A SURVEY OF AVAILABLE UNDERWATER ELECTRIC PROPULSION TECHNOLOGIES AND IMPLICATIONS FOR PLATFORM SYSTEM SAFETY

Clinton Winchester, Justin Govar, Julie Banner, Tracey Squires, Patricia Smith
Naval Surface Warfare Center – Carderock Division
Power Systems Branch, Code 644
West Bethesda, MD 20817-5700

Abstract
The majority of unmanned undersea vehicle (UUV) and autonomous underwater vehicle (AUV) applications are electrically powered, deriving their energy from chemical reactions within a battery. Unlike thermal engines, where chemical energy is metered into a combustion chamber, batteries are unique in the storage of all energy content within a limited material construction. Fuel cells are a logical cross between the concepts of electric storage battery and thermal engine. The requirements for military and some civilian AUVs demand increased battery energy density and volume compared to the overall AUV vehicle. Batteries, like fuel cells, are most cost-effective when they may be recharged and reutilized. The aspects of increased energy density, intrinsic power capability and electrical or mechanical recharging present a significant challenge in designing a power supply system that is safe under all conditions for the AUV and for the deployment platform. This paper will provide an overview of common AUV propulsion systems and discuss aspects of vehicle integration and vehicle and launch platform safety with respect to recharging, refurbishing or refueling an AUV system.

Brief Historical Overview and Perspective
The field of study related to the storage of energy and delivery of energy for underwater autonomous vehicle operation is diverse and dates to initial efforts at torpedo power systems [1]. The sub-miniaturization of microcomputer control systems and of digital processing capabilities has allowed the design of undersea sensors to be incorporated into useful tools for oceanographic, bathymetric, communication diagnostics, resource exploration and exploitation, and autonomous classification and identification of navigational hazards and the definition of safe passageways. The growth of potential AUV missions to track and transit requires increases in internalized energy storage [2, 3].

The design and optimization of the power system is a critical feature in the successful integration of a power system into a multifunctional environment of an AUV. Cost and performance have been the two most highly traded characteristics regardless of intended purpose and applications. Propulsion and electrical energy can be stored in a variety of media. Many of the power systems used have been based upon terrestrial technologies; i.e. seldom is a power generating technology unique to only the underwater environment, although there are exceptions.

For the purposes of this discussion, we will limit ourselves to electrochemical based power systems. We will note that a variety of thermal engine systems may provide energy sources for inboard conversion to electric power for system power and electric drive. Thermal systems offer different integration advantages for large AUVs, or AUVs utilizing fuels common to the support craft.

System Integration of Power Sources
The intrinsic hazards associated with a power supply system scale according to the energy storage, the design and chemical makeup of the materials to be converted. Most batteries, for example, present a significant hazard in the shear combination of reactive surface area and volume of energetic materials that can react. Fuel cell systems limit the amount of reactive material that can be exposed at one time to that required by a control system to generate the energy needed. Fuels cell systems have significant chemical energy storage hazards, depending on design and energy densification, by having to store both fuel and oxidizer. Batteries and fuel cells alike may use reactants that are intrinsically hazardous to personnel and platforms. When these are used, special training and handling systems are required.

Rarely are AUVs simply launched and recovered from a surface pier with shore-side support and refurbishment. Civilian (research and industrial) AUVs may be launched, retrieved and serviced from a surface support vessel. Military AUVs may be launched by surface ship, aircraft (fixed or rotary wing), or submarine. Military AUVs may be disposable or recovered for refurbishment and reuse, depending on the design and mission requirements. Special purpose military AUVs may also carry special payloads that also represent potential hazards from interactions with the battery.

Many of the characteristic trade-offs of an AUV power system design are captured in the list below:

Cost vs. Function
Performance vs. Cost
Performance vs. Function

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Primary vs. Rechargeable
Recharge vs. Refurbish
Energy Density vs. Power Density
Life-cycle cost goals and analysis
Low-temperature vs. High-temperature
Cost Per Hour Mission
Unique vehicle design vs. Common Cells
Specialty vs. Common Availability Cells

In commercial applications, the cost to acquire and operational costs are usually more important than total mission duration and capability. Unless special performance requirements dictate, non-commercial cell designs are usually too expensive to be justified. Requirements for AUV power sources can be seen in the modified Ragone plot of Figure 1.

