# THERMAL POWER SOURCES FOR EXTENDED AUV MISSION REQUIREMENTS

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ABSTRACT

Over the last 20 years the AUV idea has progressed from a concept to the evaluation of test bed models and the development of prototype vehicles. In the main, all current in-service vehicles are battery powered. Batteries have enabled the operating philosophy of AUVs to be demonstrated but their underwater endurance is limited to hours. Where days and even weeks of endurance are needed then alternative power sources will be required. The RNEC and the University of Calgary are currently detailing the potential of thermal power sources for extended AUV missions. This paper presents the results of a study to assess the development work being undertaken with regard to AUV thermal power sources and details the initial design of a Stirling engine/liquid metal combustion heat source for application to a submarine tube-launched AUV.

## INTRODUCTION

An Autonomous Underwater Vehicle (AUV) is defined as an untethered vessel that can operate independently of a surface or sub-surface support facility. The advantages to be gained through the operation of these vessels has long been recognized by the Defence, commercial and scientific communities. Defence applications include underwater surveillance, anti-submarine and anti-surface warfare, covert deployment of long-range stand-off weapons, and mine search and classification. It has been predicted that within the next 15 years AUVs will provide the most important adjunct support to submarines and surface vessels[1]. Present developments will probably be extended in the future to include multi-vehicle operations controlled by a master AUV or a manned submarine.

Commercially, AUVs have been used as inspection platforms for the observation of sub-sea structures and object location and identification. They are being used to support oceanic resource management by providing the platform for geophysical acoustic surveys of abyssal plains to determine and quantify the extent of mineral deposits. As the offshore economy becomes progressively important the commercial use of AUVs will increase.

Scientifically, the use of AUVs is enabling measurements of the chemical, physical and biological parameters of the deep oceans to be obtained which could provide a better understanding of global ecology and climate and the oceanic factors which affect them.

There are a number of advanced technology projects aimed at developing such vehicles, particularly in North America, Britain, Europe and Japan. In

North America the majority of the projects are funded by Federal agencies in support of Defence requirements whereas in Europe the impetus is coming more from the commercial sector and a number of international collaborative projects under the Eureka framework are drawing contributions from the marine science and technology communities for the development of prototype AUV vehicles. The United Kingdom's National Environmental Research Council (NERC) in 1987 gave approval for a European Community Research Project on scientific AUVs to commence. Named Autosub, two vehicles have been identified as being required for hydrographic, geological and geophysical oceanic measurements.

Over the last 30 years at least 48 different types of AUV have been proposed[2]. Some were built, some never advanced beyond the prototype phase, whilst others remain in concept form. As far as it is known, except for the Dolphin vehicles built by ISE Limited of Vancouver, all the present in-service vehicles are powered by conventional secondary batteries with underwater endurances measured in hours. For future missions where days and even weeks of operation are envisaged then the development of high energy density power sources will be crucial to the eventual success of many of the current programmes.

Electro-chemical power sources such as advanced batteries, fuel cells and semi-cells have the potential to provide energy densities far in excess of those available from existing battery technology. These types of power sources have attracted considerable attention for use in the AUV Prototype Programme of the Defence Advanced Research Projects Agency (DARPA)[3]. However, the development of these power systems for underwater applications will require large and long-term capital expenditure commitments. Thermal power sources can offer a lower cost, near-term solution, not as an alternative to electro-chemical systems but as a means of providing energy densities beyond those achievable from to-day's in-service batteries. This article is concerned with such power sources and their use in AUVs, particularly for Defence applications.

## THERMAL POWER SOURCES

The basic elements of any thermal power source include a method of storing or generating energy and the means for converting this energy into useful mechanical or electrical work using a heat engine. The primary forms of energy storage used or considered for use in underwater vehicle power applications are thermal, chemical and nuclear (FIG. 1). With the exception of the internal combustion engine, any heat engine has the potential to use energy from any particular energy store.

### Thermal Energy Sources

#### *Thermal Energy Storage*

Thermal Energy Storage (TES) devices may be considered to be the thermal equivalent of secondary storage batteries. The operation of a TES is conceptually very simple: an insulated tank containing a material having a high specific heat capacity is heated by some means, e.g. electrical resistance heating, a nuclear source or fuel combustion. The thermal energy received can be stored in the form of sensible heat in which case the temperature of the storage medium (e.g. a carbon block) will decrease as energy is extracted.

