THE IMPACT OF POWER SYSTEM TYPE AND VEHICLE SIZE ON RANGE AND PAYLOAD FOR UUV'S

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Abstract

This paper reviews the status and projected performance of various power system types, including batteries, fuel cells, and hydrocarbon and liquid-metal-fueled heat engines and examines the relationship between power system type and vehicle diameter on achieved range and payload.

Introduction

The Applied Research Laboratory of The Pennsylvania State University (ARL Penn State) has built and operated autonomous, unmanned underwater vehicles ranging from about 6 to 38 inches in diameter. Figure 1 shows the 38-inch diameter Seahorse vehicle, which was built for and to the specifications of The Naval Oceanographic Office.

Figure 1 38-inch diameter Seahorse UUV

This vehicle is 27 feet long and is powered by alkaline batteries. A series of watertight cylinders are carried on a structural frame within the vehicle, which has an external hydrodynamic skin and a single tailcone propulsor to propel it through the water. Syntactic foam fills some of the space around the cylinders to provide buoyancy, and the batteries, payloads, and other vehicle systems are located within the watertight cylinders, which are about one foot in diameter. The cylinders can be accessed individually for easy replacement and reconfiguration of the vehicle.

Figure 2 illustrates two general architectures found in such vehicles. The first, Figure 2a, represents the Seahorse architecture, which has the advantage of modularity; each watertight cylinder can be accessed independently. This architecture also tends to reduce the characteristic dimension of payloads that can be carried, and, since nothing can be located where the foam is, payload volume per length of vehicle section tends to be reduced.

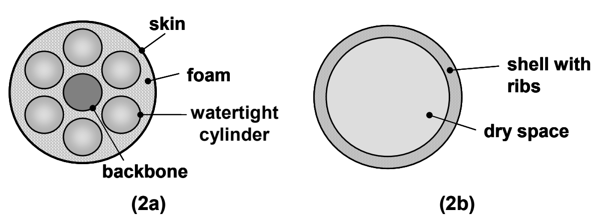

Figure 2 Flooded (2a) versus Dry (2b) Architecture

The dry architecture (Figure 2b) requires the design and manufacture of a pressure-bearing shell with the diameter of the vehicle. Incorporating ribs on the inner surface of the shells minimizes the weight of these shells in most cases. The dry architecture accommodates payloads with larger characteristic dimensions and produces greater payload volume per unit length, but requires handling larger vehicle modules during turnaround operations. The dry architecture has a slightly better mass payload capacity per unit length, compared to the flooded architecture, for most operational depths of interest.

Circular and spherical pressure vessel geometries are highly desirable in UUVs because of the uniform skin stress associated with these designs. Figure 3 shows calculated wall stresses for a circular cross section shell and for an elliptical cross section shell that produces the same internal volume per unit length.

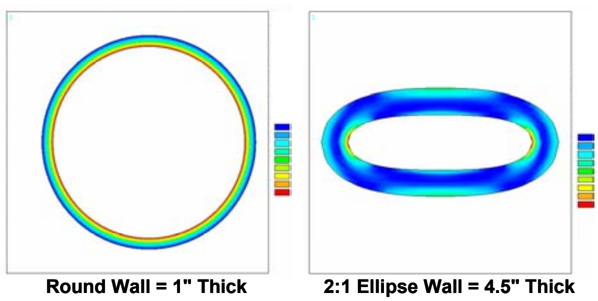

Figure 3 Wall Thickness for Round and Elliptical Cross Section

The need to stay at acceptable design stress levels at all locations in the shell and the tendency for non-circular sections to concentrate stresses, lead to a 4.5 fold increase in shell weight per unit length in the example case. In practice, this penalty can be diminished by reducing the wall thickness in low stress regions and by using internal load bearing structures to redistribute the stresses more effectively. However, both of these activities result in more complex designs that are more expensive to implement. As an example of the impact of architecture on power system selection, consider batteries, fuel cells, and hydrocarbon fueled heat engines applied to these two generic architectures. In the case of batteries, commercial cells are almost always available in dimensions that fit smaller cylinders. Batteries also usually have more trouble meeting their weight allocation than their volume allocation. As a result, they tend to work nicely in the flooded type architecture shown in Figure 2a, and derive less benefit from the dry architecture shown in Figure 2b. The fuel cells and heat engines, however, tend to reach their volume allocation before they reach their weight allocation, so they tend to benefit more from the dry architecture.