A Sampling of AUVS
A simple survey of the literature and internet provides a suite of AUV/UUV devices that require power and energy for propulsion [4, 5]. Some examples of AUV/UUV systems are the Near-term Mine Reconnaissance System, the Long-term Mine Reconnaissance System, and the Woods Hole Institute REMUS and SAHRV. EMATT is an air-deployed acoustic/magnetic target trainer from Sippican. The XP-21 and LAZARUS vehicles were previously deployed test-bed AUVs as are the Large Diameter UUV (LDUUV) from NUWC Newport and the MANTA. SEAFOX, Minesniper, SNT and Anglefish are UUV/AUVs with unique power requirements and are aimed at mine-neutralization. Other AUVs are the SPAWAR AUSS, the AutoSub and HUGINS.

Battery and Fuel Cell System Descriptions
Electrochemical power systems for AUVs run the gamut from alkaline systems to advanced lithium-ion prototype batteries. Fuel cells and semi-fuel cells have been proposed and demonstrated for AUV applications.

The following list of electrochemical systems captures some of the salient features (pro and con) for the power source, its integration to the application and the eventual integration of the vehicle to its launch and support platform.

Rechargeable Battery Systems

Lead Acid (PBA) – This is one of the systems used for test and evaluation models of AUVs regardless of the eventual power source. Limitations are weight and low relative energy content. Advantages are cost, availability and power capability. Wet-life and cycle life are adequate to permit functional design and useable applications. A limitation from formation and release of hydrogen gas during charge is systemic of all aqueous electrolyte systems. Availability of PBA in form-factors for applications will determine whether the chemistry is cost effective for use. Low maintenance valve-regulated designs offer decreased support and manning during recharge and refurbishment [6].

Nickel Cadmium - Nickel Cadmium (NiCd) is the other prevalent battery chemistry used in AUVs with more capacity than lead acids, and with essentially equivalent cost to procure and operate. Large cells are available from aircraft starting applications. Large, high performance cells are also available from electric vehicle/hybrid applications. The most significant difference between lead acids and nickel cadmium is the change from sulfuric acid to potassium hydroxide solution electrolyte. Like any aqueous system, hydrogen formation and out-gassing is possible and must be accommodated [6, 7].

Nickel Metal Hydride – A sealed variation on the NiCad system. Analogies are closer to valve-regulated lead-acid in operation. Large nickel-metal hydride (NiMH) cells have been built for automotive traction power and may be transitioned to commercial or military AUVs where appropriate. Power and energy can be considered equivalent or superior to NiCad with a lessened memory effect. The normal operation is as a sealed unit with no out-gassing, improving compatibility for sealed AUV power sections. Over-pressurization is possible under some abuse conditions [6, 7].

Silver-Zinc - This is the traditional "workhorse" battery system for military and extended duration underwater vehicle power for 40 years. The combination of simple construction, high-rate capability while maintaining energy content is unique. The high energy content of 165 Wh/kg and 400 Wh/liter energy density makes the silver-zinc system very attractive for mission and vehicle integration. The deficits to the system integration are moderate to short cycle life (10 to 50 cycles), limited wet-stand, hydrogen out-gassing and high initial costs [6, 7, 8].

Lithium-Ion Systems – The development of the intercalated lithium anode (lithium-ion system) where the need for lithium metal or alloys are precluded represents the single most significant advance in potential AUV power systems to replace silver-zincs. While the gravimetric energy content is marginally better than silver-zinc under most reasonable discharge rates, the power capability is lower, unless designed for power at the expense of energy storage. The lower energy density of the lithium-ion system increases packaging difficulties. It is becoming mandatory that all underwater rechargeable systems evaluate the performance and cost trades of lithium-ion packaging versus silver-zinc for total ownership costs. Initial costs are significantly higher for Lithium-ion systems vice silver-zinc, but extended deep cycle life (>300) and faster charge capability with no off-gassing or maintenance during charge offers considerable savings in fast turnaround, refurbishment costs, and system integration. The development and cost of large, high-capacity cells is being driven by automotive EV/hybrid requirements. Underwater propulsion systems based on modifications of the technology have been proposed. One large battery example is a demonstrator battery for the manned Swimmer Delivery Vehicle (SDV) [6, 9].

Lithium – Metal Oxide – This series of couples has been under development for 20 years [10]. The lithium metal anode offers better power at no loss to energy content, effectively providing a 30% to 50% increase in energy storage over silver-zinc at moderate power rates. The failure to obtain greater than 100 deep-discharge cycles before onset of lithium dendritic shorting coupled with high cost of manufacture (prismatic) precluded all but specialized application in AUV propulsion. The potential to obtain 200 to 250 WH/lb of cell (with vanadium oxide ambigels [11]), the immaturity of cell design and limited evaluation usage are detrimental to proposals for use.

