Underwater Glider Propulsion using Chemical Hydrides

Jo Borchsenius and Shane Pinder
Auckland University of Technology
Private Bag 92006
Auckland, 1142 NZ

***Abstract*-A novel buoyancy engine for the propulsion of underwater gliders is presented. The research explores the direct volume expansion of hydrogen gas from the reaction of lithium hydride with seawater. As a result the seawater is expelled from the reaction chamber creating buoyancy and consequently also propulsion. The hydrogen produced can then be used to create electric energy in a fuel cell for use by the vehicle control system and on-board scientific payload.**

I. INTRODUCTION

Underwater gliders are a class of Autonomous Underwater Vehicle (AUV) propelled by a change in buoyancy. This change in buoyancy is converted into forward movement by hydrodynamic forces working on the hull of the underwater glider [1]. It can be argued that, for an underwater glider, creating more buoyancy generates greater forward propulsion for a given hull design within certain boundary conditions. A greater creation of buoyancy requires the conversion of more energy, which often is of limited supply due to storage constraints within the hull of the underwater glider. Moreover, a more efficient hull design will result in more forward momentum at a given buoyancy change. Consequently, the range of the vehicle can be stated to rely much on the hydrodynamic efficiency of the hull, the energy density of the energy storage, and how efficiently this stored energy is converted into buoyancy change.

A. Hull Design

The hull of an underwater glider is critically important in the development of underwater gliders. Whether it is speed, range, accuracy, or manoeuvrability, the hydrodynamic characteristics of the hull play a significant role. Accordingly, studies to determine and improve these characteristics have been performed since the early stages of underwater glider development [2]. With the development of most underwater gliders follows a study of its hull design [3-5]. Also, studies focused on the underwater glider parameterisation and control alone has been performed [6-7]. Additionally, much work is published in peripheral fields that may prove valuable [8-9].

It is not only the hydrodynamic performance of the hull that is vital to determine the efficiency of an underwater glider. The hydrostatic performance plays a significant role. As a glider dives, it moves through waters that change in density due to compression. Consequently, an essentially rigid hull having neutral buoyancy at the surface will have increasing positive buoyancy as it moves deeper in the compressible seawater. As a result, to be able to dive solely based on buoyancy, a rigid hull needs to achieve a larger negative buoyancy to efficiently reach greater depths. This results in the need for a larger increase in buoyancy for the glider to ascend to the surface. Ultimately this leads to less efficient propulsion, as an underwater glider is propelled solely by the force created by the buoyancy change. A successful attempt has been made to simulate the compressibility of seawater in the underwater glider hull in the Seaglider [4], yet at a higher economical cost than conventional pressurised hulls [3].

The paper at hand will not discuss the properties of the hull, regardless of the importance of the subject, due to the absence of a tested hull at this stage of development. Consequently, to be able to compare the performance of the novel buoyancy engine to that of buoyancy engines used in other underwater gliders, a fictional hull with comparable characteristics to three commercially available underwater gliders [1] will be used. This will be more closely presented later in the paper.

B. Propulsion systems and energy storage

It is difficult to pinpoint exactly when and where the concept of the underwater glider was conceived, and who can be credited with the invention. The invention has previously been incorrectly attributed to Henry Stommel [6, 10] due to his much referenced paper "The Slocum Mission" published in Oceanography in April, 1989 [11]. Although Stommel has been involved, it is indicated that Doug Webb, later the founder of Webb Research Corporation (WRC), was a central character when the idea of adding horizontal propulsion to profiling floats [12-13] was discussed at Woods Hole Oceanographic Institute (WHOI) in 1978 [5, 10]. More than a decade passed before these ideas were realised and field-tested in 1991 [2]. These tests were led by Paul J. Simonetti, also affiliated with WHOI, and the glider presented is very similar in concept to the battery-powered gliders of today [1].

By now several propulsion systems for underwater gliders have been developed and tested [1-5, 14-15]. The convention is an electrically powered hydraulic system as in the commercial gliders Spray, Seaglider, and SLOCUM Battery [1, 3-4]. These systems all use electric motors to power hydraulic pumps that inflate and deflate bladders on the outside of chambers of constant volume which are isolated

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

from the external pressure. As a result, the external volume of the underwater glider increases or decreases resulting in a change in buoyancy and consequently thrust as explained previously in this paper. This chamber of constant volume is essentially a pressure vessel functioning as an accumulator. Whether it has a positive, negative, or alternating charge pressure compared to ambient conditions, pumping the liquid in and out will require a modest yet significant amount of work at some stage to complete a cycle. A larger chamber may decrease the work yet require a larger mass of the vessel at a given pressure, and vice versa. This high pressure pumping is relatively energy intensive, and when multiplying the efficiency coefficients in all the steps from energy source to buoyancy, the result is an inefficient system. It becomes apparent that a multi-stage conversion like this is not preferable when the goal is to make use of as much of the energy as possible.