Figure 4 shows a generic vehicle in the dry architecture configuration. This vehicle captures the basic characteristics of a UUV and is used as the basis for a general assessment of the performance of different size vehicles using different power generation systems reported in this paper.

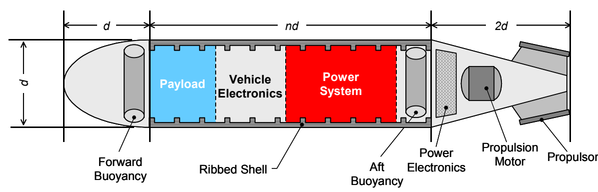

Figure 4 Generic UUV Layout

Very similar results are obtained for a flooded architecture vehicle with the general result that less performance is achieved across the board with battery systems projecting smaller decrements than the other systems. The general characteristics used in this study are:

- Vehicle l/d's of 9 are used throughout since this produces a good blend of volume delivered for power required and controllability. Calculations on specific cases of l/d's of from 6 to 12 produce the same general trends.
- A conventional propulsor with an electric drive motor is used. This methodology might begin to break down if high UUV speeds (approximately > 20 knots) were required due to the rapidly increasing motor and power electronics weight and

volume. Alternative propulsor designs such as jet thrusters or distributed thrusters could be applied to advantage in specific cases, but have not been considered in this study.

- All designs are made to be approximately neutrally buoyant to ensure optimal use of available energy in the power system.
- A buoyancy system is included as a representative percent of the vehicle displacement to allow compensation for seawater density variations, changes in vehicle CG and CB during operation, and changes in vehicle weight due to payload pickup or drop off.
- Remaining vehicle volume is distributed between the power generation system, necessary vehicle electronics, and payloads.

Power and Energy Requirements

A UUV requires enough power to propel itself at the desired speed plus enough additional power for the electrical systems that are operating at a given time. The power required for propelling the vehicle is a function of its shape, size, and speed and derives from the drag associated with the vehicle. The drag is often divided into components associated with skin friction, form, and the effect of appendages. Detailed calculations of the combined effects can be complex and computationally intensive, but well-established capabilities to calculate drag exist. The results of these calculations can be adequately represented by relatively simple approximations. Figure 5 shows a comparison of a simple power law representation of power required for a 26.5-inch diameter cylindrical vehicle verses data points for the required power as predicted by more comprehensive hydrodynamic models. Figure 5 reveals the rapid increase in required power with vehicle speed and also shows that the simple representation is reasonably accurate in this limited case. These type simplified powering expressions were further adapted for vehicle diameter changes for this study.

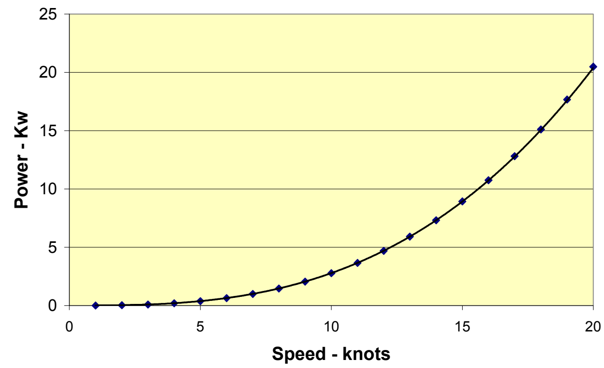

Figure 5 UUV Power Requirements

The propulsor is used to provide the power needed to overcome the drag of the vehicle. This propulsor is driven by an electric motor in most UUVs, and each of these devices has inherent losses associated with them. Representative efficiencies for the propulsor (90%) and the electric motor (94%) were used in this study to account for this effect. The net result was to increase the power required from the power electronics to compensate for the losses associated with the motor and propulsor.

Power for the various vehicle electronics systems is often referred to as "hotel" load, and it varies according to the devices that are needed to complete the vehicle's mission. It may also vary significantly as various payloads are turned on and off. A large, active sonar would require much more power to operate than an on-board computer, for instance. Table 1 shows some representative devices that might be found in a typical UUV and their estimated power requirements.

Power electronics are required to interface the power system with the power using devices. The requirements on this device depend on both the type power system used in the UUV and the type devices that consume the power.