Sodium Sulfur- The Sodium-Sulfur (Na/S) system has been proposed for use as stationary and traction power. The gravimetric energy density of the couple is very good. However, the inability to tolerate multiple freeze-thaw cycles by the alumina ceramic separator requires the battery to be maintained at an elevated temperature once operating. The energy density is equivalent to silver-zinc, however the battery design limitations for thermal insulation reduces the effective volumetric energy density. The chemistry is the only high temperature system to be demonstrated in AUVs (by Marconi using ABB battery modules [12]). Safety of the system is a concern; anode and cathode are both liquid and readily reactive in the event of separator failure [7]. The Na/S system operates at 350 C, and would explosively form steam if water were to intrude through the insulation. Underwater shock tolerance testing has not been conducted. Investigations of this couple for surface traction applications have ceased with the advent of the advance lithium-ion system capability.

Lithium – Molten Salt Systems – Like the Na/S couple, application of molten salt electrolytes promises very high power densities with energy densities 30to 40% greater than silver-zinc [6,13]. Realistically designed systems result in energy packaging approximately 20% better than silver-zinc after thermal insulations is considered. The cycle life for deep discharge are better than silver-zinc. Unlike Na/S, the standard design proposed used a rigid starved electrolyte bearing ceramic that was not shock sensitive and had much in common with the ruggedized thermal batteries in missiles. Like the Na/S system, the operating temperature is high, typically greater than 450 C. Overcharge self-balancing has been demonstrated. A lithium-aluminum alloy – iron sulfide system was proposed and extensively investigated for manned submarine battery systems. Recent investigations have shown the potential to scale up to form-fitting 21” diameter battery applications [13]. Again, energy storage coupled with high-temperature and toxic gas forming reactions (if breached by air or water) pose interesting questions and requirements for system integration. External power to preheat to operating temperatures would permit wooden stowage cold, but would limit fast availability. Use of a buffer battery has been described as necessary to permit safe cool-down prior to recovery.

Primary Battery Systems

Zinc-Alkaline (ZnMnO2) – The classic “flashlight” consumer power supply, if limited to low power requirements, can provide an acceptably cost effective power supply for limited capabilities for AUVs. Under use conditions, the cells can provide 10 Ah at 1 VDC for 55 cents, or 18 Wh/dollar. This sits well against lithium systems, where a range of 1 to 4 WH/dollar captures most lithium primary power systems. Pressure compensation modifications permit use at extremes depths. Hydrogen formation over time still must be dealt with [6, 7].

Magnesium – Silver chloride -The Magnesium silver chloride system has been used in underwater applications extensively for moderate duration and high power, and is synonymous with the descriptor “seawater battery”. Examples are sonobuoy power, torpedoes and expendable underwater devices [6, 7, 8].

Aluminum – Silver Oxide - The aluminum silver-oxide system has been developed and demonstrated as a heavy-weight torpedo propulsion system. An example of use is the French Impact MU90 torpedo [14].

Lithium – Sulfur Dioxide – Lithium sulfur dioxide (Li/SO2) system offers one of the most cost effective solutions to providing both high energy and exceptional power capability for small AUVs. The costs of common cells is low, based on Army and Navy usages for communications and sonobuoy systems, and the effective energy density is at least equivalent to, and often better than, either primary or reserve silver-zinc [6]. Cell sizes are limited by cost-effectiveness design principals to D-cell diameters; the cell is internally pressurized to 3 Bar with liquefied sulfur dioxide in solution with an organic solvent. Case dimensions larger than 1.3” become weight inefficient for end-plates. Use of dissimilar case material in the less expensive cells limits the shelf-life prior to onset of self-corrosion venting of SO2 [7]. Where temperature ranges and power capability are essential, and coupled to low cost, Li/SO2 cells represent an almost ideal power system for large scale integration.

Lithium – Oxyhalides – Lithium–oxyhalide (typically lithium – thionyl chloride) represents the current baseline standard in providing 4 to 5 times the energy density of rechargeable silver-zinc in a primary battery [15]. Power capability over a broad temperature range is less than for Li/SO2, with significant energy losses at high power and lower temperatures. The Boeing LMRS (AN/BLQ-11) system uses a series stack of 24 Li/SOCl2 cells to provide up to 100 kWh in a modular, replaceable Energy Section [16]. Other extended operation vehicles and applications, often university based experimental packages, will use a large series of lithium-chlorinated sulfuryl chloride because of their availability, relative safety (extensive safety fusing) and high energy content. A variation of the active oxyhalide battery is a reserve system that uses flowing electrolyte to increase efficiency and remove excess heat [14, 17]. Numerous hazards for the primary system have been analyzed [7].