It can also be stored as latent heat if a phase change material (e.g. molten salts) is used. Such media do not experience a significant decrease in temperature over the major part of their operating range. TES has a number of particularly attractive features in underwater applications. There are no exhaust products, operation is independent of depth, the system inherently maintains its neutral buoyancy and there are no emitted signatures. Recharging a TES system requires a conveniently available 'plug-in' heat source which ideally will be taken from a ship or submarine's domestic heat/electricity supply and so no expendables as such are required to be carried. Both sensible and latent heat TES systems have been studied and developed for underwater use. Energy storage densities would be of the order 0·1 to 0·2 kWh/kg which are significantly better than the ubiquitous lead-acid battery[4-6]. The TES-Stirling engine system has been the subject of some development in France in recent years[7].

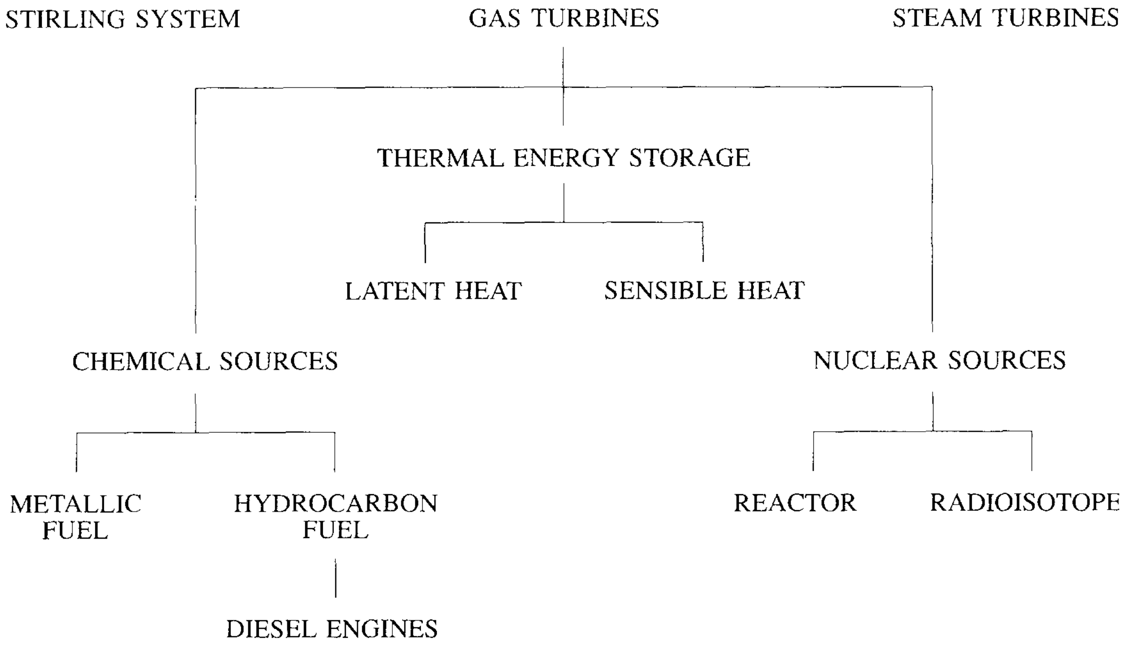

FIG. 1—HEAT ENGINE/ENERGY SOURCE COMBINATIONS

*Nuclear Sources*

Nuclear energy in the form of thermal energy can be provided by the use of nuclear reactors or by radioactive isotopes. The US Navy's experimental midget submarine, the NR-1, uses a 1·9 MW (e) nuclear source and small reactor systems have been built in the 100 kW range for use in small manned submersibles. Although attractive from an energy density point of view, reactor systems would be most likely precluded from AUV applications on the grounds of safety, size and the technical problems of scaling down the size to meet current AUV requirements.

With a radioisotope nuclear power source, the thermal power output is a linear function of the number of unstable spontaneously decaying nuclei present. Power is produced at all times regardless of the amount of isotope remaining. Such isotope mediums include cobalt, strontium and thulium. Radioisotopes have been developed in the 20 kW range for space applications and have been proposed for undersea stationary power systems[8]. However their energy conversion efficiencies, which are the order of 16–18%[9], are somewhat low for AUV applications.