Table 1 UUV Subsystem Power Requirements

Subsystem Device	Power Required (Watts)
Control computer	200
Intelligent controller	100
Inertial navigation	25
Global positioning system	1
Doppler velocity sonar	30
Data recorder	50
Casualty monitor	10
Control surface actuator interface	11
Actuators (4)	120
R. F. subsystem	5
Acoustic telemetry	25
Minecountermeasure sensors	500

Power electronics will have some losses themselves and will contribute mass, volume, and cost to the power system. The impact of the power electronics system on the total system depends upon the requirements placed on it, so the power electronics system should be optimized with the power generation system and vehicle as a whole, recognizing that its impact on system performance can be significant. Figure 6 shows the power electronics associated with a 50 kW pulsed power system. It was as big as the energy storage flywheel it operated and had an efficiency of about 75%.

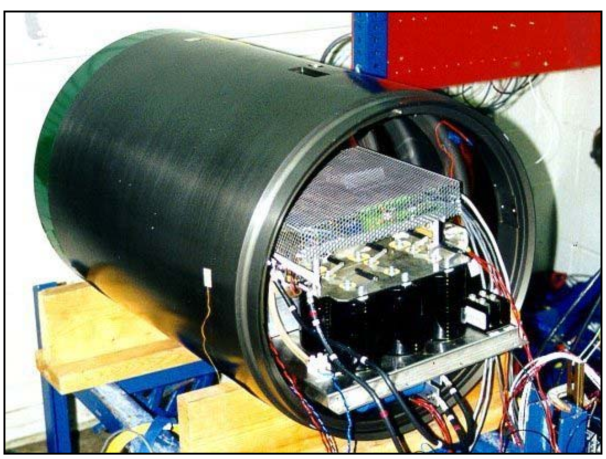

Figure 6 Power Electronics

Given that required propulsive power diminishes quickly as vehicle speed is reduced, and given that most power systems provide more output energy as they are drawn on more lightly, it is clear that UUV range will increase as speed is reduced. However, since some hotel power is required to keep a UUV operating at any speed, the presence of a maximum range exists for every vehicle and its value depends on the vehicle drag characteristics and hotel power requirements. Figure 7 illustrates this behavior for a 26.5-inch diameter vehicle operating with a 1 kW hotel load. It should be noted that the vehicle speed for maximum range and the vehicle speed for optimum sensor operation do not necessarily coincide. In addition, desired mission execution time and mission time for minimal energy consumption also do not necessarily coincide as illustrated in Figure 8.

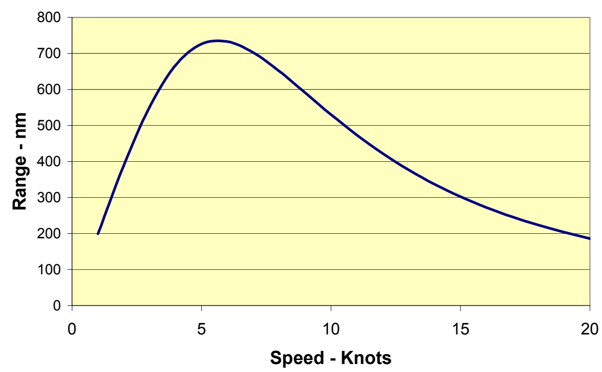

Figure 7 Energy Requirements

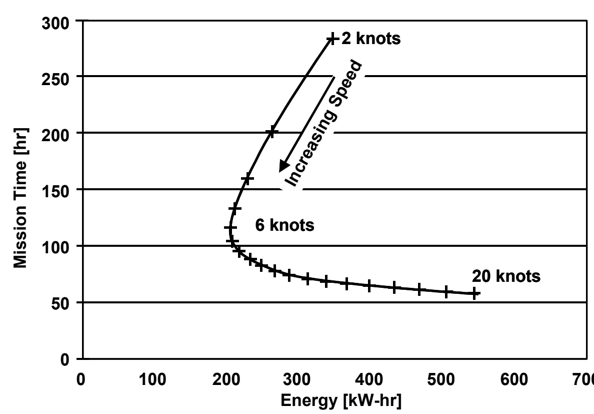

Figure 8 Mission Energy Optimization

These considerations are independent of the type system actually used to generate power for the vehicle and they indicate the potential benefit that can be derived from a more sophisticated energy system controller that interacts with, or is embedded in, the main vehicle mission controller.