Lithium – Molten Salt Systems – Lithium metal or lithium alloy molten salt primary batteries (aka thermal batteries) have been proposed for use for many underwater applications requiring run times of up to an hour and energy densities equivalent to reserve silver-zinc. High quality thermal insulation and large thermal mass will allow operation for a long as 4 hours under some conditions for special designs. Special purpose built batteries for developments have been shown, including a 15 kW, 15 minute, 90 VDC battery system with an energy content of 90 WH/kg [18]. These systems are ideal for emergency power and one-use expendable systems. The power density of the design coupled with high-voltages typical of motor drive represent a moderate hazard for system integration and platform integration in the event of an accidental activation. Additionally, the pyrotechnic charge to activate the electrolyte adds to the potential hazards of the system [7].

FC Systems Free-Flood and Sealed

There are two conceptual types of fuel cell systems for AUVs, sealed and free-flood [19]. The sealed systems represent the common design of fuels and oxidizers in separate tanks or storage medium. The free-flood design integrates use of seawater as the working medium for ionic conduction and reactant delivery. Examples of these are magnesium or aluminum anode systems with either oxygen supplied cathodes, or hydrogen peroxide as a catholyte reactant [20].

Hydrogen – Oxygen FC – This is the conventionally thought of fuel cell system at its simplest, reaction of hydrogen and oxygen to form water. At present, the Kockums Type 212 submarine is using this system with a proton-exchange membrane (PEM) as part of the extended air-independent propulsion (AIP) power system. Studies have been conducted to evaluate the assembly of operation of a H2/O2 PEM fuel cell in a 21" sized underwater vehicle [21]. The energy storage and performance limitation typically yield not much greater than 300 WH/kg of equivalent gravimetric energy storage, and a volumetric limit of 350 to 400 Wh per liter. These values are considerably poorer than present primary batteries and advanced rechargeable systems. Improvements in fuel sources and oxygen carriage may permit increases in energy storage and operation [22].

Metal – Air Cathode – Examples of this system are typified by a magnesium or aluminum anode structure [23] with either a static or flowing electrolyte system and a source of oxygen supplied to a cathode structure. In air, the oxygen would be derived by natural pressure or by recirculation [24]. Underwater, the seawater becomes a supporting electrolyte source and conductivity salts are added. Oxygen is supplied from solid storage (oxygen candles) or high pressure or liquefied oxygen tanks. In self-adjusting static systems, the electrolyte salt precipitates out to maintain an operating environment [21]. A variation of this system uses a counter-flowing electrolyte separated by an ion-permeable membrane [20]. Quantities of hydrogen peroxide or acids are metered into the counter flow to supply reactants to a current collector.

Advanced Electrochemical Propulsion

The present and future prospects for many AUV applications still present lithium-metal and lithium-ion batteries as dominant high-performance power systems. Power and energy analyses for high performance, extended range/duration AUV applications show a preference to sealed battery systems for small to moderate devices. 21" diameter applications, in classic torpedo shape-factors, represent a cross-over point between pure battery capability, fuel-cells and thermal engines.

The ability to quickly recharge underwater at a docking station to permit extended autonomous operation increases the need for sealed battery systems, where no external fuel system is needed. The organic and inorganic based lithium-ion systems permit fast charge capabilities, principally from the thin structure of the reactants across the current carrier substrates.

The near-term present limit in performance capabilities of gravimetric and volumetric energy dense systems appear to be 450 to 500 watt-hours per kilogram (750 to 900 watt-hours per liter), for a practical sealed RECHARGEABLE cell system. For PRIMARY systems, practical cells may have a top-end limitation of 950 to 1000 Wh/kg, and volumetric storage of 2200 Wh/liter [11]. These capabilities are derived from present capabilities with optimization of packaging and material utilization. In any event, these values also represent potential for hazards to personnel and platforms from the extreme density of energy storage and the concurrent requirement for moderate to high power for AUV propulsion.

Vehicle Integration and Analysis

The integration and optimization of a power source to a vehicle requires a multi-disciplined approached to the development of energy models, mission and duration requirements, understanding both capabilities and limitations. These must often be gauged against future mission growth potential. It is not uncommon for a vehicle power source design to be developed *in vacua* from the realities of a vehicle operation or some of the lesser known limitations of the electrochemical couple as embodied in the battery as reduced to practice.

