TECHNOLOGY NEEDS FOR AUTONOMOUS UNDERWATER VEHICLES

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ABSTRACT

This paper considers the technology needs for autonomous underwater vehicles as the middle layer of a three-layer process. The first layer is the high level User Requirement, which may be stated in the form of business objectives such as 'competitive running cost' or 'less than 1 hour per week downtime'. These business objectives map on to the middle layer of specific, but generic technology needs such as 'lightweight pressure vessels' or 'energy-efficient propulsion'. Finally, these technology needs may be met by a number of candidate solutions, forming the third layer, for example, 'composite materials' or 'fuel cells'. The time horizon for the adoption of candidate solutions probably spans at least a decade. Some are the subject of current research by the marine technology community, others are in development by other parts of the science and engineering base or by industry and some are on or even over the horizon. This three-layer approach to setting out the technology needs provides for a clear focus on user needs and avoids the pitfall of focusing on challenging technological problems that may not lie on the critical path to making autonomous underwater vehicles a commercial success. For, only by becoming a commercial success for their manufacturers can AUVs be afforded in the numbers needed to contribute to marine science and industry.

1. INTRODUCTION

Europe is a leader in the design, construction and operation of autonomous underwater vehicles (AUVs) for scientific and commercial purposes. Leading examples include:

- HUGIN – an ocean survey AUV from a Norwegian consortium led by Kongsberg-Simrad, equipped with swath bathymetry and precision navigation, Stokersen (1997);
- MARTIN – an AUV from Maridan, Denmark, that has carried out mineral reconnaissance demonstrations and sidescan sonar surveys in inland and continental shelf waters, Bjerrum (1995);
- AUTOSUB – an ocean science AUV from the Southampton Oceanography Centre, UK that has completed over 200 missions in UK, US and Bermudan waters including physical oceanography, fisheries research and sediment transport studies, Millard *et al.* (1998);
- SARA – a project launched by the Italian National Commission for Research, involving public and private organisations to produce an AUV for the extreme conditions found in Antarctica, SARA (1999).

In all, Janes Underwater Technology 1999/2000 lists eight different European AUVs, Janes, (1999). This is undoubtedly an underestimate. If we take a broader view of the term AUV then we can also add:

- Autonomous Surface Craft – for example, the *Caravela* Eureka project led by the University of the Azores for a 1000 km range surface craft with an autonomous winch, Caravela (1999), and the Survey Autonomous Semi-Submersible project in the UK, led by SeaSpeed Engineering Ltd., SASS (1999);
- One-dimensional autonomous underwater vehicles, or moored profilers, such as the YoYo 2000 designed and constructed within a MAST III project led by the University of Paris, see Provost (1996) for a description of an earlier version.

Europe is also active in the military AUV/RCV business, although here, the definition of an AUV may become rather blurred as several of the military vehicles have high bandwidth communications links that may enable real-time control to be effected. In essence, these may be classed as remotely controlled autonomous vehicles. Examples include:

- Marlin – a submarine launched mine countermeasures vehicle from Marconi Naval Systems, UK, Janes (1999), p.17.
- Seafox – a one-shot mine disposal vehicle from STN Atlas, Germany and MineSniper a vehicle for a similar task from Kongsberg-Simrad, Norway, Janes (1999), p. 36.

Despite differences in purpose between AUVs designed for scientific, commercial or military users, many of the basic sub-systems are similar, at least in a generic sense. Detailed specifications may differ, but nevertheless there is significant commonality. The requirements-driven approach taken in this paper to identify technology needs is valid for all three of these applications.

First, we will consider the user requirements in section 2, followed by the broad technology needs in section 3 where we also consider some of the candidate solutions. This approach is summarised in Figure 1. From the outset, it is important to grasp the complexity of the relationships between user requirements and technology needs. An apparently straightforward user requirement, for example a target figure for range or endurance, does not map one-to-one with a technology need. Rather it maps to many. In this example, while the range specification is obviously linked to the 'inexpensive energy source', it is also mapped to 'lightweight energy source', 'lightweight pressure vessels' and 'efficient propulsion'. Conversely, a technology area such as reliable software maps to several of the user requirements. While it may seem obvious, this systematic approach is, nevertheless, helpful is setting out clear objectives for future AUV developments.