### *Chemical Sources*

There are two basic types of chemical heat sources, combustion of hydrocarbon fuels and chemical reaction systems using metallic fuels. The use of hydrocarbon fuels requires the provision of a stored oxidant and the removal of excess combustion products from the operating system whatever energy converter is used. Oxidant and exhaust gas management can be problematic. The use of metallic fuels and suitable oxidizers under certain conditions can yield power/energy densities comparable to those attainable with nuclear reactor systems[4]. For example, lithium (Li) when injected with sulphur hexafluoride ($SF_6$) has the following exothermal chemical reaction equation:

$$8\ \underset{\text{(low melting point metal)}}{\mathrm{Li}} + \overset{\text{(liquifiable gas)}}{\mathrm{SF_6}} \longrightarrow 6\ \overset{\text{(molten products)}}{\mathrm{LiF} + \mathrm{Li_2S}} + \underset{\text{(theoretical rate of heat release)}}{14\ \text{kWh/kg of lithium}}$$

When the reaction occurs in a totally enclosed combustion chamber the products of reaction lithium fluoride (LiF) and lithium sulphide ($Li_2S$) can be stored in the volume originally occupied by the consumed lithium. Thus there are no excess products which have to be disposed of, and the mass density of the combustion system remains the same. Consequently the operation of the system is independent of depth. Underwater systems using metallic fuels and heat engines have been developed for torpedo and stationary power applications[10].

## Thermal Energy Converters

The conversion of thermal energy into either mechanical or mechanical/electrical power is achieved using heat engines. The main contenders for AUV applications include the Synthetic Atmosphere Diesel (SAD) engine, the Stirling engine and the gas turbine. Other candidates are the Rankine and the Wankel engines.

### *Synthetic Atmosphere Diesel*

A diesel engine that can operate without the presence of 'free air' is described as working in either the closed (FIG. 2), recycle or semi-closed cycle mode. In all these cases an artificial or synthetic oxidizing atmosphere is used and this gives rise to the generic description 'synthetic atmosphere diesel' or SAD. The first underwater SAD engine system was patented at the turn of this century. The concept has attracted periodic interest, especially in recent

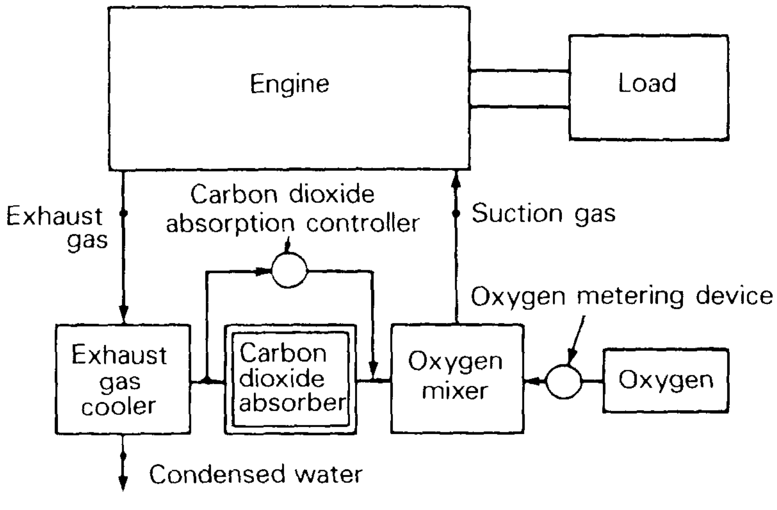

FIG. 2—CLOSED CYCLE DIESEL CONCEPT

years, and undergone a significant amount of development[11]. In a SAD system some of the exhaust gases are recirculated to the engine intake where they are mixed with oxygen. These gases are the substitute for the nitrogen of normally aspirated air. A proportion of the exhaust gases, equivalent to the amount of oxygen that has to be added, must be removed from the system. In some cases a greater proportion is extracted.

The removal and ejection of the unwanted combustion products—mainly carbon dioxide ($CO_2$)—is the major problem associated with the development of SAD systems. If carbon dioxide is recycled back into the engine then its relatively poor thermodynamic and heat transfer properties adversely affect the performance of the engine. Subsequently an inert gas such as argon has to be added to recreate the properties of 'free air' and so maintain an acceptable system efficiency.