Although slightly inefficient, the underwater gliders show modest energy consumption compared to that of most other AUVs using propellers or water jets as propulsion. This enables an underwater glider to have an impressive range and endurance. As an example, the commercial underwater glider Spray can cover up to 7000 kilometres or endure 330 days without human intervention or the use of costly ship time [1]. This is possible by using 52 primary DD lithium CSC cell batteries weighing a total of 12 kilograms and storing 13 megajoules at a cost of USD2850 per set. Also SLOCUM Battery and Seaglider make use of primary cell batteries and exhibit impressive endurance. The added cost of the primary cell batteries compared to that of rechargeable batteries is justified due to the extended endurance it provides.

Possibly even more astonishing is SLOCUM Thermal, harvesting its propulsion energy from the ocean in which it operates [5]. This system was in development at the same time as the first test trial of the SLOCUM glider in 1991 and is based on the volumetric expansion and contraction of melting and freezing of the working fluid. The thermal cycle has an efficiency of approximately 3% due to the small temperature difference, but because of the virtually unlimited source and sink of heat this does not present a significant limitation. The vehicle is limited in range only by the batteries that power the control system and scientific payload, or a possible failure. However, since it is relying on a temperature difference from surface to bottom of at least 10 degrees Celsius, it is not functional in polar regions as well as certain regions of the temperate oceans during certain seasons. Also, shallow operation presents a limitation. [5, 14]

Another approach is to use hydrogen fuel cells. This is not a novel concept in underwater vehicles. In 1980, mature attempts at powering submarines by the use of fuel cells was underway by Siemens [16]. There are promising prospects [17] for the use of Proton Exchange Membrane Fuel Cells (PEMFCs) in AUVs where advantages such as over 60% efficiency, neutral buoyancy, and low thermal signature are possible. Surprisingly, although verifying the efficiency and low thermal signature of PEMFCs reported in [17], others [14] present the development of an underwater glider propulsion system making use of the waste heat of a PEMFC to power a thermal engine similar to the one used in SLOCUM Thermal [5]. Although complex, this is a promising system. Yet, similarly to SLOCUM Thermal it will be limited by the storage of hydrogen and oxygen to provide sufficient energy to the control system and scientific payload, as well as providing sufficient waste heat to power the thermal engine. Considering electrical power outputs of 50 to 150 Watts over a period of approximately 30 minutes per cycle [14], the energy needed is substantial given an efficiency of a PEMFC in the range of 60%.

The presented buoyancy engines for underwater gliders show impressive performance. Nevertheless there are a few limitations to be seen. They are highly dependent on working pressure, and show limited efficiency in the usage of the onboard energy storage. SLOCUM Thermal is not limited by the size of its energy supply but it is geographically limited. The identification of these limitations led to the development of the proposed design. Use of a power source to directly create volume change would eliminate the losses affiliated with conversion of energy from one form to another.

C. Generating buoyancy through hydrolysation of chemical hydrides

Many chemical reactions result in a direct volume change, such as the oxidisation of hydrogen and carbon from hydrocarbons in a conventional combustion engine. These reactions rely on the available gaseous oxygen in the air, which for obvious reasons is not readily available beneath the ocean surface. However, there are several reactions resulting in volumetric expansion that can occur in this environment. One is the hydrolysation of chemical hydrides, where the volumetric expansion occurs mainly due to the release of gaseous hydrogen from the hydride and water. As with many of the alternative methods of storing hydrogen, the storage in chemical hydrides has received great attention in the last few decades. Furthermore, among the various alternative methods of hydrogen storage it may be considered as one of the more mature technologies. The volume of available literature on the subject is enormous, and there is a vast variety of studied hydrides and corresponding technologies. Due to this variety, the definition of a hydride is vaguely defined. The term hydride is widely used for both a hydrogen anion, and various compounds containing hydrogen. However, in this paper the term hydride will refer to a compound consisting of hydrogen chemically bonded to metal, and it is these chemical hydrides that are of interest in this paper. The chemical hydrides can be further divided into simple hydrides and complex hydrides. Simple hydrides consist of one host metal, typically from group 1 or 2 in the periodic table of the elements, bonded to respectively one or two hydrogen atoms (for example, LiH or MgH_2). Complex hydrides refer to a metal bonded to a cluster consisting of another metal and hydrogen, typically also a metal from group 1 or 2 bonded to respectively one or two

metal atoms from group 13 in the periodic table which is bonded to 4 hydrogen atoms (for example, $LiAlH_4$ or $Mg[BH_4]_2$). Due to mass requirements in hydrogen storage, the metals from period 2, 3, and 4 in the periodic table are of greatest interest. Several other complex hydrides exist (such as Na_3AlH_6) [18-19]. A survey based on the studied literature [18-39] has determined the preferred hydride for the intended use. Table I shows a qualitative comparison of a selection of chemical hydrides.