2. USER REQUIREMENTS FOR AUVS

As AUVs become tools rather than technical curiosities, user requirements rather than spectacular technology will come to the fore. This can already be seen in Europe as vehicles originating in research programmes or laboratories transfer to the commercial marketplace. Whereas running cost, for example, may be of only marginal interest during the development phase of an AUV, it becomes a critical parameter for routine operation. Similarly operations such as launch and recovery need to become less prone to risk, vehicles will not always be used and deployed by experts.

The evolving nature of the demand for AUVs is also evident when we see commercial companies setting out their goals for the new technology. For example, the energy companies BP Amoco and Shell have both produced documents setting out their corporate expectations of the benefits required from AUVs with examples of scenarios of how they might be used offshore, SUT (1999). Consultancies and professional journals have added their interpretation on market and user requirements, see for example Anon (1999).

3. TECHNOLOGY NEEDS AND CANDIDATE SOLUTIONS

Figure 1 provides a list of some of the more important technology needs and candidate solutions. It is clearly impossible to provide a comprehensive list within the scope of this paper. A common thread running through this section is the opportunity (indeed necessity) of making best use of technology and methods developed outside of the marine community in order to solve, cost effectively, a number of the problems posed. Equally, across Europe, there is a wealth of expertise and experience in the different technologies that make up an AUV.

3.1 Reliable Software

The reliability of an *autonomous* underwater vehicle owes much to the fundamental decisions on the control architecture, the analysis and design methods used to produce the software and the integrity of the human-machine interface when it comes to coding missions. Experience shows that decisions on control and software architecture remain with the vehicle throughout its life. While modular construction should apply to software as much as to the hardware of the vehicle, the basic philosophy of the system is unlikely to change. It is therefore imperative that the early decisions allow for future growth. Fortunately, AUVs can make use of a vast pool of knowledge and experience of generic real-time command and control systems. For the current or the next generation of practical AUVs there is little need to innovate – the research community has already generated a large range of candidate techniques and architecture, several of which have emerged as industry standards. Upon this infrastructure, the superstructure of the chosen AUV control method can be built. Table 1 provides some examples, taken from the procedures used in the Autosub project, McPhail (1998). The table also identifies gaps in our current capabilities.

3.2 Competitive running cost and affordable capital cost

In the era of experimental AUVs a full accounting of the running costs was a secondary issue. As we move towards commercial use of AUVs the running cost, typified by a day rate, becomes one of the main criteria for market acceptance. The components of the day rate include: energy cost, both directly and, for secondary cells, capital depreciation; maintenance and support costs, including the engineering support team, costs related to health and safety and compliance with regulations as well as the capital depreciation of the entire vehicle over its expected life.

3.2.1 Energy cost

A number of energy sources have been used for AUVs, ranging from common primary batteries such as manganese alkaline, exotic primary batteries such as high-temperature sodium-sulphur, through secondary cells of various types to semi-fuel cells (such as aluminium oxygen batteries), fuel cells, and internal combustion engines. But, when faced with running routine missions, the practical choice narrows considerably. Operators tend to err on the conservative side for a number of reasons, including safety, ease of maintenance, ease of procurement and transportation and affordability given the likely number of missions to be tackled. As a result, energy costs form a significant part of the day rate, and this is an area where new, cost-effective technology is desperately needed. Gone are the days where the mean-time-between-failures limited AUV mission duration. Affordable energy capacity is the limiting factor. Comparative costs are not always readily available, but Table 2 provides some information, based on the power consumption of the Autosub vehicle. Clearly, Lithium Ion secondary cells offer one possible economic option for the future, especially if they can be formed into batteries larger than those presently available. The safety and reliability issues of charging hundreds or thousands of cells also need to be resolved.

But, when we look at the energy density in Wh/kg of the cells in Table 2, we see that even Lithium Ion is rather poor. Fuel cells offer the potential for much higher energy densities. Table 3 shows that, in principle, energy densities of over 10,000 Wh/kg may be available in the future, a factor of 100 better than we have available today. One of the more intriguing possibilities is that the laptop computer of the future may be powered by a fuel cell based on hydrogen stored within carbon nanotubes, Dyer (1999). Such an application would provide the mass market that would reduce costs. Ocean engineers could surely use such technology within small AUVs.