Power and Energy Systems

There are a variety of power systems that could be used in a UUV. They differ in their state of development, cost, performance, and suitability for the particular needs of a specific UUV executing a specific mission. The required power for a candidate system depends on the maximum power needed at any time during an operation. This might be due to higher speed operation, a payload that requires high power, or a combination of the two. The power system and the devices that receive the power, such as the motor that drives the propulsor, must be designed to produce this power even if it is only needed occasionally. The energy that is available determines the length of time that power can be produced. Available energy derives from the quantity of reactants that is available and also from the power level that the energy is used at. For all power systems, there is an operating condition that maximizes the amount of energy produced, and the location and nature of where this condition occurs varies from one type power system to another. Thus, different type energy systems perform better and worse in different applications.

Typical batteries operate independently of the environment they are used in (with the exception of transferring heat) and are the current standard in UUVs. They have the advantages of being established products with widespread commercial availability, well-documented performance, a modular nature, and scalability. Batteries have a broad range of cost and performance with the two attributes generally rising and falling together. Since an electrochemical conversion system is included within each battery, they tend to be heavier than alternative power systems. The need to transport ions through an electrolyte in batteries also makes internal resistance, and the associated losses, an important factor when both discharging and charging batteries. Batteries typically produce more energy at low rates of discharge than they do at high rates. It is not unusual for a given battery to produce as little as half the energy at its maximum discharge rate that it does at a low discharge rate.

Battery power systems are realized by assembling individual batteries in series to get the desired voltage and then by adding series stacks in parallel to get the required energy (current). In actual systems, it is desirable to be able to reconfigure these assemblies on the fly to accommodate changing power demands and individual battery casualties. However, the circuitry associated with doing this also detracts from system energy density, so classic engineering optimization practices need to be applied when designing battery systems for UUVs.

Both primary (single-use) and secondary (rechargeable) batteries have found application in UUVs. The primary systems generally provide better specific energy, and the secondary systems usually provide lower per kilowatt-hour cost over the life of the system. Both may require cooling to reach the highest levels of performance, and the benefit of this should be assessed from a total system point of view.

Lead-acid, silver-zinc, alkaline, nichol-metal hydride, and more advanced lithium batteries have been and are being used in UUVs with large associated variations in performance and cost. The widespread use of batteries in UUVs is rooted in the reliable and predictable performance that they have produced. Figure 9a shows alkaline battery assemblies for the Seahorse UUV, and Figure 9b shows a nichol-metal hydride battery assembly for another underwater application. Since battery technology is mature, it is likely that battery performance and cost in UUV applications will change more incrementally in the future.

(9a) Alkaline (9b) Nichol-metal hydride

Figure 9 Battery Assemblies for Underwater Applications

Fuel cells effectively divide batteries into an electrochemical engine and separate reactant supply systems. A great deal of work is being done on fuel cells, but this work generally uses atmospheric air for oxygen and for coolant. DARPA conducted two large projects to adapt fuel cells to UUVs in the early 1990's. The primary challenges with fuel cells for UUVs are fuel and oxygen storage, fuel cell system volume and efficiency, and development costs for specific UUV applications. Fuel cells have the potential for quiet, efficient operation in UUVs with relatively cheap and easy turnaround.

Proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFCs) are leading candidates for UUV power systems, particularly for larger diameter vehicles. The PEM cells are undergoing vigorous development for terrestrial transportation systems. They require relatively pure hydrogen for their fuel and are relatively intolerant of the carbon monoxide and other byproducts that come from reformers. In underwater applications, challenges in fuel storage, oxygen storage, and system integration exist. Reformation of standard hydrocarbon fuels is possible, but adds volume and operational penalties. At a system level, compact assemblies are needed as are approaches for cooling and humidifying the cell membranes. Figure 10 is a photograph of a nominal 800-watt PEM cell stack under test. Department of Defense testing of 5 kW PEM cell systems that use reformed natural gas as the fuel indicate that total system efficiencies tend to be in the 25 to 30% range, which is considerably below the often cited theoretical stack efficiencies, as would be expected.