Methods which have been developed for $CO_2$ removal include chemical and sea water scrubbing. Chemical scrubbing using metallic hydroxides is an attractive option since it is not difficult to design and build a working system. However, such compounds are not regenerative which means that expendable scrubbing mediums have to be carried on board the vessel taking up premium space, a great disadvantage for long missions. Alternative chemical systems are being investigated.

Carbon dioxide is readily absorbed by sea water, the absorption rates being governed by sea water temperature, the absorption pressure and the mass flow rates of the exhaust and sea water. Although the use of this technique eliminates the need for the carriage of scrubbing chemicals, the present systems are either highly efficient and bulky or are compact and have low removal efficiency. The development of high efficiency compact scrubbers will be crucial to the success of the SAD systems.

The unwanted exhaust has to be ejected into the surrounding sea water or stored on board. The Italian company Maritalia have developed a unique storage method for manned vessels[12] but it has not, as yet, been considered for the AUV application.

Although SAD systems have been and will continue to be developed for use in manned submersibles their application to AUVs is still problematic. Nevertheless, the diesel engine is a proven and efficient energy converter.

### *The Stirling Engine*

The Stirling engine is an externally heated dynamic energy converter that can use any heat source. Comparable with the performance of a diesel engine but quieter in operation, it has been developed for space, terrestrial and underwater applications. The leading industrial developers of underwater Stirling technology are Kockums Marine AB of Malmo, Sweden. In 1988 they retrofitted a Swedish NACKEN Class naval submarine with two 75 kW hydrocarbon-fuelled Stirling engine-generator sets for use as underwater battery chargers. The installation increased the submarine's underwater endurance by a factor of between five and eight and subsequently she was accepted into operational service in March 1990.

In the Kockums system heat energy is supplied to the engine via a tubular heat exchanger sited in an external and pressurized combustor. Oxygen in liquid form (LOX) is stored on board the vessel in cryogenic containers. Pressurization of the combustion chamber (2 to 3 MPa) allows exhaust gas to be discharged without further compression into the sea water at depths down to 200 m.

Kockums is now developing a 600 kW Stirling for use in a large conventional submarine and a 5 to 15 kW engine, the 4–95, for AUV applications. The physical dimensions of the intended AUV are similar to those of the DARPA vessel (see below).

### *Gas Turbines*

Gas turbines may be operated in either the open or closed cycle mode. Closed cycle operation is particularly advantageous for an underwater vehicle where air- and depth-independent operation is required. The closed cycle gas turbine, like the Stirling and the Rankine engines, has the inherent advantage of being able to operate with any heat source. It also has a high specific power to weight ratio and produces low vibration levels. Such systems have been developed in the 30 kW power output range for space applications by Garrett (Fluid Systems Division) of Phoenix. A derivative of this concept has been proposed for AUV applications[13].

A closed cycle gas turbine working on the Ericsson rather than the Joule/Brayton cycle would provide an especially attractive system, especially if liquid metal combustors were used as the energy source.

## PRESENT AUV THERMAL POWER SYSTEM DEVELOPMENTS

Of the thermal power sources so far considered it appears that Kockums is leading the field with a Stirling system. A prototype powerplant system which fits into a hull section of 44 inches diameter is currently under development so that direct energy comparisons can be made with the DARPA vehicle. This latter vehicle has an energy storage requirement of 3360 kWh and, within the physical parameters of the vessel, preliminary studies have indicated that only advanced electro-chemical power sources are potentially capable of meeting this very demanding specification. It will be some time before such a powerplant is available. In the meantime the DARPA vehicle is to be fitted with a silver-zinc (AgZn) battery.

The energy sub-section of the Kockums AUV consists of a liquid oxygen tank, fuel oil tank and associated control systems designed for use with the 4–95 Stirling engine, (FIG. 3). The energy capacity of the prototype system is projected at 600 kWh which corresponds to 60 hours of operation at a draw of 10 kW. This is twice the energy storage capacity of an equivalent AgZn battery system and would give an AUV the ability to operate for days rather than hours.