3.2.2 Capital Cost

For an AUV of today, perhaps running on primary alkaline or silver zinc secondary cells, the energy cost will form a large part of the day rate for the vehicle. But when the energy cost looks set to reduce, through adopting new technology possibly as discussed above, the capital depreciation will form the bulk of the day rate. Detailed discussion of minimising costs through production engineering and careful specification and sourcing of modules is best tackled by another author. Some key points might include:

- Adoption of open standards for sub-assemblies; reduced labour costs;
- Use of generic sub-assemblies, gaining from quantity production for other markets;
- Minimising complexity;
- Designing-in ease of maintenance;
- Use of techniques and systems to ensure a long service life.

3.3 Payload Flexibility

While some AUVs may operate with the same sensor or instrument payload throughout their service lives, others may need to provide for greater flexibility in their payload capacity. This flexibility may need to be provided because the vehicle may be used on a wide variety of tasks, akin to a general-purpose research vessel. Conversely, the payload may itself be evolving rapidly and the vehicle will need to be able to cope with the necessary upgrades.

Payload flexibility will need to encompass *inter alia* available volume; shape; distribution; mass; materials; mounting; power requirements; data requirements (both *from* the payload and *to* the payload); any intake requirements (for example, for water sampling or chemical analysis) and hydrodynamic consequence (for example, the need for external fairing or transducer windows). It is evident that these issues of providing for a flexible payload will need to be considered very closely when judging the target capital cost of the vehicle. Adopting open standards for payloads will be a significant advance. Establishing an European thematic network may provide the springboard for collaboration.

One step beyond the idea of the need for a flexible payload capacity for sensors or instruments is the need for payload capacity because the prime purpose of the AUV may be as a cargo carrier. The first example of this purpose for an AUV may well have been International Submarine Engineering’s Theseus AUV, where it carried (and laid) a fibre optic cable within the Canadian Arctic, McFarlane (1997). Particularly important for this type of AUV is an automatic ballast and trim control system. At present, many AUVs avoid the need for active buoyancy and trim control by always running positively buoyant and relying on prior trim adjustment. This is time consuming and can not always be done at sea if the payload has to be changed.

3.3.1 Sensors and Instruments – another challenge set by AUVs

Europe has a strong presence in the oceanographic sensors and instruments market. While many of the instruments already available can, and have, be used successfully within AUVs there is a challenge to the supplier companies in producing a broader range of innovative instruments specially adapted for use in AUVs. In some respects, there are fewer constraints compared to producing stand-alone instruments, for example: more power may be available to the instrument, the data recording and control facilities may already be available and existing instruments may already be present to provide other necessary measurements. Some groups have already taken standard shipboard instruments and modified them for use on AUVs (e.g. a scientific fisheries echo sounder, USIPS (1999)) or modified innovative moored instruments (e.g. a flow cytometer, Cytobuoy (1999)). But, there is much more that can and should be done.

3.4 Adequate Range and Depth

Adequate range and depth have been traditional AUV specifications. They are strongly interrelated. As shown in Figure 1, an adequate range depends on having a lightweight energy supply (see section 3.2.1), but it also depends on having a lightweight pressure vessel to hold that energy supply. In *extremis*, of course, the need for a pressure vessel could be removed, and the energy source operated at ambient pressure. Its weight would need to be compensated by another form of buoyancy – but that may (or may not) be a simpler, or less expensive, problem. Such an approach is employed in the HUGIN II vehicle, where the energy source is an aluminium-oxygen semi-fuel cell, Vestgård (1999). However, most AUVs use a pressure vessel to house the energy source. Consequently, for every kilogram extra displacement of the pressure vessel, a kilogram of battery payload has to be given up. Key materials properties for pressure vessels to house AUV energy sources are the bulk modulus and the stiffness as a function of the material's density, Table 4.

The entries in Table 4 show that composite materials and ceramics are very attractive compared to high strength metals. However, their very nature means that material properties may vary and it may not be possible to achieve the promised benefits. Many suppliers are still some way from being able to deliver thick section composite pressure vessels that meet the theoretical specifications. For example, the Strength Index for Carbon Fibre Reinforced Plastic in Table 4 is based on a Youngs Modulus of 497 MPa, at the lower end of what has been achieved. Some laboratories have achieved values up to 750 MPa. Manufacturing difficulties, inhomogeneities in the materials and inadequate theoretical models that do not take account of all the failure mechanisms conspire to reduce the performance advantage of composites. Research programmes are tackling the issues, and no doubt practice and theory will converge in the not too distant future, see for example, Graham (1995).

