AUV (Aoki, 2004), full technical details of the implementation and performance are scarce. It is imperative to consider all of the modules, particularly reactant storage, and reactant product disposal when estimating the system parameters of a hybrid energy source based on fuel cell or combustion technology.

Having sacrificed the simplicity of an energy source based solely on one type of electrochemical battery, the choices that need to be made, and the factors that must be considered when designing a hybrid energy system require a modelling and simulation tool to ensure rigorous design and effective performance. The modelling tool needs to incorporate accurate representations of the performance of the energy storage components, together with the interconnection and glue logic to enable realistic simulations of the hybrid system and its modes of operation. That is, the modelling tool should cover charge and discharge, start-up, steady state and pulsed loads.

The virtual test bed (VTB) software, developed at the University of South Carolina (<http://vtb.engr.sc.edu>), has been designed specifically for detailed modelling and simulation of power systems, including batteries, fuel cells and engine-generator combinations (Dougal et al., 2002). The battery and fuel cell models within VTB are based on a combination of electrochemical fundamentals and actual cell performance data. Circuit components such as diodes, switches, buck converters are included, which, together with the schematic editor, enables the user to simulate system operation and performance.

In this paper we take a step-by-step approach to setting out a validated concept design for an AUV hybrid energy system, and we assess its key characteristics. We describe the use of VTB as a simulation tool, and show that its model for an 18650 lithium ion secondary cell agrees with independent test data. The outputs of the VTB model for a H-Power D35 fuel cell are compared with independent test data for a Ballard Mk 5 fuel cell. These steps provide confidence in the realism of two key elements of the hybrid system design. Next, we review the state of the art in reactant storage for use with fuel cells, sufficient to enable realistic estimates of the mass of sub-systems such as hydrogen and oxygen storage to be included in system-level performance estimates of specific energy. From this, we then describe a schematic for a fuel cell – lithium ion hybrid energy system capable of providing 800 kWh, and detail its electrical performance under different imposed loads.

2. The Virtual Testbed modelling package

VTB is a freely available package that provides a set of tools for virtual-prototyping power systems (Dougal et al., 2002). It comprises a library of modules that can represent the physical, electrical and thermal characteristics of components likely to be used within power systems. Many of the characteristics of those modules can be adjusted by the user to extend the range of devices modelled. A schematic editor is included, which enables virtual circuits to be built that obey coupling laws for interconnection of signals and data and electrical and thermal quantities. The results of simulations may be examined with the built in Visualisation extension Editor (VXE) in the form of graphs, rendered 3D representations and data-driven animations. New models can be added through a user-defined device utility that aids constructing Visual C++ source code. At run-time, a resistive-companion solver (Dougal et al., 2002) executes, in a discretised form, the differential-algebraic equations for the circuit elements and their interconnections.

3. Verification of VTB cell and fuel cell models

3.1 18650 lithium ion secondary cell

AEA Technology has extensive experience of lithium-ion battery performance, from the invention of the cell chemistry in the 1980s (Goodenough et al., 1985) to the design and construction of large battery packs used in spacecraft. To model the performance of such batteries in demanding environments, AEA

Technology developed BEAST (Battery Electrical Analysis Sizing Tool) as a software package to predict battery performance. BEAST incorporates knowledge of the variations of voltage and resistance through discharge and charge, and also includes prediction of capacity fade through the life of a battery. In particular, BEAST contains detailed performance characteristics of the Sony 18650 hard carbon lithium ion cells, validated against millions of hours of test data and actual data from battery packs on spacecraft. BEAST, therefore, forms an excellent reference against which the performance of VTB simulations can be assessed.

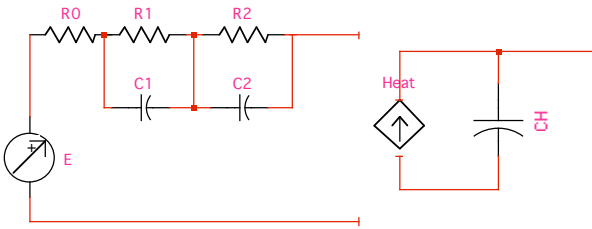


Figure 1 Randles equivalent electrical circuit (left) for an 18650 lithium-ion cell, with a simple thermal model (right) with temperature as an output variable.