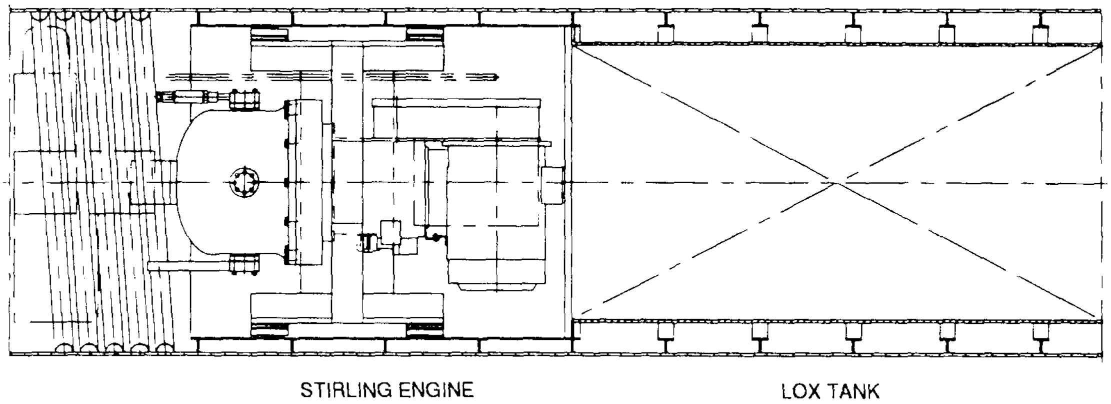

FIG. 3—LAYOUT OF KOCKUMS AUV

The 4–95 Stirling engine was originally developed by United Stirling in the 1970s for use in both the automotive Stirling engine and solar power programmes. More than 50 engines were built and more than 150 000 running hours have been accumulated. Initially designed as a 40 kW engine, the 4–95 has been derated within the 5 to 15 kW range for AUV applications.

This should further improve its reliability. The combustion pressure of approximately 3 MPa will ensure exhaust compressor independence to about 400 m. The first phase of the project which includes construction and testing of a prototype engine system is now complete. The second phase involving the integration of the engine into the hull section complete with LOX and fuel storage tanks, is scheduled for completion in 1991. The complete section will have its own compensating tanks and will be neutrally buoyant. The displacement of the section is 3·5 tons with half the section being occupied by the LOX, fuel and compensating tanks, the other half by the engine and controls[14].

Garrett of Phoenix have patented a design for a closed cycle gas turbine system using a liquid metal heat source. The design is based on Garrett's cumulative experience of similar torpedo and space power systems. For the torpedo application a liquid metal combustion heat source, designated a Stored Chemical Energy Propulsion System (SCEPS), is combined with a steam (Rankine) energy conversion system. The Royal Navy is developing a similar power source with Dowty Fuel Systems which is known as the Closed Cycle Thermal System (CCTS). The AUV SCEPS is designed for operation with a closed cycle gas turbine in which a molten fuel (lithium) is injected with an oxidant (sulphur hexafluoride) in a totally enclosed combustion chamber. The energy released in such combustion systems in terms of volumetric and gravimetric capacities is far greater than from hydrocarbon fuelled systems[15]. The AUV energy hull section has a projected energy storage capacity between five to eight times greater than is currently available from existing battery technology.

Technomare, Marine Systems and the University of Bologna, have patented a SAD system, the Cryo-Thermal Engine, for AUV applications[16]. As previously stated, the major problem associated with SAD systems is the provision of an efficient exhaust management and treatment device. In this particular system the technique developed for the removal and control of the $CO_2$ is based on the liquefaction of combustion carbon dioxide after low pressure compression. Cooling is provided by the evaporation and superheating of the oxidant, in this case LOX. The project is linked to the development of the Advanced Robot for Underwater Survey (ARUS) AUV which is part of the Eureka EU191 programme[16]. Eureka is a European collaborative venture with the aim of improving European competitiveness in world markets. The EU191 project is concerned with the development of future generations of ROVs and AUVs.