There is also a need to better characterise material properties under high pressure. This applies especially to composites, syntactic and closed cell foam and the many other more mundane components within an AUV (e.g. cabling). The differential compression (and thermal expansion) between these components of an AUV and the seawater results in a net buoyancy change, which may increase or decrease with depth. This will be a non-trivial problem for deep diving AUVs that do not use a buoyancy control mechanism.

Another way to tackle the user requirement for range, depth and manoeuvrability may be to employ biomimetics – mimicking the form and construction of marine animals. This is a growing field of research including flow control and turbulence reduction, Techet et al. (1999); propulsion *via* oscillating bodies, Nakashima and Ono (1999) and manoeuvrable, fast starting vehicles, Kumph *et al.* (1999).

3.5 Appropriate Communications

The word autonomous should not be taken to mean that there is no need for one- or two-way communication with an AUV. Indeed for some applications, a physical or an acoustic communication link may be an essential component of the system. One can conceive of using an 'acoustic umbilical', for example, when there is a need for real time data transmission or accurate navigation. Much research has been undertaken in Europe on acoustic communications, and the results of this research may be applied to AUVs; it is by no means possible, today, to always purchase off-the-shelf solutions for AUV communications. Higher value products are possible through combining communications and navigation. The recent invention of the DGPS buoy/AUV positioning system integrated with acoustic modems is a good example of a value-added communication and navigation system, Coudeville and Thomas (1998). Key developments needed from acoustic modems are the obvious ones of longer range and or higher data rates with minimal error by systems capable of handling the Doppler shift induced by a moving platform. But the real issue is to integrate the AUV's communication link within an underwater communications network, Welsh and Topham (1999).

When on the surface the AUV has a larger number of options for data communications, including line-of-sight radio modems and satellite links. While radio modems are a mature technology, there is rapid growth in the low earth orbiting satellite communications industry. Reliable operation is, perhaps, yet to be achieved through any of the newer systems, particularly as some of the operating companies face financial difficulties. The older established methods such as ARGOS still have a place, but their orbital configurations mean that, other than in an emergency, they are of very limited use for AUV communication.

3.6 Navigation

AUV navigation specifications will vary from one application to another. For deep ocean oceanographic surveys a dead-reckoning position error of up to 1 km may be acceptable, whereas for geophysical site surveys the need may be for position errors of 5 m or less. Below we consider technology needs in the two broad areas of position fix acquisition and dead reckoning.

3.6.1 Position fixing

Obtaining position fixes when surfaced, using either GPS or GPS with real-time differential corrections has been proven many times on AUVs. The specific problem of obtaining valid ephemeris messages after having been submerged for several hours has also been overcome, either by using antennas well clear of washover, or using a special receiver that de-fragments the messages, Meldrum (1996). It may be a rather ambitious statement, but what is now needed is the underwater equivalent of GPS. That is, a wide area navigation system that may do away with the need for an operator to install a local area navigation system. Of course, for particularly accurate position fixes there may still be a need for purpose-installed systems. The need for a wide-area 'underwater GPS' is not limited to AUVs, many other applications could be found for such a system.

3.6.2 Dead Reckoning

Dead reckoning (DR) may be considered as a method of interpolating between position fixes, and therefore the requirements are closely connected to the specifications and availability of such fixes. In general, the DR problem for an AUV is solved by combining measurements of depth, heading and vehicle velocity (which may or may not be velocity over the ground) and, in some cases, vehicle acceleration. These measurements may be combined in an inertial navigation system (INS), or they may be combined by the AUV programmer. There has been a recent trend towards lower cost, but high specification INS modules appearing on the market, to the benefit of the AUV community, for example see Kearfott (1999). This trend should be encouraged.

An area that still needs attention is the measurement of vehicle speed over the ground in deep water, beyond 500 – 1000 m height that forms the practical limit for virtually all of today's Doppler velocity logs. While correlation logs can, in principle, provide longer ranges for the same size and weight, there are none readily available for the commercial AUV market. An interim target might be a velocity log that will operate at ranges of 3000 m with a velocity accuracy equivalent to 0.1% of distance travelled.

3.7 Interchangeability

Interchangeability has been a theme throughout much of this paper – the AUV designer and operator can only benefit from the availability of a range of modules for the initial construction of the vehicle and for the sensor and instrument payload. By adhering to existing open standards and by working together to agree new standards where necessary, the AUV development and user communities can both benefit. Commercial end users of AUVs will expect to see products that conform to open standards; they will not want to be tied to a particular brand of vehicle, sensor or tool. As operating methods develop, for example docking and the use of AUVs for intervention and control tasks, these aspects, too, will need to be standardised to ensure interoperability.

