POSSIBLE FUTURE PROPULSION SYSTEMS FOR SUBMARINES

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ABSTRACT

This article is concerned mainly with methods of increasing the underwater endurance of non-nuclear submarines at patrol speeds. Consideration is given to the selection of types of power generation systems and, where appropriate, the storage of fuels and oxidants for air-independent systems. The possible benefits in performance obtained for the various selections are compared. Longer term future prospects, such as membrane technology for the extraction of dissolved oxygen from seawater, and alternative forms of energy storage and propulsion are mentioned briefly.

Introduction

Modern diesel electric submarines are required to operate dived for considerable periods, sometimes entailing transits to and from an extended patrol, dived throughout. In such circumstances batteries are used when totally submerged and a reserve of battery charge has to be maintained. To run the diesel engines for battery charging a schnorkelling mast needs to be raised for the induction of air. This requires the submarine to come to periscope depth and expose masts as well as increasing its noise signature from running the engines. She thus exposes herself to increased risk of detection as well as interrupting her operational role. Increasing the submerged endurance increases the potential effectiveness of the submarine and reduces the risk of detection. Fitting a submarine with a power supply which meets the total demands whilst submerged at patrol speeds would result in many operational advantages. Improvements in batteries, although of importance in enhancing a submarine's submerged high speed capability, may not achieve a significant increase in low or medium speed endurance. One could therefore envisage a need for an air-independent power system which in the real world means a small nuclear system or one which relies on a stored supply of fuel and oxidant.

Air-Independent Power Systems

The operational performance of any such system is based on a number of interdependent factors. TABLE. I gives commercially available performance data including power output per unit weight and volume of oxygen and fuel, the oxygen consumption in terms of the necessary stored volume being the most significant.

Closed Cycle Diesel

Closed cycle diesel (CCD)[1] generators are practicable with an overall efficiency of less than 30% and a life of a few hundred hours. With development, engine life may be expected to improve. In a practical scene it is possible that inexpensive throw-away engines could prove attractive. Currently, specific oxygen consumption is more than 1 kg/kWh. It may prove possible to increase plant efficiency by adopting Argon injection techniques

TABLE I—*Performance of air-independent power systems*

System	*Output Power* (kW)	*kW/kg*	kW/m^3	$kg\ O_2/kWh$	*kg Dieso/ kWh*	$kg\ H_2/kWh$
CCD	up to 100	0·17	~140	>1	~0·3	—
Stirling	75	0·125	~100	~1	~0·3	—
Small Nuclear	25	0·0026		—	—	—
	100		25	—	—	—
Alkaline Fuel Cell	3	0.01	32		—	—
	7·5	0·1	125	0·4	—	0·05
	12		92		—	
Phosphoric Acid Fuel Cell	200		36		—	—
	375		43			
	500		153	0·44	—	0.055
Solid Polymer Fuel Cell	10	0·3	260		—	
	34	0·2	260	0·37	0·047	

and reducing parasitic losses with regard to overboard discharge of exhaust gas. The main problem remains one of noise, a situation the overboard discharge proposals may worsen. Thus closed cycle diesel engines may not be particularly suited to covert operations but may prove a contender for emergency power supplies.

Stirling Engines

Stirling engine generators, under development for the Royal Swedish Navy[2], are a practical reality at a power level of some 75 kW per engine. They are complex compared with diesel engines, making routine maintenance difficult at sea. Currently, specific oxygen consumption is about 1·0 kg/kWh and efficiency above 30%. Systems based on stored gaseous or liquid oxygen have been made. Noise performance should be better than for a diesel engine.

Fuel Cells

Fuel cells[3] with an efficiency of more than 50% (and possibly 70%), noise performance perhaps similar to that of a battery, and potential for a 30 000 hours life, show a marked potential improvement compared with other options. It is however at present necessary to use hydrogen as a fuel, either stored (almost certainly in metal hydrides for safety reasons) or obtained by reforming a suitable stored fuel such as methanol, and oxygen. A system based on metal hydride and liquid oxygen stores has been developed in Germany[4]. Use of a reformed fuel presents the problem of the necessity to discharge waste gas such as carbon dioxide. Waste water from the fuel cell reaction may be used as compensating water. The specific oxygen consumption depends on the type of fuel cell considered, but is between 0.37 and 0·5 kg/kWh for those types most suitable for underwater operation (based on power density and power per unit weight).