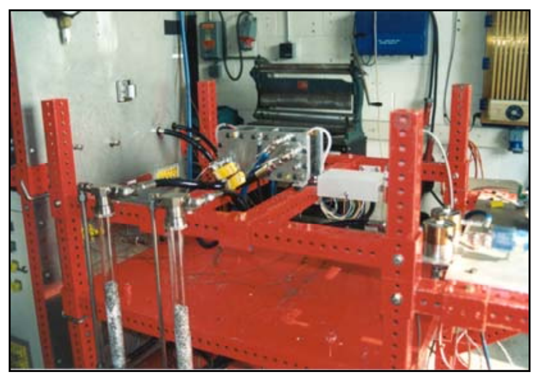

Figure 10 PEM Cell Testing

SOFCs operate on the same general principles as PEM cells, but use membranes that operate at much higher temperatures. This approach is more compatible with using liquid hydrocarbon reformers and less sensitive to undesirable reformer byproducts than is the case for PEM cells. Some reformers have been demonstrated for SOFCs that are compact enough to indicate that including a reformer with an SOFC in a large UUV could be a viable option. The issues associated with oxygen storage and system integration parallel those discussed for PEM cells.

The lack of a ready source of oxygen for UUVs poses a significant problem for fuel cells and any other power systems that rely on oxidizing reactions to make power. There are numerous possibilities for storing oxygen, and, while oxygen generally stores more compactly than hydrogen, achieving increasingly dense oxygen storage generally involves more complex systems. Figure 11 shows the storage density of oxygen for a range of different compounds. Figure 11 considers only the chemical constituents involved and does not account for the equipment needed to effect the controlled delivery of oxygen. For example, tanks would be required for compressed oxygen gas storage. In some cases, oxygen-carrying constituents could be used to the advantage of the system and in others they could not. For instance, the water in a sodium perchlorate solution could be used as a coolant and distribution gas in a solid oxide fuel cell, but the residual lithium chloride from a lithium perchlorate system would have to be disposed of without attendant benefit. In general, both oxygen storage and fuel storage and reformation systems must be selected and optimized in a full fuel cell system context when designing UUV power systems.

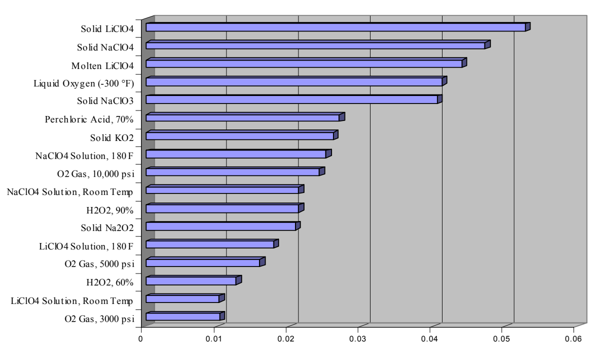

Figure 11 Oxygen Storage Densities

There are numerous heat engines that could be used to power a generator that would provide electricity for a UUV. These engines range from the conversion of standard spark ignition and compression ignition motor generator sets rigged for underwater operation to specifically designed Rankine and Stirling engine/alternator systems. These systems share the need for an oxygen source with fuel cell systems, and the oxygen systems potentially available for them are the same as those previously discussed. Hydrocarbon fuels can be used directly with these systems and have the potential to provide easy turnaround and cheap operational costs. As was the case with fuel cells, heat engines must fit in the available space and leave room for the fuel and an oxygen source. Heat engines cannot easily be made as small as batteries can, and they tend to be less efficient as their size is reduced. They do have the advantage of being able to be optimized for any power level and, unlike batteries and fuel cells, are generally more efficient when operated at higher power densities.

Commercially available spark ignition and diesel engines have been modified for underwater operation in many laboratories, including ARL. These adaptations require limited development, and the modified engines generally do not perform as well as the terrestrial configurations. The needed modifications typically involve the recirculation of exhaust gases or an inert gas in the case of diesels. In larger UUVs, these conversions could improve on the performance of lower specific energy batteries when mission energy is relatively large and mission power relatively small. Hydrocarbon refueling would be relatively simple during turnaround, while the oxygen replenishment process would depend upon the oxygen storage method chosen. Commercial spark ignition and diesel engine/alternators would likely have higher vibration levels than fuel cells or batteries configured for the same application. Isolation mounts could be used to mitigate this effect, with an attendant system performance reduction.