Another concept proposal for a thermal powered AUV is that of Challenger Oceanic Systems and Services and Marlin Engineering Limited of the United Kingdom. The LR6000 (FIG. 4) has been designed to provide a platform for continuous underwater sampling and surveying on a global scale. The propulsive system will be a choice between a SAD or a Stirling system to

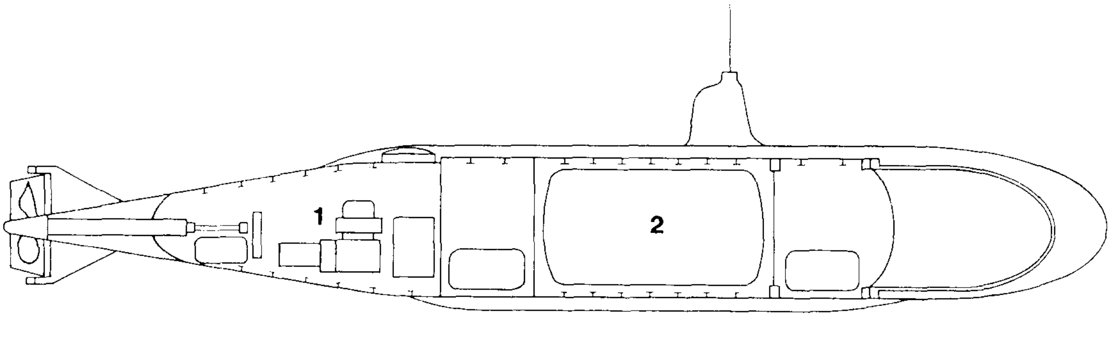

FIG. 4—THE CHALLENGER AUV—LR6000
1: Stirling engine 2: LOX tank

give the required range of 6000 km. The 12 tonne vehicle will require 5 kW shaft power at 6 knots assuming a drag coefficient of 0·9 and propulsive efficiency of 60%. A hotel load of 2 kW will be needed to drive pulsed acoustic systems and run standard oceanographic instrumentation as well as providing energy for the communication and navigation systems. Interaction between the vehicle and the land-based operator is one of the key elements in this proposal. Many available satellite systems only provide one way communication, are not continuously visible and can be expensive to use. An alternative being considered is Meteor Burst Communication (MBC). The principle of MBC operation is the use of ionized trails of meteors to reflect radio waves from the remote station to strategically positioned master stations. About 10 billion meteors enter the atmosphere daily, allowing regular radio transmission. This system has already been used in remote regions such as Alaska by oil companies.

## AUV RESEARCH AT THE RNEC/UNIVERSITY OF CALGARY

The Royal Naval Engineering College, Manadon, and the University of Calgary have been engaged in the design and specification of anaerobic heat engines for underwater applications for over a decade. Current research has centred around the design and operation of Stirling engines, the development of SAD systems and the use of computer-based underwater powerplant selection and simulation models. In a recent collaborative survey carried out to assess the potential of thermal power sources for AUV applications it was found[17] that:

(*a*) There is a general lack of published data concerning the volumetric and gravimetric energy densities of underwater propulsion systems. The data that have been released are open to various interpretations. It is not always apparent if they relate to the primary energy source, the conversion process, the energy sub-system, the total propulsion system or the complete vehicle.

(*b*) Thermal power sources have the potential to offer between two and eight times the energy storage capacities now available from conventional battery technology within the limitations dictated by space and weight.

(*c*) The development of AUV thermal power sources remains conceptual due to several factors:

  (*i*) There are only a few companies capable of developing such energy sub-systems, and expertise is limited.

  (*ii*) The USA's Department of Defense has concluded that only fuel cell powered AUVs will be able to facilitate long endurance military missions and consequently fuel cell research and development dominates to the exclusion of other technologies.

  (*iii*) Due to the high development costs and potential risk, the scientific and commercial communities are more disposed to the use of existing battery technology. The missions and endurances of their AUVs will be tailored to the on-board energy storage capacities of such batteries.

### AUV Design Study

As part of the Manadon/Calgary collaborative programme on underwater power systems the concept of a thermal powered AUV is under detailed investigation. The study is centred around an anticipated requirement for a submarine tube-launched AUV for extended reach operations. The aim of the project is to determine the potential mission profiles obtainable from a torpedo shaped AUV powered by various thermal systems. A computer-based simulation is being developed for this project which will allow the performance of a wide range of different energy source/energy converter combinations to be assessed readily. However, in the initial phase of the work it was decided to select the system which appeared to provide the best solution within the constraints of the specified vehicle criteria.