TABLE I
Comparison of chemical hydrides [a]

	LiH	MgH_2	$LiBH_4$	$NaBH_4$	$Mg(BH_4)_2$	$Ca(BH_4)_2$	$LiAlH_4$
Wt% H (a)	25.4	15.3	37.0	21.3	29.2	23.1	21.2
Reacts with water	Y	Y	Y	Y	N	U	Y
Reasonably safe	Y	Y	N	U	U	U	N
Easily controllable reaction	Y	N	U	U	U	U	N
Readily available literature	Y	Y	Y	Y	U	N	Y
Hydrogen yield under pressure	Y	U	U	U	U	U	U

[a] Y=Yes, N=No, U=Unknown

The chemical hydrides presented in table I are selected due to a gravimetric hydrogen content exceeding 15%. The beryllium hydrides have not been considered suitable due to toxicity and are therefore left out of the presentation [18]. Lithium borohydride and lithium aluminium hydride are considered as unsafe due to their highly corrosive and irritant nature [40]. Further, magnesium hydride is considered difficult to control due to passivation when reacted with water [33], whereas lithium aluminium hydride has a melting point of 125 degrees Celsius, which may be a safety concern with the heat generated from reaction [21]. Other potentially interesting hydrides have been disregarded due to the lack of available literature, such as the complex aluminium borohydride being a liquid at ambient conditions exhibiting 17% gravimetric hydrogen density and the highest known volumetric density of 150 kilograms per cubic metre [18]. From table I it is clear that among the remaining hydrides, LiH is the most promising candidate based on the set criteria. It has high gravimetric hydrogen content, it does react with water, it is considered relatively safe, and the reaction is easily controlled. Moreover LiH, and the reaction product LiOH already present in seawater, are not regarded to be particularly toxic, or exhibit adverse environmental effects [40-41]. Also of importance is the readily available literature both on the physical nature of the hydride, and on previous studies on the reaction between LiH and seawater at high pressure in similar applications [22, 39]. Additionally there are available studies of LiH suspended in slurry [22, 26, 29].

D. Chemical hydride slurry

Slurry can be defined as "a mixture of a solid and a liquid to make a pumpable mixture [26]." Suspending the LiH in a liquid media to form slurry both eliminates the need for isolation from external pressure, and facilitates the control of reaction. Reference [22] states that LiH represents an explosion hazard in large quantities if not suspended in slurry, due to the high reaction rate, high heat of reaction, and creation of hydrogen. McClaine seems to be a central figure in the extensive work done on hydrogen storage in chemical hydride slurries funded by the US Department of Energy (DOE) hydrogen program [26, 29, 36]. Their early work presented in 2000 reports the development of a successful hydrogen generation system using LiH in light mineral oil [26]. This work, along with the work published in 1965 by deVries at the Bureau of Naval Weapons [22] is of great interest for the development of the buoyancy engine presented in this paper. Experimental data [22] have been presented verifying the complete reactivity of LiH and seawater to a depth of 800 metres. It is further shown that slurries of LiH suspended in various liquids exhibit equivalent hydrogen yields to that of plain LiH particles at complete reaction. Moreover it is shown that reaction rate can be controlled by altering grain size of the LiH as well as the amount and type of liquid media used in the slurry [22, 26]. It is worth noting that the results presented in [22] show significant variability between seemingly similar experiments. Moreover the results in [26] are expressed without exhibiting precise values. Nevertheless, the two reports are considered to verify the functionality of the concept presented in this paper.

E. Generation of additional energy

Hydrogen possesses several appealing properties. It is nontoxic and releases 142 megajoules per kilogram, which is more than three times that of liquid hydrocarbons [27]. The energy is released by reaction with oxygen, either through combustion or by use of a fuel cell [26-27], only giving off water as the product of reaction. These properties make hydrogen a very attractive energy carrier for onboard energy storage in mobile applications. Hence the opportunity to further use the generated hydrogen to fuel a hydrogen fuel cell becomes apparent. It is shown that the purity of hydrogen generated from LiH slurry is well within the requirements for efficient use in a PEMFC [26]. Further the volumetric density of hydrogen in an easily pumpable 60% LiH mineral oil slurry reacted with water is 118 kilograms per cubic metre releasing 3937 Watthours per litre, and a gravimetric density of 5110 Watthours per kilogram or 15.3% hydrogen. Due to hydrogen being a low molecular weight gas with a critical temperature of approximately 33 Kelvin, it is difficult to achieve a competitive volumetric density in its pure form [42].