Free-piston Stirling engines are under development for underwater and space applications. These engines offer improved efficiency and very low vibration levels. When operated in pairs, near total balance has been achieved when active control of the phase angle between the engines is maintained. Figure 12 is a schematic of how such a Stirling engine could be used in a UUV, and Figure 13 is a photograph of a 3 kW Stirling engine developed for use with a liquid-metal heat source in an underwater application. This engine has been designed for use in UUVs as well. Using this engine with a standard hydrocarbon logistics fuel would require the development of a hydrocarbon combustor for the underwater environment and the development of a combustion gas products post-processor.

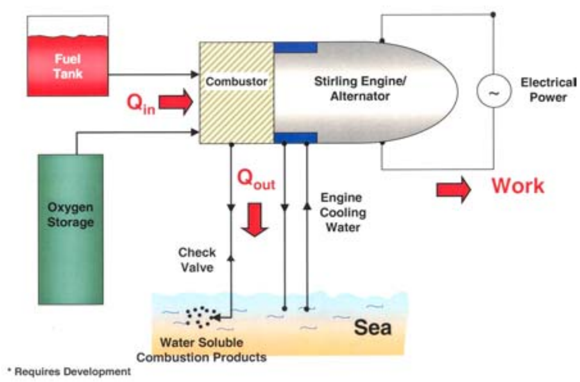

Figure 12 Stirling Engine/Alternator Power System

Figure 13 3 kW Stirling Engine

Some work is being done on this type of combustor, with the objectives of achieving complete combustion through proper mixture of the reactant streams and maximum transfer of combustion energy to the engine via efficient combustor designs. Figure 14a shows analytical predictions of the temperature distribution in such a combustor for two different oxygen sources. Figure 14b is a photograph of a representative combustor, which uses hydrogen fuel and was built to power a 1000 horsepower Rankine system. The ability to achieve combustor designs with exceedingly small volumes is exemplified in Figure 14b. These combustors can be designed to operate at the prevailing depth pressure or to operate well above the anticipated depth pressure. Each approach is favored under some conditions, but the second approach is preferred under more cases of current interest.

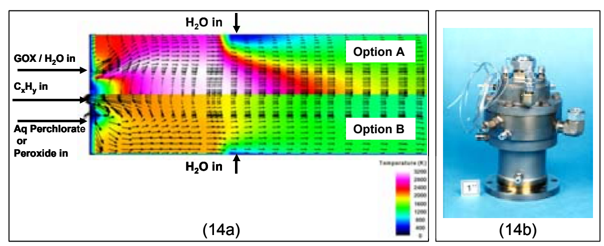

Figure 14 Rankine Combustor Simulation

It has been shown that the carbon dioxide produced by these combustors operating at representative powers will dissolve within several meters of the discharge port if it is dispersed finely enough. Alternately, the resulting CO_2 can be completely dissolved onboard with a system of the type shown in Figure 15. Such systems have been built and tested. The approach that yields the best overall system performance appears to be one in which the CO_2 is partially dissolved onboard and then pumped overboard, along with the solvent water, with a compressor ring pump.

While Stirling engines are capable of efficiencies in the 40+% range, they do not have the specific power capabilities of turbine engines. Therefore, as required power increases in response to the need for higher speed vehicles or higher power payloads, a point is reached where better system performance can be achieved using a less efficient Rankine cycle with a very power dense turbine/alternator. Figure 16 shows a 1-inch pitch diameter impulse turbine that is under development by ARL and which operates at over 400,000 RPMs. It produces about 3 kW and is currently being integrated with a companion alternator.