4. CONCLUSIONS

In following an approach beginning with user needs specified in non-technical language, leading to identifying a set of technology requirements, which rarely map one-to-one with user needs, this paper has attempted to suggest some candidate technology areas where advances are required. Not all of the needs have the same priority, much will depend on the priorities of individual users. For scientific users, a very personal order of priority might be:

1. Increased energy density at an affordable cost;
2. Increased depth rating;
3. Improved reliability in mission programming and mission simulation;
4. Wider range of suitable sensors and instruments;
5. Wide-area underwater navigation system available for all users;
6. Improved two-way communications.

Many technology needs and candidate solutions have been omitted from this paper, which could only touch on some of the issues. There is a need to continue this debate if AUVs are to transfer successfully from the research arena into the commercial world.

ACKNOWLEDGEMENTS

My thanks go to Peter Stevenson for his advice on materials and their properties.

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Figure 1 Diagram to show the cascade from user requirements through technology needs to candidate solutions.

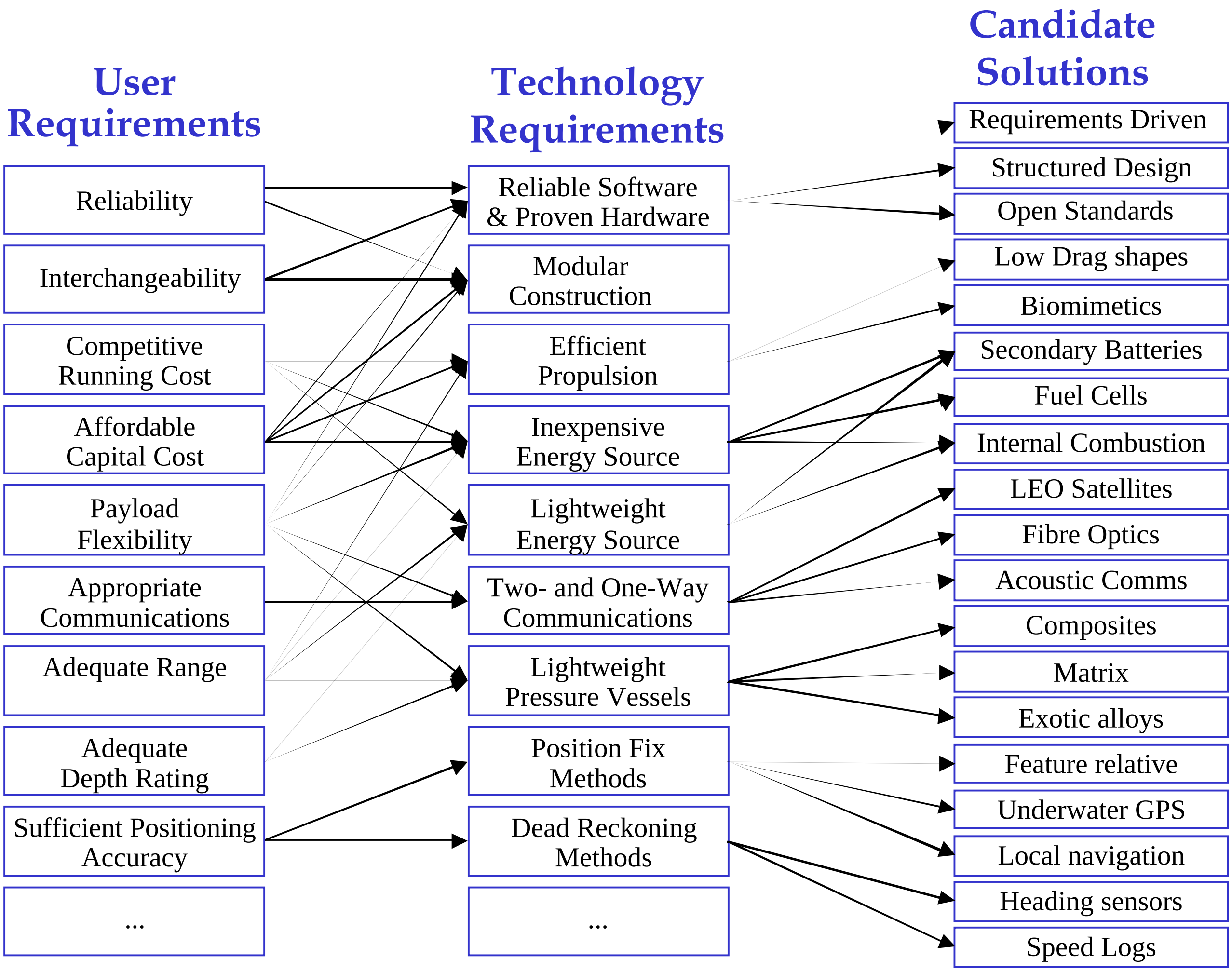

Table 1. Aspects of AUV software and control, current examples and outstanding needs