Consequently, the storage in LiH slurry compares attractively to the storage of hydrogen as liquid or as compressed gas. Liquid storage does provide a compact energy source of 70.8 kilograms per cubic metre, yet the equipment to keep the hydrogen below 33 Kelvin is relatively complex and expensive [27]. Compressed hydrogen can be stored in carbon fibre composite pressure vessels achieving working pressures up to 450 Bar, yet still only achieving 4% hydrogen by mass in the system. Additionally, the storage of large volumes of highly flammable gas at 450 Bar is not without inherent risk [27]. Comparatively, the LiH slurry has been shown to be prevented from igniting due to the high vapour pressure of the mineral oil used in the slurry. Moreover, the mineral oil also prevents the LiH from reacting with moisture in the air [26].

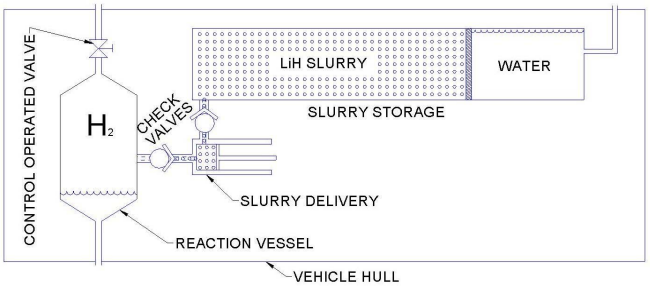
II. CONCEPTUAL DESIGN

A. Buoyancy engine

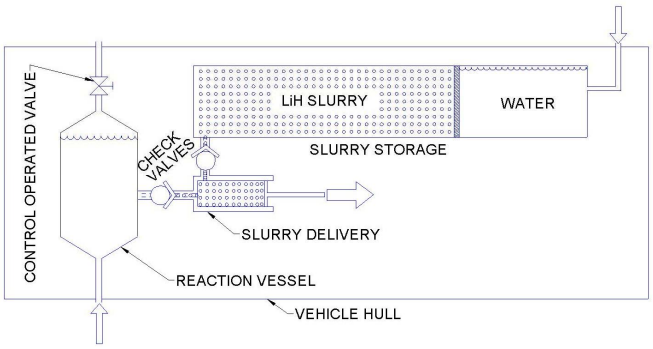
The proposed buoyancy engine uses the hydrolysation of a chemical hydride to generate hydrogen and resultant buoyancy. Since it is a chemical reaction that drives the buoyancy change, the buoyancy engine will from here on be referred to as a Chemical Buoyancy Drive (CBD). Figure 1 gives a schematic view of a full cycle of the CBD from surface to bottom and to surface again.

The positively buoyant underwater glider at surface has the reaction chamber filled with hydrogen from the previous cycle as shown in Figure 1a. Further it can be observed that the slurry delivery piston assembly is depleted of chemical hydride slurry to the extent needed at the depth and speed of the previous dive. The piston is to be spring loaded to ensure that, in any scenario the normally open solenoid holding it were to lose its signal, fuel is delivered resulting in resurfacing of the glider. Accordingly, the control system operated valve on the reaction chamber is normally closed to contain the buoyant hydrogen.

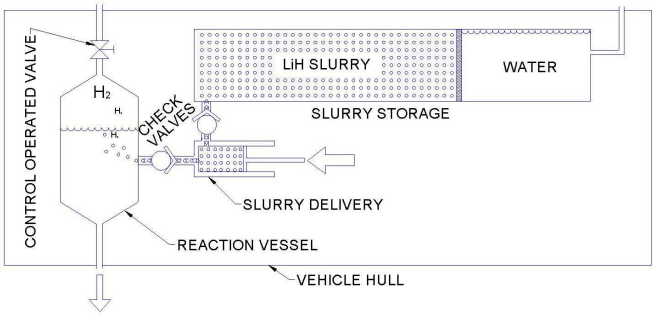
Before ascent can be initiated, the slurry delivery system will need to be fully re-charged as shown in Figure 1b where the movement is indicated by the large arrow. The charging of the slurry delivery system results in a decreased volume of the neutrally buoyant slurry left in the storage. This volume will automatically be filled by seawater as shown with a smaller arrow by the open inlet to the slurry storage. The flexible slurry storage is in concept a wet section separated from the seawater by a metal bellow, flexible bladder, or floating piston as shown here. All three alternatives have previously been shown to be successful in similar applications [5]. Once recharging is complete it is followed by opening of the control-system-operated valve, flooding the reaction chamber through the bottom inlet as indicated by the small arrow. Once the reaction chamber is flooded, the normally closed valve will close, and the underwater glider dives to its predetermined depth.



a) At surface the reaction chamber is filled with hydrogen from the previous cycle giving positive buoyancy



b) To initiate descent the slurry delivery is re-charged and the reaction chamber is flooded



c) At bottom depth the slurry is delivered initiating the chemical reaction generating hydrogen expelling the seawater from the reaction chamber resulting in positive buoyancy and ascent.