Table 1 Key parameters for the 18650 lithium ion cell as used by the VTB model from Gao et al. (2002).

Parameter	Value
R0 – Ohmic resistance	50 mΩ
R1 – Charge transfer resistance	25 mΩ
R2 – Polarisation resistance	75 mΩ
C1 – Charge transfer capacitance	4 F
C2 – Polarisation capacitance	400 F
CH – Heat capacity	925 J kg ⁻¹ K ⁻¹
M – Mass	41 g
Valid temperature range	-20 to 45°C

The representation of an 18650 lithium-ion cell within VTB is in the form of a Randles equivalent circuit (Figure 1). This equivalent circuit comprises a variable emf source (E), which is a function of state of charge and temperature; an ohmic internal resistance (R_0), which comprises terminal and current collector resistance; an RC combination (R_1C_1) that models the double layer capacitance and charge transfer resistance, while the combination R_2C_2 models the polarisation dynamics of the cell. Values for these elements for the 18650 cell are shown in Table 1. The R_1C_1 time

constant is of the order of 0.1 s, while R_2C_2 is about 30 s, and affects significantly the performance of the cell under dynamic loads.

Comparisons of VTB and BEAST single cell discharge profiles at constant currents of $C/10$, $C/5$, $C/2$ and C (where C is the rated capacity of the cell in Ah, in this case 1.5 Ah) at temperatures of 0, 20 and 40°C indicated very close correlation between the two simulators. Figure 2 shows the results at 20°C. For the first half of each discharge the VTB and BEAST curves were virtually identical. For example, at $C/10$, the mean difference was 5.2 mV (0.13% of the mean cell voltage of 3.98 V over this period), with a range of 53 mV. However, over the second half of each discharge, VTB consistently indicated a higher voltage than BEAST, until the actual end point of 2.5 V, when the simulations converged. At $C/10$, the mean difference over the second half of the discharge was -110 mV with a range of 133 mV. The difference was greater at 40°C, and extended over the full period of discharge, which points to VTB overestimating the reduction of cell internal resistance at higher temperature.

In terms of capacity, at 20°C and $C/10$ the BEAST and VTB models predicted the nameplate capacity of 1.5 Ah. However, because of the difference in terminal voltage estimates, the predicted energy capacity differed: BEAST showed 5.41 Wh (against a nameplate capacity of 5.4 Wh while VTB predicted a higher capacity, at 5.50 Wh, a difference of 1.7%. Within an UUV using secondary cells, it is likely that a greater safety margin than this would be allowed.

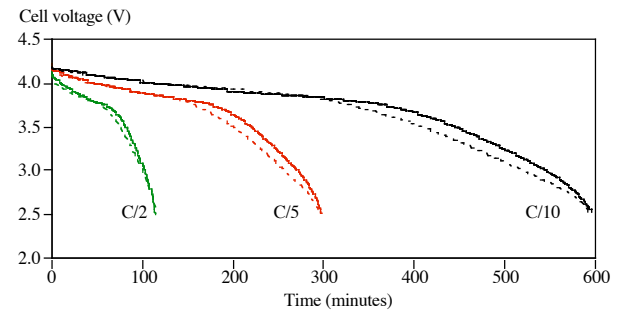


Figure 2 Discharge curves at rates of $C/10$, $C/5$ and $C/2$ for VTB (solid lines) and BEAST (dashed lines) for a hard carbon Sony 18650 lithium-ion cell at 20°C.

3.2 Fuel cell model

VTB contains a model for a generic proton exchange membrane (PEM) fuel cell that includes prediction of the terminal voltage, heat produced and the fuel and air consumption rates, together with their variation with temperature, as functions of current load. The

model outputs are determined by a set of adjustable parameters, of which an illustrative subset (9 out of 18) is shown in Table 2. Parameter values are a mix of those determined by experiment (e.g. R0, R1 and R2) and those by specification or inspection (e.g. cell area, number of cells). The writer of the model (M. J. Blackwelder) has defined the parameters determined by experiment such that they can be used as estimates for fuel cells of different configuration and from different manufacturers. For example, the parameters R0, R1 and R2 are defined per cm² of cell area and per cell. Unfortunately, these are not truly universal constants, and they will, for example, depend, among others, on the thickness of the membrane material used in a particular cell by a particular manufacturer. The default parameters in the model were estimated from an H-Power D35 fuel cell stack¹.