If a hydrocarbon fuel is used then the vehicle must carry oxygen. Since more oxygen than fuel is consumed in the combustion process the storage of oxygen is an extremely important factor. When stored in liquid form (LOX) oxygen has a volumetric carrying capacity almost 850 times greater than gaseous oxygen (excluding installation requirements) at the bubble point. Therefore LOX appears to be the better option. However, LOX has to be stored in well-insulated tanks to reduce boil-off. The ratio of actual tank volume to $O_2$ storage capacity increases as the latter decreases. For the AUV application it was determined that a tank approximately five times the volume of the stored LOX would be necessary. When this is considered in light of the redundant space which must be provided to maintain neutral buoyancy, then the use of LOX is not an attractive option for long reach AUVs.

Subsequently the SAD was discounted for this particular application as it can only be used with a hydrocarbon fuel. The gas turbine and the Stirling engine can operate with any heat source but the Stirling is a more efficient prime mover. Its good part-load operating characteristics also make it suitable for the AUV application as a direct drive propulsor eliminating the need for a drive motor. Furthermore the Stirling is the most technically advanced of heat engine underwater powerplants. A particular Stirling engine can readily be uprated or derated to match the maximum transit speed of the AUV; it is therefore extremely flexible in operation. The choice of a Stirling engine was thus made on logistical, technical and familiarity grounds.

The energy source became a choice between a TES or a liquid metal combustion system. Based on theoretical energy densities (FIGS. 5 and 6), only the liquid metal reaction systems could provide the AUV with long reach potential. It was decided to select a lithium sulphur hexafluoride reactor energy source. Other reactions offer greater heat releases but there has been a lot of experimental work done on $LiSF_6$ systems and it was considered that development risk would be low.

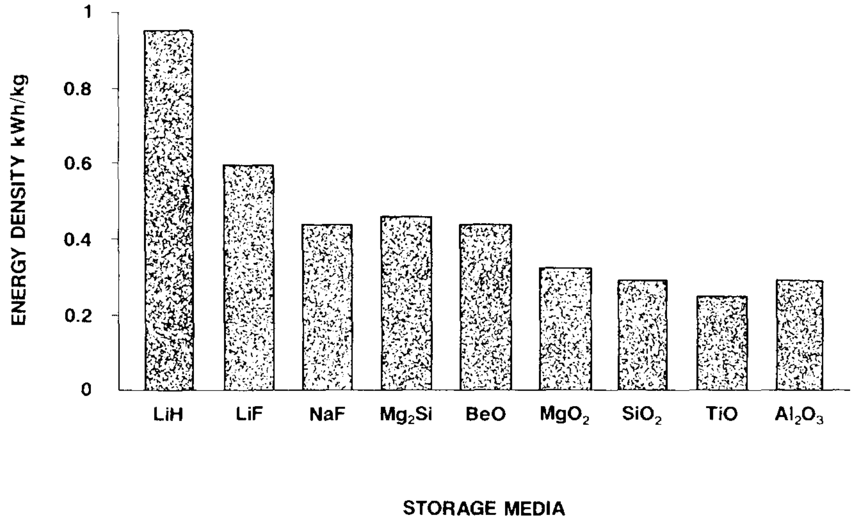

FIG. 5—THERMAL ENERGY STORAGE DATA

The metal combustion Stirling was therefore the chosen power system. A significant difficulty with this type of system was identified as the method for transferring heat from the reactor to the Stirling engine heater tubes. There are three basic methods by which this could be done: by direct immersion of the engine's heater tubes in the combustion vessel, by the use of an externally mounted heat exchanger, or by a heat pipe arrangement. For this particular application all three methods are considered to be feasible and all are being investigated. A major factor in the final choice will be the ease of refuelling/replacing the lithium boiler, especially under water.