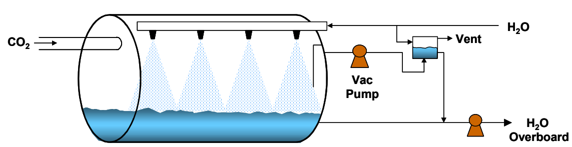

Figure 15 CO_2 Absorption

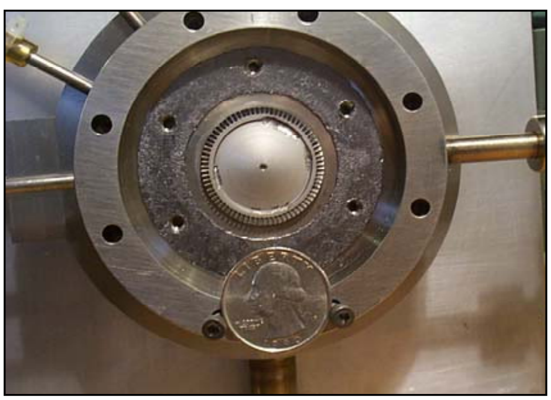

Figure 16 3 kW Turbine Wheel

Many UUV operations of interest will be conducted at various powers and speeds. It is possible that rather large differences between the highest and lowest required power will occur in some of those cases. When large dynamic ranges in power are required, it is likely that improved performance can be achieved with hybrid power systems that consist of high and low power equipment that can be independently operated. Such systems might take the form of battery networks that can be remotely reconfigured in different patterns under different power demands or a low power fuel cell and a high power Rankine system that each operate with hydrogen and oxygen.

Thermoelectric convertors and thermophotovoltaic (TPV) convertors have received some attention as potential power systems for UUVs. While TPVs show some promise as an emerging technology, present costs are probably too high and present performance is probably too low to compete with the previously mentioned options at this time. Continued development could change that assessment. Thermoelectrics are a more mature technology and appear to have characteristic efficiencies that are too low to be competitive.

Projected Performance for Various Power Systems

Extensive design studies are required to succinctly characterize the performance potential of the various power systems cited when they are used in different-sized vehicles performing different missions. However, the reasonably large differences in performance level among broader subgroups of the various power systems allows an initial assessment to be made using a more modest set of preliminary designs, accepting the fact that the embedded uncertainty will prevent definitive conclusions from being drawn about specific power systems in specific applications. This paper reports results obtained using this approach and uses specific energy results derived from approximately 20 preliminary designs executed for all mentioned type power systems in some representative applications.

The following were inputs to all preliminary designs:

- Propulsive power based on the general model previously discussed
- Vehicle l/d of 9
- Shells designed for 1000 foot depth
- Motor and power electronics for 20 knots
- 4 knot reference speed
- 250 watt baseline hotel load
- 10% buoyancy system
- 50 lbm navigation and data package (each)
- 2000 lbm payload

Commercial information was used where available for component weights, volumes, and other performance characteristics. The designs were developed for neutrally buoyant vehicles, including providing extra volume in vehicles where component weights were the limiting factor and accepting limited component weights where volume was the limiting factor.

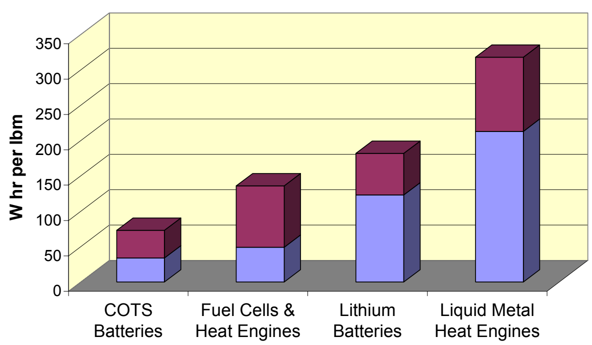

Figure 17 Representative Energies

The results of these design studies are summarized in general terms in Figure 17, which shows a range of representative energy densities for four broad categories of energy systems. The first is for commonly available commercial batteries and includes results for alkaline D cells, various silver-zinc systems, nichol-metal hydride systems, and lithium-ion systems. Preliminary designs were done for vehicles from 32 to 68 inches in diameter, although all battery types were not designed into all diameters. Figure 17 shows the range of specific energies estimated for this broad category of power systems for this range of vehicles. Performance is for 4-knot operation, with the ability to go up to 20 knots with an attendant reduction in specific energy that depends on the power system type.

Specific energies were calculated in a similar fashion for fuel cells and heat engines that used liquid hydrocarbons for fuel, for advanced lithium primary batteries, and for heat engines that used metal fuels in closed combustion processes. The fuel cells and heat engines were ultimately lumped together because of the broad overlap of design results and the level of uncertainty in those results.

When these specific energies are translated into achieved range at 4 knots with a 2000 lbm payload, Figure 18 results. Figure 18 shows that a broad range of performance variation is present in each subgroup, that the subgroups do have different levels of performance, and that there is significant overlap in the performance characteristics of most subgroups.