A variety of trade studies are required to optimize a power system to a vehicle. These studies may principally address power buss integration, optimal motor supply power and voltages, and weight distributions. The studies also address the perverse nature of trying to efficiently fit a square peg into a round hole, as is typical of many applications of prismatic cells structures in cylindrical pressure vessels.

The typical trade studies for commercial (industrial) power systems rely on low-cost power systems capable of supporting operations. Cost studies have been presented previously by other researchers and authors. Cost per hour of operation (support man-power) typically outweighs the unit acquisition cost of a battery assembly. The number of cycles and the rapidity of charge or turn-around also figures heavily into cost models and performance models.

The development of conformal manufactured lithium primary and lithium-ion secondary "pouch" technologies offers a vehicle integration that permits elimination of a portion of the hull structure [9]. Pressure tolerant design cells have been demonstrated previously. Fully sealed systems could be incorporated as a functional component of the hull.

Platform Integration and Analysis

As identified earlier, most civilian AUVs will be supported from surface vessels, with launch, control, recovery and refurbishment being conducted while at sea. Presently, military task oriented AUVs have transitioned from basic research and development with numerous units in the fleet or actively in the advanced process of active production development and fleet transitions. Some examples of “active” duty AUVs include the AutoSub, MK39 EMATT, REMUS, and the MK30 Torpedo Target. Near term military systems include the AN/BLQ-11 LMRS, SAHRV and the SEAFOX.

The Mk39 EMATT is an example of a simple AUV with special requirements for air-deployment from either fixed or rotary wing aircraft. The Mk39 is powered by lithium-sulfur dioxide cells and may be carried and launched from within the crew space. Toxicity of sulfur dioxide requires the battery integration into the EMATT and the EMATT into the aircraft to be well controlled and requires numerous safe guards to preclude accidental release of SO2 into the crew-spaces. Prior to permitting use, the battery and EMATT vehicle with its launch support equipment were evaluated using standard Navy safety guidelines for lithium battery systems. The combination of procedures, battery redesign and system level safety devices permitted the eventual deployment.

Another example of a moderately sized AUV is the SAHRV (Semi-Autonomous Hydrographic Reconnaissance Vehicle) based on the Woods Hole Oceanographic Institute (WHOI) REMUS (Remote Environmental Monitoring UnitS). This AUV is capable of using a multiple of power sources, from lead-acid to lithium-ion rechargeable batteries. For Navy use, the lithium-ion batteries were evaluated using S9310-AQ-SAF-010 to permit an evaluation of hazards [25, 26].

The AN/BLQ-11 has base-lined a specially design lithium oxyhalide battery derived from HED Battery (nee ALTUS) technology and developed under various Navy contracts. The vehicle integration of the battery to support submarine launch, recovery and replacement of the “energy section” has required close coordination between system integrator and platform engineering. The LMRS will use a silver-zinc rechargeable battery to augment mission needs when extreme long range or long-duration operations are not required. The proposed submarine launch, recovery and replacement platform has driven en enormous amount of design, system integration and demonstration testing using S9310-AQ-SAF-010 as a basis for the eventual hazards analysis for sub-based deployment and operation. The integration of the battery into the vehicle and logistics has required the development an analysis of numerous alternatives. The cautious design methodology taken has been to develop a robust system with numerous independent fail-safes, safety devices and checks, software oversight and alarm functions with hardware redundancy [16].

The modular nature of the LMRS Energy Section will accommodate upgrades and retrofits of superior or alternate design battery chemistries or other power systems as the AN/BLQ-11 system “spirals” in an evolutionary fashion. Special platform integrations will be necessary depending on the nature of the replacement energy systems [27].

Discussions regarding the use of advanced fuel cell systems from inboard submarines, especially when these systems support electrolytic replenishment of ship oxygen, turns to fuel cells. The ability to derive fresh water and then manufacture oxygen with a concurrent generation of hydrogen offers a natural integration for powering AUVs from organic resources for large shipboard installations. The obvious advantage of organic refueling is offset by integration of the reactant storage and relatively poor energy density of the resulting system. High pressure or liquefied gas storage have mechanical, operational and shipboard safety drawbacks that must be addressed. The low energy performance of a H2/O2 system must be evaluated versus convenience of the refurbishment supplies [22].