Figure 1. A complete cycle of the CBD

At the moment this depth is reached the chemical hydride slurry will be delivered into the reaction chamber, as shown by the large arrow in Figure 1c, instantly reacting with the seawater. The reaction generates hydrogen which will expel the water and the negatively buoyant hydroxide through the open outlet in the reaction chamber as shown by the small arrow. Once the reaction is completed so is the cycle, resulting in positive buoyancy as shown in Figure 1a. The glider will ascend until it reaches the surface, and the cycle can be repeated.

The CBD shown schematically in Figure 1 is a comparatively simple design. This open design will function

independently from pressure given that the chemical hydride slurry is neutrally buoyant, the slurry delivery system is sufficiently large for the pressure at operating depth, and that the reaction is not compromised by various undetermined high pressure effects. Although this paper presents the use of LiH specifically, the concept should be functional for essentially any chemical hydride that reacts in a similar manner with water.

The schematic only functions properly for neutrally buoyant slurry, whereas the LiH in toluene which have been mostly used until now exhibit a density of approximately 0.8 grams per cubic centimetre. Consequently, a mixture of hydrides of different densities to obtain a neutrally buoyant slurry is currently being explored.

B. Buoyancy Generated from Lithium Hydride

The amount of seawater expelled and the resulting buoyancy created will be virtually the same volume as the expanded volume achieved by reaction. LiH generates close to theoretical amounts of hydrogen when reacted with seawater both at surface conditions and while under pressure [22]. At surface conditions, this relates to 3.08 litres H_2 per gram of LiH as can be calculated from the chemistry of the LiH reaction with water,

$$LiH + H_2O = LiOH + H_2$$

and the ideal gas law.

The actual expelled volume will differ slightly from the above calculation, which is based on the ideal gas law, although at surface it will be substantially the same. As pressure increases, the generated hydrogen will be increasingly compressed. Accordingly, the ideal gas law breaks down and is less indicative. An additional source of error is found in the solubility of hydrogen in water at high pressure. It is nonetheless considered a reasonable approximation at depths of 1500 metres, or approximately 150 atmospheres. In Figure 2 below required amounts of LiH for a given volumetric expansion at depths up to 1500 metres is shown.

Figure 2 shows that to generate a volume of 300 millilitres of hydrogen will require approximately 1 gram of LiH per 100 metres depth, accordingly at 1500 metres a total mass of 15 grams LiH is needed.

C. Comparative volumetric expansion

As previously stated, the battery powered underwater glider Spray has a 12-kilogram battery package consisting of 13 megajoules energy stored in primary cell batteries which enables a range of 7000 kilometres, superior to that of SLOCUM Battery and Seaglider [1]. A stated lifetime of 1000 cycles to 1500 metres at 300 cubic centimetres volumetric expansion makes comparison convenient. Using ideal gas calculations for the equivalent expansions gives the need for 15 kilograms LiH which is comparable to the 12 kilograms of batteries used by Spray. In terms of cost this approximates to 2400 USD from the prices quoted for small quantities, which compares well to the 2850 USD for the batteries in Spray. However, there are several factors not taken into account in this simplified comparison.

- The LiH is delivered as slurry resulting in a higher total mass
- The LiH slurry can have neutral buoyancy, whereas the batteries will need to compensate with a pressure resistant increased volume
- The 12 kilogram batteries also power the control system and payload