Table 2 Some key parameters of the VTB fuel cell model¹.

Parameter	Value
OCV per cell	1000 mV
Valid temperature range	-10 to 60°C
Valid pressure range	10 to 500 kPa
R2 – Constant part of R	1.92Ωcm ² cell ⁻¹
R1 – Linear temperature coeff	-0.01Ωcm ² cell ⁻¹ K ⁻¹
R0 – Quadratic temperature coeff	1.52.10 ⁻⁵ Ωcm ² cell ⁻¹ K ⁻¹
A – Cell area	130 and 180 cm ²
N – Number of cells in stack	35
U – Heat creation (liquid water)	1.482 J s mol ⁻¹

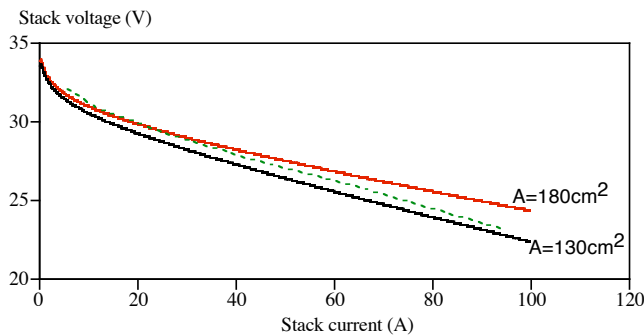


Figure 3. Voltage against current for a Ballard Mk 5 fuel cell (experimental data - dashed line) and for VTB simulations at N=35, A=130cm² and A=180cm² at a temperature of 333.15K (60°C).

Our objective was to test the validity of the VTB generic fuel cell model against experimental data. Data

on the performance of a Ballard Mk 5 fuel cell was available at AEA Technology, and N (number of cells in the stack) was set at 35 and temperature to 60°C to match the experimental data. Figure 3 shows the Ballard Mk 5 data (dashed line) together with VTB simulations at cell areas of 130cm² and 180cm². Neither match is perfect. There are three regions in the figure: first, below 10 A, where both VTB simulations predict lower voltage; second, between ~10 and ~30 A, where the VTB simulation at A=180cm² is a good fit; and third, over ~30 A where the VTB simulations straddle the Ballard data, with a maximum error of ~0.8 V. The *shape* of the Ballard curve most closely matches the A=130cm² VTB simulation, with an offset that does not change significantly with current. This suggests that the VTB OCV estimate is too low, and also that the VTB internal resistance parameters are about correct for the Ballard cell as well as the H-power cell.

4. Reactant storage for PEM fuel cells

A full analysis of the advantages and disadvantages of each fuel and oxidant option is beyond the scope of this paper, however, illustrative performance figures are provided to help scope the outline design of a hybrid system for an AUV.

4.1 Fuel

Fuel storage for use with fuel cells is an enormous topic of research in many industrial nations. There appears to be, as yet, no solution off-the-shelf that would provide an AUV with a specific energy of over 500 Wh.kg⁻¹. This is mainly because the mass overhead in fuel storage, or fuel reforming or processing is too high. There are also AUV-specific engineering issues that would need to be solved to make some of the available systems practical. In the case of hydrogen as a fuel, the Urashima vehicle uses AB5 metal hydride as a store. For each 1 kg of hydrogen, this requires some 66 kg of hydride. Compressed gas at 70 MPa within lined composite cylinders can reduce this mass overhead significantly. For example, Sirosh (2002) describes a CFRP cylinder with a permeation-resistant polymer lining, with an in-tank regulator to “confine high gas pressures within the tank and thus eliminating high pressure fuel lines downstream”. This TriShieldTM tank has a mass overhead of 16.6 kg per kg of hydrogen. At present, compressed gas seems to offer better performance than cryogenic storage. Linde AG built a double walled stainless steel cylinder with multilayer vacuum ‘superinsulation’, with a thermal conductivity of 0.05 W.K⁻¹. The total tank system

¹ (see Fuel_Cell_PEM_12022002.pdf at http://vtb.ee.sc.edu/modellibrary_new/index.asp)

mass is 90 kg, for a mass of hydrogen stored of 4.6 kg at an internal pressure of 0.6 MPa, a storage overhead of 18.6 kg per kg of hydrogen. Reforming hydrogen from methanol/water, for example using a Genesis 20L reformer, is perhaps feasible within an AUV, but poses several engineering challenges. The mass overhead with reformers is more difficult to estimate, but with current products, is about 17 kg per kg hydrogen. This is the figure we will use in the conceptual design.