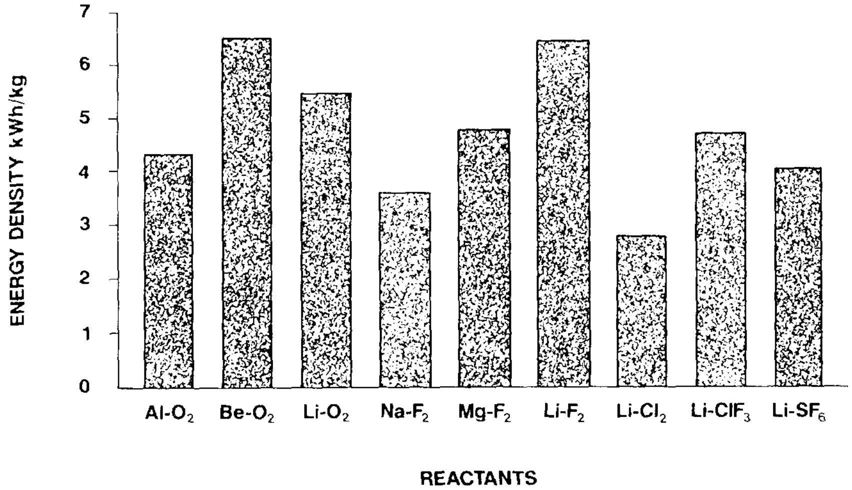

FIG. 6—METAL COMBUSTION ENERGY DATA

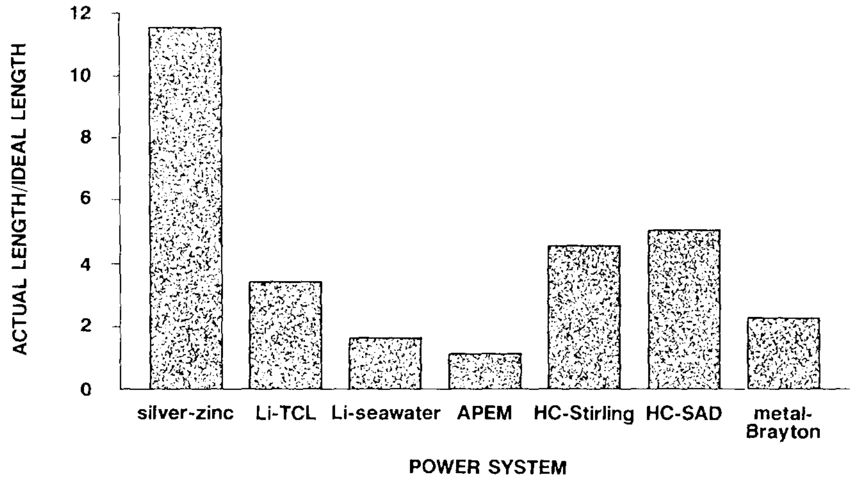

FIG. 7—DARPA VEHICLE POWER SYSTEM PACKAGING RATIO; IDEAL RATIO = 1

Initial calculations using baseline energy data and conservative energy/ power conversion and heat transfer efficiencies indicate that a 6·25 m length AUV with a usable powerplant section of 2·24 m would result in approximately 400 kWh of stored available energy. Several mission profiles are possible depending on the speed of the AUV, giving either hours or days of on-station operation.

The selection of the power converter and energy source is not straightforward and there have been many attempts to compare different powerplants using a variety of criteria. However, for a realistic comparative assessment, a specific vehicle must be identified with a well defined mission profile. FIG. 7 is an attempt to compare selected electrochemical and thermal power source energy capacities for the DARPA AUV, the data having been taken from the open literature. The comparison is not exhaustive since only the most developed systems have been considered. In terms of volumetric energy storage capacities alone, advanced electrochemical systems appear to have far greater potential than thermal power sources and are an order of magnitude better than conventional batteries. However, the selection of a power plant should not be made on this basis alone as there are other important considerations—for example development costs, time to reach technical maturity, availability of technology and compatibility with the mission requirements.

In summary, FIG. 7, which is based on energy storage data, indicates that battery systems will give an AUV hours of endurance, thermal power sources will provide the same vehicle with days of operation, and advanced electrochemical power sources have even greater potential, i.e. weeks.

## CONCLUDING REMARKS

AUVs have the potential to fulfil a large number of underwater roles particularly those which are Defence-orientated. However, there are system issues which need to be further addressed with regard to AUV development, particularly in the area of high energy density power sources. Existing batteries are incapable of providing long reach facilities to AUVs and it will be some time before the advanced electro-chemical systems are available. In the near term the use of thermal power systems appears attractive, especially if metal combustion heat sources are used.

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