Nevertheless, the concept of an "electrochemical reactor" that limits the availability of a fuel and oxidizer reactants to a limited surface and volume substantially less than the total volume of reactants does offer enhancement of safety characteristics. Most batteries, by contrast, have all the reactants located within a shallow volumetric layer with sufficient surface area to support the required power levels. In many cases, the exposed reactant surface area may be higher than needed to accommodate cell packaging and vehicle design limitations [6, 7, 21]. For a fuel cell, the reaction surface is sized to the power requirements, a large surface area decreases energy storage and increases energy robbing parasitic self-discharge from diffusion across the membranes [21].

Seemingly simple and robust power systems can fail catastrophically under moderate to severe abuse. One such case has been made in the popular press [28]. The cook-off of a silver-zinc reserve battery in a Mk37 torpedo cannot be confirmed as the cause for the loss of the SSN USS Scorpion. However, the details of the public account can be taken as cautionary tales for system design and platform integration. Co-location of energetic systems wherein a single point failure can potentially cause a critical event must be avoided. Robust engineering and design can effectively place several interlocking systems between a relatively minor event and a cascading chain of events that could lead to disaster.

The design trade-off studies for any AUV must include the potential hazards or consequences of operation of the AUV and power supply for the users and platform [29]. While this may seem an obvious concept, the complexity of proposed AUVs and the integration of the AUV into established military platforms require substantial early development and consideration. Power sources with the best energy content or capability for a mission or application in an AUV may not be the easiest system to handle inboard in crew-space, weapons magazine or a weapons room. An evaluation using the guidelines of hazard risk analysis [30] should be conducted as part of any system integration trade study. Such an analysis chart is shown in Figure 2.

Summary and Conclusions

The advantage of AUV for numerous underwater operations is being demonstrated on a daily basis. The need for simple power systems with longer duration is an ongoing operational and financial need. The increase in energy density from aqueous systems to inorganic lithium based systems increases the potential for hazards to personnel and support/launch platforms.

The advantage of electric power for AUVs, with the reduction and minimization of moving parts from mechanical generation is obvious. The system complexity and cost as energy density increases and refurbishment or reuse become important, has been illustrated. Increased mission requirements and volumetric energy constraints result in energy storage densification.

Batteries and fuel cells offer cost effective solutions to power system integration issues. The natural hazards associated with stored electrochemical energy must not be taken lightly. Even large zinc-alkaline battery packs can produce lethal shocks or cause fires with ejection of caustics and shrapnel.

The energy content scaling of closed fuel cells has been illustrated and the relative system safety advantages of not having intimate combination of fuels and oxidizer has been shown as intuitive. The limitation of fuel cells, with regard to power and packaging, has been described.

A well designed AUV will almost always have a uniquely designed power source, perhaps built of common component elements (cells or membrane structures) but with special power and energy performance requirements applied to the overall system. The analysis and integration of the power source into the AUV structure and then into the platform and working system must be done with overall system safety in mind.

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Figure 1: Ragone Plot – Batteries of Interest for AUVs

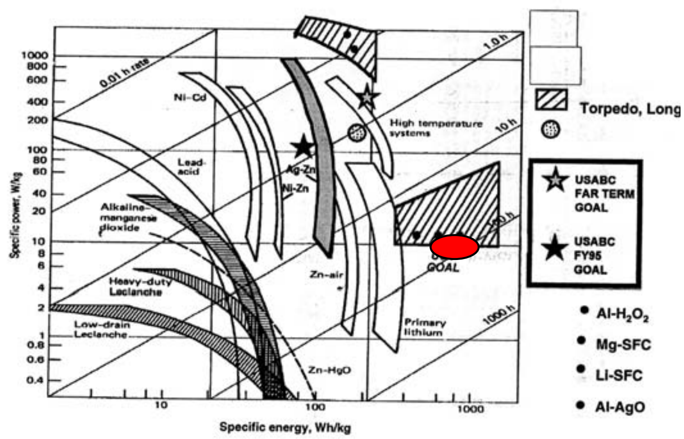

Figure 2: Hazard Risk Assessment Table

FREQUENCY OF OCCURRENCE	HAZARD I CATASTROPHI	II CRITICA	III MARGINA	IV NEGLIGIBL
(A) Frequent	1	2	3	4 A
				4 B
(B) Probable	[illegible]	[illegible]	[illegible]	4

HIGH (CAE (ASN-RDA) USSOCOM)

SERIOUS (PEO)

MEDIUM (PM)

LOW (PM)