4.2 Oxidant

Options for oxidants within an UUV include compressed oxygen gas, liquid oxygen and hydrogen peroxide.

For compressed oxygen gas, lightweight aluminium cylinders are available. The Luxfer M265 cylinder is an example of current technology. This cylinder stores 7507 litres of gas at a pressure of 15.3 MPa in a cylinder of diameter 248.9 mm and 1319 mm in length, weighing 39.5 kg empty and 50.2 kg when full. The storage overhead for this option is 3.7 kg per kg of oxygen.

An advanced lightweight liquid oxygen storage (LOX) system has been developed for use in a 21" diameter UUV by Sierra Lobo Inc. (Ohio, USA). This system is described in Habersbusch (2003) and Habersbusch et al., (2002). Funded by ONR via a Phase II SBRI award, the LOX system has been designed to work with a 1 kW output PEM fuel cell. The prototype stores 50 kg of LOX at -179°C and is capable of delivering between 0.1 and 100 g.min⁻¹ of gaseous oxygen (sufficient for a fuel cell operating between 10 W and 1 kW). The system truly is lightweight, being 0.94 m long, 0.32 m in diameter and weighing only 13.6 kg empty (63.6 kg when full). This provides far more mass-efficient storage, at an overhead of only 0.27 kg per kg of oxygen.

Hydrogen peroxide has the advantage of being liquid at room temperature, and readily produces oxygen via catalytic decomposition. At low concentration (3-5 mmol) it is used in the semi-fuel cell within the Hugin AUV (Hasvold et al., 2002); and at 50% concentration, it has been used in the Fuel Cell Technologies semi-fuel cell (Adams, 2002). 70% hydrogen peroxide is usable with care, and, making assumptions on the mass of the container, support systems and heat exchanger, the estimated storage overhead is 2.3 kg per kg of oxygen.

For the purposes of our conceptual design in this paper, we will take the Sierra Lobo cryogenic oxygen store as the preferred oxidant storage technology.

5. Lithium ion – fuel cell hybrid UUV energy source

5.1 Conceptual design

One strategy for the operation of a lithium ion fuel cell hybrid system is as follows. When power/current demand from the load is near the fuel cell best efficiency point the fuel cell will provide the power. At times of low current demand the fuel cell will recharge the lithium ion battery (at a current near the point of highest efficiency) and provide power to the load. At times of high current demands the lithium ion battery provides power.

One problem with this strategy is that at high current demands, when the lithium ion battery provides all the power to the load, the fuel cell is effectively switched out of the circuit by reducing the duty cycle of the DC-DC converter to zero (with the Fuel Cell still consuming oxidant and fuel during this time). A more energy efficient approach would allow the fuel cell to provide power to the load at all times, with the current that the fuel cell provides to the load being limited to its optimum efficiency point and the lithium ion battery providing all the remaining current at times of high demand. This control strategy requires the DC-DC converter, which is used to adjust the output of the fuel cell to the load, to be controlled in current mode rather than in voltage mode.

To achieve this control strategy a 'ControlLogicA' model was written to incorporate a current mode controller for the fuel cell's DC-DC converter, and added to the VTB library of modules. 'ControlLogicA' monitors the Fuel Cell current as the duty cycle (to control the DC-DC converter) is adjusted to achieve the optimum fuel cell current even as load varies. Figure 4 shows the hybrid power system test circuit.

To test this control strategy, the properties of the models were set to the following values:

- Fuel Cell: H-Power D35 default values except – No. of cells = 120, A = 292 giving a nominal terminal voltage of 120 V;
- Lithium ion battery: Sony 18650 model, all defaults except – No. of cells in series (NS) = 24, No. of cells in parallel (NP) = 60 and SoC = 90% giving a 100.8 V, 90 Ah battery;
- The charge control model has the battery voltage set to 100.8 V and charge current to 10 A
- The 'ControlLogicA' model properties were: AUV Bus Voltage = 80V; lithium ion only

operation for first 20 minutes; fuel cell optimum current of 10 A; charge lithium ion battery at load

currents < 8 A and minimum lithium ion Voltage of 60 V.