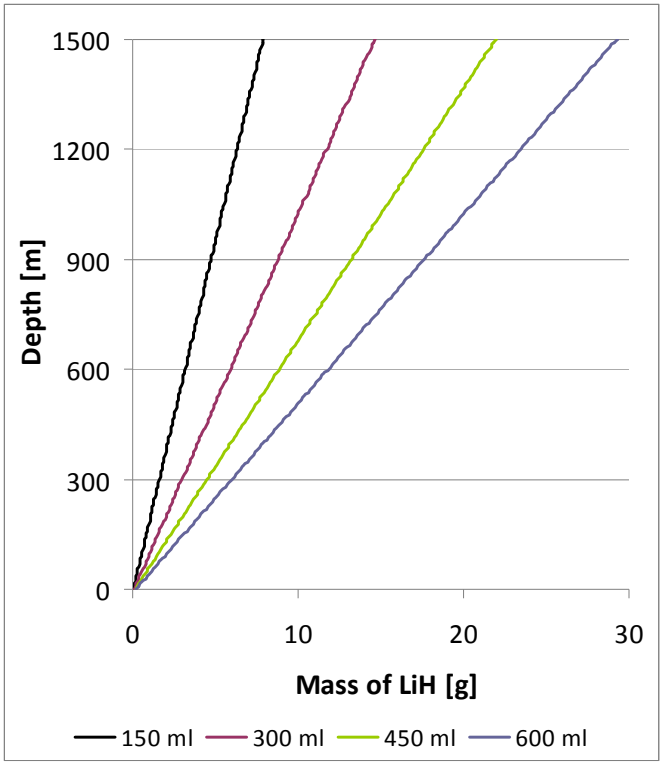


Figure 2. Buoyancy vs. pressure

These factors will alter the result of the comparison, yet the added mass from slurry and buoyancy will somewhat offset one another. Regarding the power usage of the batteries in Spray for the control system and payload, it is worth mentioning that the potential gain in electrical energy from the generated hydrogen is not yet taken into account either. This is covered in the following section.

D. Additional electric energy

As mentioned, the hydrogen gas generated for buoyancy can be further used for energy in a fuel cell together with oxygen. As already stated, hydrogen contains 142 megajoules per kilogram. When reacted with oxygen in a PEMFC having an efficiency of 60%, hydrogen generates 85 megajoules per kilogram. Given 3.8 grams hydrogen per cycle calculated using the ideal gas law for the comparative example to Spray, hydrogen generates 0.32 megajoules electric energy per cycle. Compared to the 0.013 megajoules per cycle used by Spray,

there would be over 20 times more available energy using LiH as the initial reactant. However, there is a prerequisite to enable this energy in the additional mass of oxygen, oxygen storage and the PEMFC itself which must be taken into account. Making an estimate of the mass of a complete system at this stage will be highly inaccurate at best; hence it has not been attempted.

E. Various design considerations

In addition to the design considerations already covered, there are a few identified aspects presenting an influence on the design.

Of the LiH reacting with the seawater, most of the Li+ ions will form the subsequent hydroxide. However, a fraction will probably react with the other anions present in the seawater. The major ionic constituents of the salt content in seawater have been identified, and the solubility of the resulting lithium compounds has been determined. These compounds could potentially have been deposited in repeated cycles, thus presenting a potential detrimental effect in valves or orifices. This has been determined to be of little concern due to the high solubility of the lithium compounds in water. Be that as it may, the lithium hydroxide itself may reach the limit of its solubility at operation deeper than 1000 metres due to the amount of LiH needed at these pressures. This is an effect that needs further exploration to verify the functionality of the CBD at greater depths. A solution to such a problem may be to simply flush the reaction chamber during each cycle.

An attractive concept with the use of chemical hydrides for energy storage is the possibility of regeneration of the consumed hydride. In the example using LiH, the reaction product LiOH could possibly be rehydrogenated into LiH using less energy than that needed for the production of gaseous hydrogen [26]. Potentially the regeneration process may even show superior to that of hydrocarbon refineries [36]. Although for the current intended use in underwater gliders, the regeneration process is just a future prospect and will not initially be exploited.

The possibility of further usage of the hydrogen to generate electricity through a fuel cell has been explored, and a conceptual schematic has been designed. The concept is deemed practically feasible, yet at this stage of development is left for future research.

Buoyancy is created by the generation of hydrogen. Since the hydrogen is compressible this enables possible improvements in efficiency. If the CBD were to create only a minor positive buoyancy at maximum depth it would nonetheless begin to ascend, albeit slowly. As the underwater glider reaches shallower waters, the hydrogen will expand, and the speed will increase. Consequently, a substantially smaller amount of LiH will be consumed per cycle. It is worth noting that this may cause practical challenges for the accuracy of the subsurface navigation as the speed and rate of ascent would no longer remain constant.

III. FUTURE POTENTIAL

Functionality of LiH reacted with seawater for hydrogen generation has been verified to depths of 800 metres. However, no literature has been found reporting the depth or pressure at which the reaction ceases to occur. At depths greater than 800 metres, the solubility of hydrogen in the seawater is expected to have a noticeable effect. Further, the compressibility of hydrogen can not accurately be determined using ideal or van derWaals gas equations. The isolated compressibility of hydrogen is possible to determine mathematically based on more complex equations of state such as the Beattie-Bridgeman, Hannes-Knapp, or virial. However, the resulting buoyancy considering the effects of hydrogen solubility will be difficult to determine accurately. Moreover, there will be an additional uncertainty in a theoretical determination due to incomplete reaction as a result of pressure. Consequently, to verify functionality at greater depths, the actual volumetric expansion of hydrogen at high pressure must be determined. Also, the reaction rate at elevated pressures is of interest and will be recorded in experiments intended.