Aspect	**Example**	**Needs**
Requirements Capture		Continuing exchanges with new user communities.
Structured Analysis and Design	Jackson, with extensions for real time by Hatley/Pirbhai	Proven.
Software Engineering tools	Software through Pictures ™	Proven.
Control Philosophy	Event Driven	More complex architectures such as Subsumptive , Hierarchical, Hetrarchical or combinations could be considered for more complex AUV tasks. See for example, Barrouil & Lemaire (1999)
Hardware Architecture	Distributed Network	One example of several possibilities for this and the following three, closely related choices. Other possibilities include CANbus, FieldBus …
Development Tool	LonBuilder ™ (Echelon)	
Hardware Implementation	Neuron (Motorola)	This particular choice has limited computational power – probably limiting applications for more complex tasks.
Network Protocol(s)	LonTalk, Ethernet	Proven.
Coding	C++	Proven.
Source Code Version Control	Unix SCCS	Becomes more important when multiple vehicles with different specifications need supporting.
Mission Simulation	No provision at present	Scope for development, would be beneficial to link to standard command vocabulary, see below.
Mission Control	Proprietary scripting language	No standard currently available. Autonomous Undersea Systems Institute in the US is beginning to develop a standard vocabulary, Komerska *et al*. (1999)

Table 2 Energy Cost comparison based on a ~ 35 kWh pack within Autosub

Battery Technology	Range (km) for 300 kg battery	Wh/kg	Number of Cycles	Capital Cost €	Other Cost* €	Cost per km €
Lead Acid (secondary)	70 weight limited to 7kWh	~ 25	50	1000	500	0.5
Alkaline (primary)	250	~ 120	1	5000	500	22
Silver Zinc (secondary)	250	~ 180	20 to ~85% discharge	70,000	15,000	17
Lithium Ion (secondary)	250	~ 150	500 estimated full life	130,000	125,000	2
Lithium Ion (secondary)	250	~ 150	100 actual missions	130,000	25,000	6

* Includes staff costs in ensuring safe charging and maintenance

Note that no AUV currently operates with a secondary lithium ion battery pack. The Japanese remotely operated vehicle UROV 7K has operated with a 6 kWh lithium ion pack, Janes (1999) p. 8.

Table 3 Candidate Fuel Cell technologies

Type	Potential Wh/kg	Notes
Methanol + reformer	6,200	Potential to use cells developed for the automobile industry. Prototypes available.
Hydrogen (as hydride)	370 – 2,800	2,500 – 3,300 Wh/litre
Hydrogen (cryogenic)	33,000	Probable storage difficulties within an AUV
Hydrogen (in carbon nanotubes)	16,000	Potential for ~ 32,000 Wh/litre, unproven at present

This table makes use of information provided in Dyer, C.K., 1999. Replacing the battery in portable electronics, Scientific American, Vol. 281 (1), pp. 70-75.

Table 4 Properties of some materials for use as pressure vessels for an AUV energy source

Material	**Stiffness Index ($E^{1/3}/\rho$)**	**Strength Index (s/ρ)**	**Remarks**
Steel 62-45B	1.0	1.0	
Titanium 318	1.4	2.2	
Forged Aluminium 7076	2.0	1.4	
Glass Fibre RP	2.2	2.2	55˚ winding angle filament wound
Carbon Fibre RP	3.5	3.8*	55˚ winding angle filament wound based on E=470 MPa
Alumina Ceramic (*)	2.4	8.1	But limited in flexural strength. E=2500 MPa
Boralyn E15-T6	2.3	3.5	
Boralyn H35-T8	2.6	2.1	

The stiffness index dominates for a tube that is subject to failure through buckling under compressive load. The important comparison factor is the third root of Youngs Modulus (E) divided by the density, as the buckling pressure rises with the third power of E. For shallower depths, buckling is most likely to occur before material failure, given by the strength index.