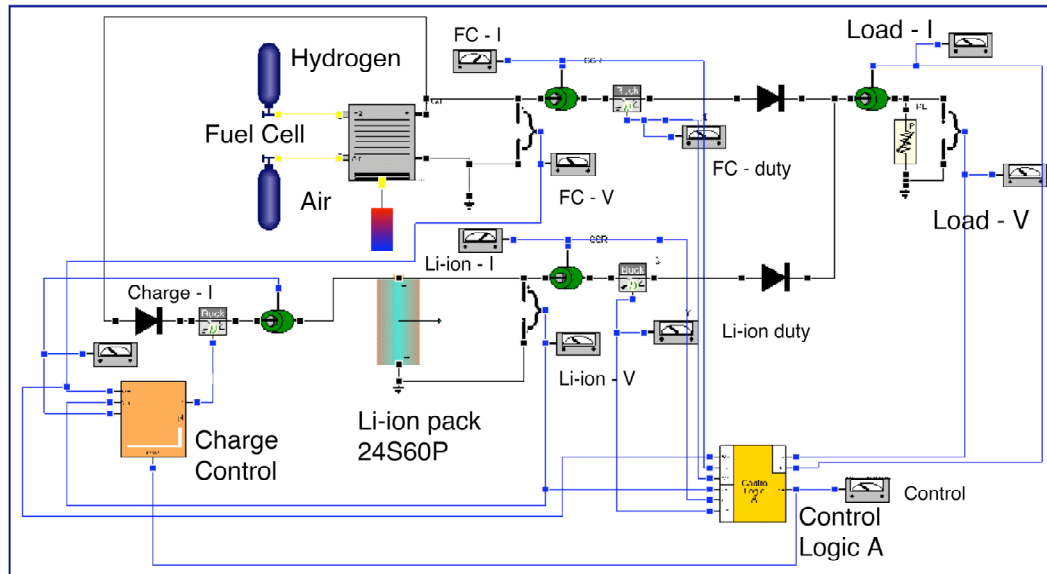


Figure 4 Virtual prototype of the control circuit arrangement for a hybrid fuel cell lithium ion battery AUV power source, modelled using VTB, with a custom-programmed Control Logic module.

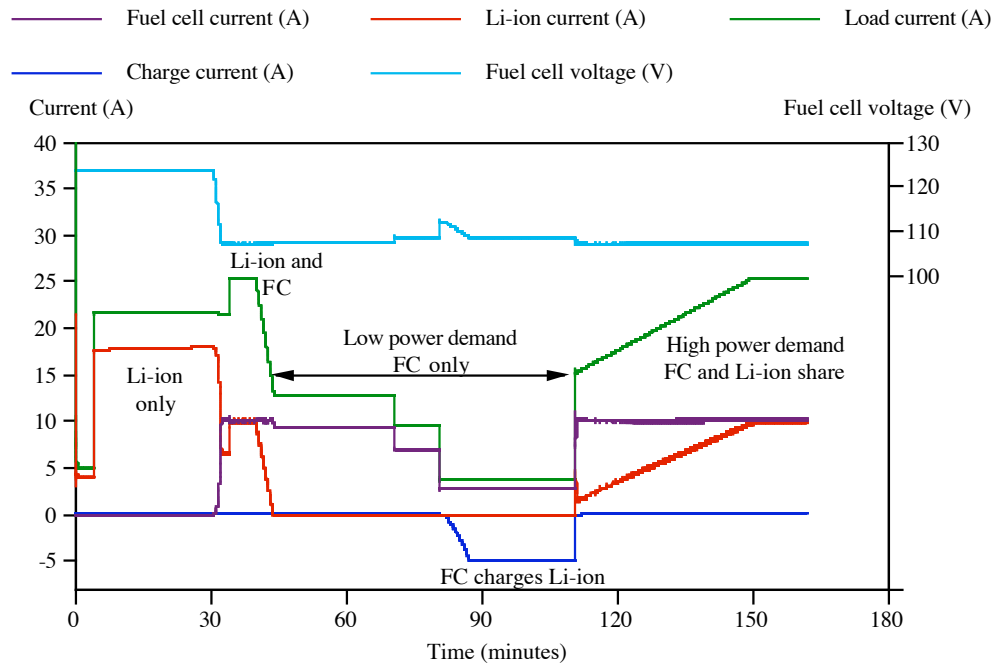


Figure 5 Current waveforms during a mission simulation for the load, fuel cell and Lithium ion battery, together with the fuel cell voltage