The current design of the CBD is simple, and it does not take full advantage of the energy potential in the reaction of LiH with seawater. This is a deliberate choice to ensure functionality in this early stage of development. Moreover, this simple design eliminates the need for isolation from external pressure as the whole system is kept at ambient conditions. Consequently, if the LiH is shown to remain reactive to over 110 megapascals, this enables the use of this system to be functional at the deepest regions of the ocean. Finally, the simplicity of the design minimises manufacturing costs.

Accordingly, the next stage of our work, currently underway, examines the reaction of LiH in various slurries with seawater in a sealed reaction vessel, to determine the rate of reaction as pressure increases. The information obtained from this study will inform future directions for research.

IV. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support for the IEEE Oceans student poster competition provided by the Office of Naval Research Global. John Robertson at AUT Applied Sciences generously provided helpful input and access to laboratory space. His support is sincerely appreciated.

V. REFERENCES

1. Rudnick, D.L., R.E. Davis, C.C. Eriksen, D.M. Fratantoni and M.J. Perry, *Underwater gliders for ocean research.* Marine Technology Society Journal, 2004. **38**(1): p. 48-59.
2. Simonetti, P., *SLOCUM glider: Design and 1991 field trials*. 1992, Webb Research Corp.
3. Sherman, J., R.E. Davis, W.B. Owens and J. Valdes, *The autonomous underwater glider "Spray".* IEEE

Journal of Oceanic Engineering, 2001. **26**(4): p. 437-446.
4. Eriksen, C.C., T.J. Osse, R.D. Light, T. Wen, T.W. Lehman, P.L. Sabin, et al., *Seaglider: A long-range autonomous underwater vehicle for oceanographic research.* IEEE Journal of Oceanic Engineering, 2001. **26**(4).
5. Webb, D.C., P.J. Simonetti and C.P. Jones, *SLOCUM: An underwater glider propelled by environmental energy.* IEEE Journal of Oceanic Engineering, 2001. **26**(4): p. 447-452.
6. Graver, J.G., R. Bachmayer and N.E. Leonard. *Underwater glider model parameter identification*. in *Proc. 13th Int. Symp. on Unmanned Untethered Submersible Technology (UUST)*. 2003.
7. Graver, J.G., *Underwater gliders: Dynamics, control and design*, in *Mechanical and aerospace engineering*. 2005, Princeton university. p. 273.
8. Mueller, T.J. and J.D. DeLaurier, *Aerodynamics of small vehicles.* Annu. Rev. Fluid Mech., 2003. **35**: p. 89–111.
9. Stelle, L.L., R.W. Blake and A.W. Trites, *Hydrodynamic drag in steller sea lions (Eumetopias Jubatus).* The Journal of Experimental Biology, 2000. **203**: p. 1915-1923.
10. Donaldson, P., *Tracing a eureka moment.* Unmanned Vehicles, 2007: p. 17.
11. Stommel, H., *The SLOCUM mission.* Oceanography, 1989.
12. Davis, R.E., J.T. Sherman and J. Dufour, *Profiling ALACEs and other advances in autonomous subsurface floats.* Journal of atmospheric and oceanic technology, 2001. **18**: p. 982-993.
13. Roemmich, D., S. Riser, R. Davis and Y. Desaubies, *Autonomous profiling floats: Workhorse for broad-scale ocean observations.* Marine Technology Society Journal, 2004. **38**(1).
14. Wang, S., C. Xie, Y. Wang, L. Zhang, W. Jie and S.J. Hub, *Harvesting of PEM fuel cell heat energy for a thermal engine in an underwater glider.* Journal of Power Sources, 2007. **169**: p. 338–346.
15. Guo, C. and N. Kato, *Mini Underwater Glider (MUG) for Education*.
16. Psoma, A. and G. Sattler, *Fuel cell systems for submarines: from the first idea to serial production.* Journal of Power Sources, 2002. **106**(1-2): p. 381-383.
17. Barbir, F., *Proton exchange membrane fuel cell technology status and applicability for propulsion of autonomous underwater vehicles*. 2002, Proton Energy Systems.
18. Orimo, S.-i., Y. Nakamori, J.R. Eliseo, A. Zuttel and C.M. Jensen, *Complex hydrides for hydrogen storage.* Chemical Reviews, 2007. **107**(10): p. 4111-4132.
19. Kong, V.C.Y., D.W. Kirk, F.R. Foulkes and J.T. Hinatsu, *Development of hydrogen storage for fuel cell generators II: utilization of calcium hydride and lithium hydride.* International Journal of Hydrogen Energy, 2003. **28**(2): p. 205-214.
20. Kojima, Y., Y. Kawai, H. Nakanishi and S. Matsumoto, *Compressed hydrogen generation using chemical hydride.* Journal of Power Sources, 2004. **135**: p. 36-41.
21. Kong, V.C.Y., F.R. Foulkes, D.W. Kirka and J.T. Hinatsu, *Development of hydrogen storage for fuel cell generators. I: Hydrogen generation using hydrolysis hydrides.* International Journal of Hydrogen Energy, 1999. **24**: p. 665-675.
22. DeVries, G., *High-pressure gas from Lithium Hydride and sea water*. 1965, Bureau of Naval Weapons.
23. Breault, R.W., C. Larson and J. Rolfe, *Hydrogen for a PEM fuel cell vehicle using a chemical-hydride slurry*, Thermo Power Corporation. p. 952-956.
24. Mao, W.L. and H.-k. Mao, *Hydrogen storage in molecular compounds*, in *Proceedings of the National Academy of Sciences (PNAS)*. 2004, The National Academy of Sciences p. 708-710.
25. Züttel, A., *Hydrogen storage methods.* Naturwissenschaften, 2004. **91**: p. 157-172.
26. McClaine, A.W., D.R.W. Breault, C. Larsen, D.R. Konduri, J. Rolfe, F. Becker, et al., *Hydrogen transmission/storage with metal hydride-organic slurry and advanced chemical hydride/hydrogen for PEMFC vehicles*, in *Proceedings of the 2000 U.S. DOE Hydrogen Program Review*. 2000, Department Of E nergy Hydrogen Program.
27. Schlapbach, L. and A. Züttel, *Hydrogen-storage materials for mobile applications.* Nature, 2001. **414**: p. 353-358.
28. Ashby, E.C. and S.A. Noding, *Hydrometalation. 6. Evaluation of lithium hydride as a reducing agent and hydrometalation agent.* The Journal of Organic Chemistry, 2002. **45**(6): p. 1041-1044.
29. McClaine, A.W., S. Tullmann and K. Brown, *Chemical hydride slurry for hydrogen production and storage*. 2004, Department Of Energy Hydrogen Program.
30. Fort, Y., *Lithium hydride containing complex reducing agent: A new and simple activation of commercial lithium hydride.* Tetrahedron Letters, 1995. **36**(34): p. 6051-6054.
31. Jeppson, D.W., J.L. Ballif, W.W. Yuan and B.E. Chou, *Lithium literature review: Lithium's properties and interactions*. 1978, Hanford Engineering Development Laboratory.
32. Matsunaga, T., F. Buchter, K. Miwa, S. Towata, S. Orimo and A. Züttel, *Magnesium borohydride: A*