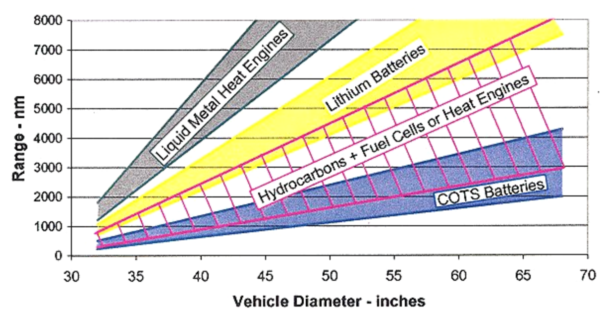

Figure 18 Range vs. Vehicle Diameter for 2000 lb Payload at 4 knots

In general, it can be seen that the commercially available batteries used in most UUVs generally provide relatively low performance. It can also be seen that much higher performance is available from advanced lithium primary batteries. Hydrocarbon-fueled fuel cells and heat engines occupy the region between the two battery types and actually overlap both battery regions to an extent. These systems offer particular promise to ease the turnaround process and to reduce operating costs, in the author's opinion. Liquid-metal-fueled heat engines project the highest level of performance in this study, but also require the most development.

With the exception of commercial batteries, all of these systems require some development before they can be used in specific applications. It is the author's assessment that high performance lithium batteries are the closest to being developed products and that hydrocarbon fueled heat engines are the next closest. However, with the very significant development efforts currently under way for fuel cells and because of the lack of efforts on hydrocarbon-fueled heat engines for underwater applications, it is not clear which of these technologies will be ready for widespread application to UUVs first. Liquid-metal-fueled heat engines have been demonstrated in the laboratory in prototype systems, but will require significant development for application in operational UUVs.

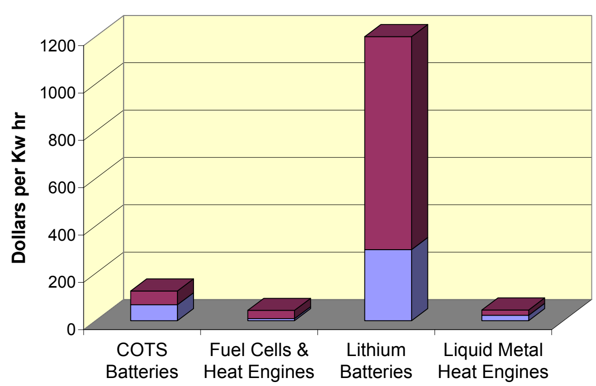

Figure 19 Estimated Cost per kW after Development

Estimates of per kilowatt-hour costs have been made for the various subgroups after development is completed. These results are shown in Figure 19. The results for commercial batteries are for both primary and secondary cells. In the case of secondary cells, initial cost is amortized over the life of the cell. In the case of fuel cells and heat engines, fuel cell or engine cost is amortized over the life of the convertor and the cost of reactants is added to that. For advanced lithium batteries, anecdotal information is used for current costs, and data for commercial D cells is used to estimate the lower cost that one might associate with large production rates of the advanced batteries. Costs for the liquid-metal-fueled heat engines amortizes engine cost over the life of the engine and includes the cost of disposable fuel cartridges for each run. Both batteries and liquid-metal-fueled heat engine cost estimates include the cost of disposal of the batteries and the disposable heat cartridges, about \$6 per lbm. The large difference in projected cost per kilowatt-hour for liquid-metal-fueled heat engines and lithium batteries is thought to be the result of the need to throw away the "conversion system" for the batteries after each use.

Conclusions

The following conclusions have been drawn in the course of this study.

- Numerous power system options are potentially available to improve the range of contemporary UUVs.
- Some of these options may both reduce operational costs and simplify the turnaround process.
- Liquid-hydrocarbon-fueled heat engines and fuel cells appear to provide a particularly attractive subgroup of power system options.
- The present level of technology demonstration in the fuel cell and heat engine subgroup makes it difficult to differentiate their relative performance.

- Advanced lithium batteries provide very good energy density, but are and probably will remain expensive.
- Liquid-metal-fueled heat engines require additional development, but could provide better performance that advanced lithium batteries at significantly lower per kilowatt-hour operational cost.