Figure 5 shows the waveforms for the circuit test of figure 4. Initially, the load current is supported entirely by the lithium ion battery, as the fuel cell reaches operating temperature. As the fuel cell comes on-line, the lithium ion current drops, but then increases, as the load demands more current. With the fuel cell contributing its maximum of 10 A, the battery provides the balance. As the load decreases, to a point where it is below the capacity of the fuel cell, no current is drawn from the battery. As the load decreases further, part of the fuel cell output is used to charge the battery until the load increases sharply, and continues to increase, causing the charging to end, the fuel cell to contribute its maximum 10 A towards the load and the battery current to increase to provide the balance.

5.2 Sizing strategy

The first parameter to be determined for the hybrid power circuits is the value of the AUV bus programmable load voltage (the voltage that is applied to the programmable load running the power profile). This determines the maximum voltage (and voltage range) needed for the lithium ion battery and also the voltage of the main energy source. The choice of bus voltage is influenced by the maximum load power; a profile with very high power peaks (several kW) will require a high bus voltage in order to reduce the current in the system, thereby reducing resistive losses. In this design, the lithium ion battery voltage range must always exceed the bus voltage value, as a DC-DC step down converter is used to control the output of the battery to the load. For example, a 70 V AUV bus will require a lithium ion battery with a minimum voltage range of 70 V, which at 2.5 V per cell determines the number of cells in series, in this case 28, implying a maximum battery voltage of 118 V (at 4.2 V per cell). The fuel cell source voltage must exceed the lithium ion battery voltage in order that it can re-charge the battery through the charge DC-DC step down converter. Hence in this example the fuel cell voltage should be around 150 V or so.

The next step is to determine the control strategy parameters. At what load current does the main energy source recharge the lithium ion battery? What load current would be set for lithium ion battery only operation etc? These parameters can be judged from the power profiles.

Further steps in the energy source sizing for the capacity of the energy sources, size of fuel and oxidant storage tanks, number of parallel strings required for the batteries, are determined by making initial calculations on the total time, and at what current levels, the load requires of the energy source. From this

point the energy source sizing becomes an iterative process of running the hybrid circuit simulations (starting with the initial energy source sizes) and changing the size values in order to meet the power requirements of the load. The simulations presented here assume that the average temperature of the mission runs is 20°C.

Two mission scenarios can be used as examples to exercise the hybrid energy system design:

- 7-day Type A – cruising speed of 2.5 ms⁻¹, varying sensor load, with high-speed sprints. Total energy required: 519 kWh
- 7-day Type B – cruising speed of 2.5 ms⁻¹, with varying sensor and communications loads. Total energy required: 161 kWh.

The power waveform profile for the 7-day Type A mission has an ideal shape for the hybrid power systems. Periods of low power demand can be serviced by the fuel cell and the high power peaks can be supported by the lithium ion battery. There are long periods of low power demand during which the Lithium ion battery can be recharged by the fuel cell. The profile does pose a major problem in the size of the high power peaks, which will have a large impact on the size of the lithium ion battery required to complete the mission, and on the amount of fuel required for the main energy source in order to recharge the battery.

The 7-day Type B profile poses more problems for the hybrid power system control than the Type A profile and these are discussed below.

5.3 Sizing the 7-day Type A mission requirements

The high power peaks in the load profile at 32 kW for 2 hours were the main factor that determined the bus voltage. To reduce current, a bus voltage of 200V was chosen. The actual optimum fuel cell current for the VTB model (based on a H-Power D35 stack) is not known, so a figure of 15 A was used in the Control Logic parameters. The low power demand in this profile would produce load currents ~ 5A, hence the 'Charge lithium ion at currents below' parameter was set to 8 A so that the fuel cell could charge the lithium ion during these periods. Initial sizes for the lithium ion battery 60S-150P (a 252 V 225 Ah battery) and a fuel cell stack voltage of 280V proved inadequate to meet the power profile: the lithium ion battery discharged too rapidly during the high power peaks and the fuel cell was not able to fully charge the lithium ion during the low power demand periods.