new hydrogen storage material. Renewable Energy, 2008. **33**(2): p. 193-196.
33. Huot, J., G. Liang and R. Schulz, *Magnesium-based nanocomposites chemical hydrides.* Journal of Alloys and Compounds, 2003. **353**.
34. Christie, T. and B. Brathwaite, *Mineral commodity report 19 - Beryllium, Gallium, Lithium, Magnesium, Uranium and Zirconium*, Institute of Geological and Nuclear Sciences Ltd.
35. Li, Z.P., B.H. Liu, K. Arai, N. Morigazaki and S. Suda, *Protide compounds in hydrogen storage systems.* Journal of Alloys and Compounds, 2003. **356-357**: p. 469-474.
36. McClaine, A.W. and K. Brown, *Storing and transporting energy*. 2007: United States.
37. Messer, C.E., *A survey report on Lithium Hydride*. 1960, United States Atomic Energy Commision.
38. Gibb, T.R.P. and C.E. Messer, *A survey report on Lithium Hydride*. 1954, United States Atomic Energy Commission.
39. Pitcher, G.K. and G.J. Kavarnos, *A test assembly for hydrogen production by the hydrolysis of solid lithium hydride.* Int. J. Hydrogen Energy, 1997. **22**(6): p. 575-579.
40. Aral, H. and A. Vecchio-Sadus, *Toxicity of lithium to humans and the environment—A literature review.* Ecotoxicology and Environmental Safety, 2008. **70**: p. 349-356.
41. Kjølholt, J., F. Stuer-Lauridsen, A.S. Mogensen and S. Havelund, *The elements in the second rank - an environmental problem now or in the future?* 2003, Danish Environmental Protection Agency, Danish Ministry of Environment.
42. Speight, J.G., *Lange's handbook of chemistry*. Sixteenth ed: The McGraw-Hill Companies.