A process of iterating the lithium ion battery size and the fuel cell stack voltage followed, giving a solution

based on a battery of 80S-240P (336V 360Ah) and a fuel cell stack voltage of 360 V. The fuel and oxidant storage tank capacity sizes were then calculated, such that the complete 7-day Type A simulation almost depleted these supplies.

Figures 6–8 show the VTB simulation outputs for the Fuel cell lithium ion battery hybrid circuit running the 7-Day Type A profile and using the following model parameters:

- **Fuel Cell:** stack voltage of 360 V (N=360);
- **Lithium ion Battery:** 80S-240P giving a 336 V 360 Ah battery. Approximate mass of 900 kg;
- **Battery Charger:** Charge current = 40 A;
- **Control Logic A:** UUV bus voltage = 200V.

Figure 6 shows that the chosen fuel cell set-up produce a solution that copes well with the load current and peak charging current without the stack voltage dropping below 300 V. The battery provides additional current for the sprints (Figure 7). At the end of each sprint the charge remaining is ~ 24%. With the chosen fuel cell set-up, it takes some 24 hours to fully recharge the battery, while the fuel cell also powers the vehicle.

Fuel usage rate (Figure 8) reflects the current demand (load+charge) and fuel remaining (Figure 8) shows that the initial capacity and usage estimates were correct. At the end of this mission, ~5% fuel remains.

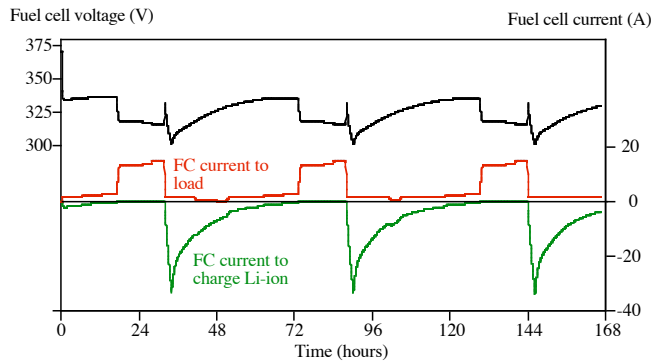
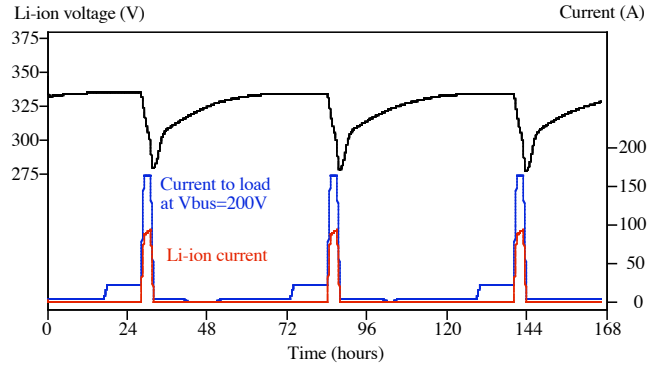


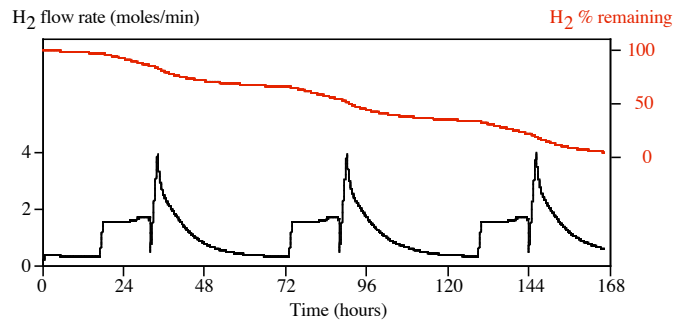
Figure 6 Fuel cell voltage and current profiles with time over the 7-day Type A mission.

The specific energy of this hybrid system is simply the total energy available (519 kWh) divided by the energy system mass, including reactants and reactant storage. In this example, the total energy system mass is 1715 kg, comprising 120 kg for the fuel cell and ancillary support components, 24 kg for the hydrogen, 408 kg for hydrogen storage, 207 kg of oxygen, 56 kg for oxygen storage and 900 kg for the lithium ion battery.



With a specific energy of 303 Wh.kg⁻¹ this hybrid system is

Figure 7 Lithium ion battery voltage and current profiles with time over the 7-day Type A mission, together with the



total current load provided from the 200 V vehicle bus.

on a par with the specific energy of primary lithium manganese dioxide batteries.

Figure 8 Fuel cell hydrogen consumption rate (moles/min) and fuel remaining (%) over the 7-day Type A mission.

5.4 Sizing the 7-day Type B mission requirements

The Type B profile poses slightly different problems for the hybrid power circuit parameters; the main problem is that there is little variation in power levels throughout the 7-day period. There is only a short period of low power during which the fuel cell can re-charge the battery. As a result of this, the energy source sizing was heavily biased towards the fuel cell being the dominant power source, the battery would contribute only a small amount of current during the long ~900 W demand periods. As the power levels overall are much lower than in Type A the bus voltage can be lower: 75V was selected as an initial starting point (giving a load current of 13A for the high- and 11A for the low-power demands). A fuel cell optimum current of 7 A was selected for this circuit. A number of simulation runs were performed

to establish the appropriate levels to set for the 'Charge lithium ion at load current below' parameter and the number of parallel string required for the lithium ion battery.

The solution for this circuit was found to be a 30S-18P (126 V 27 Ah) battery and a fuel cell stack voltage of 150 V. The charge current was set at 3 A (approx C/10 for this size battery). The hydrogen and oxidant storage tank capacities were calculated as for mission Type A.

The resulting parameters were:

- **Fuel cell:** stack voltage 150V (N=150);
- **Lithium ion battery:** 30S-18P giving a 126 V 27 Ah battery with an approximate mass of 26 kg;
- **Battery Charger:** Charge current = 3 A;
- **Control Logic A:** UUV bus voltage = 75V.

The specific energy of this hybrid system is higher than for the Type A mission. This is because the battery required is smaller; there is no need for sprint power capability. In this example, the total energy system mass is 328 kg, comprising 100 kg for the fuel cell and ancillary support components, 7 kg for the hydrogen, 119 kg for hydrogen storage, 60 kg of oxygen, 16 kg for oxygen storage and 26 kg for the lithium ion battery. With a specific energy of 490 Wh.kg⁻¹ this hybrid system would have a specific energy higher than primary lithium manganese dioxide batteries.

6.0 Conclusions

The concept of using hybrid energy sources to power AUVs has the potential to provide high specific energy at a lower cost than when using primary lithium batteries. This has been illustrated using the VTB modelling tool to simulate two lithium ion fuel cell hybrid systems with two different 7-day mission scenarios.

The robustness of the VTB tool in modelling the individual components of the hybrid system was tested against experimental battery and fuel cell data and reasonable agreement shown. Care has been taken to use realistic estimates of the mass overhead of fuel cell reactant storage in order to avoid over-optimistic estimates of system specific energy. In the case of cryogenic oxygen storage for use in an AUV significant progress has been made recently. Practical hybrid systems await further developments in AUV-compatible fuel storage and the engineering challenges in dealing with reaction products need to be solved.

With PEM fuel cell stacks now easily available at ~\$5,000 for 1 kW as turnkey systems, there is an opportunity for engineers to develop affordable hybrid systems of high performance and high reliability.

It is clear that when using this strategy, any mission that requires a sprint or high power section is going to need a large battery. In the case of the Type A mission 90 0kg of lithium ion battery, the battery assisting the Fuel Cell when the sprint power is required. If the strategy and the system was changed by adding additional fuel cells, providing sprint power would be possible without the large battery. By using the same reactant storage the additional weight to the system would be 360 kg (3 times 120 kg) but the battery weight would reduce significantly. The battery would only be required to supply sprint power while the three additional fuel cells warmed up. Having a smaller battery would also speed up the recharge. To size the smaller battery we could assume it takes 30 minutes for the fuel cells to warm up (Figure 5). Therefore the battery has to supply 100 amps (Figure 7) for 30 minutes, which is 50 Ah. This is 13% of battery used in the "Type A" mission scaling to a weight of 125 kg. The resulting specific energy of this system would be nearly 400 Wh/kg (total mass of 1300 kg).

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