Commercial data for fuel cells of several types are listed in TABLE I. Based on consideration of power densities and specific oxygen consumption, the alkaline and solid polymer electrolyte types are currently most suitable for submarine use. Other types, such as the direct methanol cell or the molten carbonate electrolyte cell, may be sufficiently developed in the future to make them suitable candidates. Of those systems requiring a supply of fuel and oxidant it is seen that a solid polymer fuel cell system is the most effective in terms of power density and specific oxygen consumption.

The choice of fuels for fuel cells is wide and TABLE II lists some possibilities. However, some of these are very reactive or expensive and final selection for underwater use depends on such criteria as reactivity, storage method, the method of reforming to produce hydrogen, and the problem of contamination from additives in fuels such as diesel oil. The choice of oxidant is thus limited to gaseous or liquid oxygen or chemicals such as peroxides or heavy metal oxides which can produce oxygen by dissociation. TABLE III lists data for the most practicable oxidant and fuel stores.

TABLE II—*Fuel cell fuels*

Fuels
Hydrogen
Hydrocarbons
Alcohols
Hydrazine
Ammonia
Sodium amalgam
Potassium formate
Glycol
Glucose, etc.

Hydrogen from Reaction with Water
Calcium hydride
Lithium hydride
Magnesium
Boranes

TABLE III—*Fuel and oxidant storage*

fuel	*oxidant*	*possible type of storage*	*kg O_2/m^3 store*	*kg H_2/m^3 store*
Dieso	—	tanks	—	—
Methanol	—	outboard flexible containers	—	110
Hydrogen	—	solid metal hydride	—	10 to 25
	HTP	outboard flexible containers	380 to 490	—
	LOX	cryogenic tanks	100 to 380 (depends on pressure)	—

Alternative Energy Storage

Thermal stores may be envisaged for use when submerged. They require a secondary plant such as a thermoelectric generator or heat engine for power conversion. The heat in the store would need to be replenished by the combustion of fuel in air whilst schnorkelling or using an on-board store of oxidant. In each case exhaust gases need to be discharged. The acceptability of such systems is questionable because of difficulties in managing the storage temperature, and because of complexity and the probable overall size.

The possibility of using a magnetic field produced by a superconducting winding is a conceptual candidate for energy storage. Energy could be transferred inductively and the store would also need to be recharged from a power source using fuel and air or an on-board store of oxidant. Consideration needs to be given to practicable sizes of magnetic fields and the containment of the mechanical forces involved in a high current winding. However, results of initial calculations show that this is not competitive with conventional batteries in terms of power density.

Membrane Technology

The systems discussed so far require oxygen and could possibly benefit in the long term by the development of membrane technology for the extraction of dissolved oxygen from sea water. The concentration and distribution of dissolved oxygen in the oceans depends upon the solubility (which is a function of temperature), salinity, pressure, physical interchange across the air/sea interface, transportation within the oceans, and biological processes. Examples of concentrations of dissolved oxygen in sea water are shown in Figs. 1 and 2. Concentrations above between 3·5 and 4 ml/l are thought to be suitable for the application of an artificial gill. In the warmer oceans there is a gap between 70 or 100 m and 1000 m depth in which the oxygen concentration falls rapidly to a value which is too low for the application of an artificial gill. In the northern Atlantic, a region of particular interest to NATO, the concentration of dissolved oxygen is relatively high down to at least 300 m, varying from 5 to over 7 ml/l.

In order to extract dissolved gas from a liquid it is necessary to expose the liquid to a porous surface such as a semi-permeable membrane which will transport only gas molecules. A large surface area of membrane in a small volume is also desirable thus creating a densely packed separator. Current industrial membrane technology offers products with both these

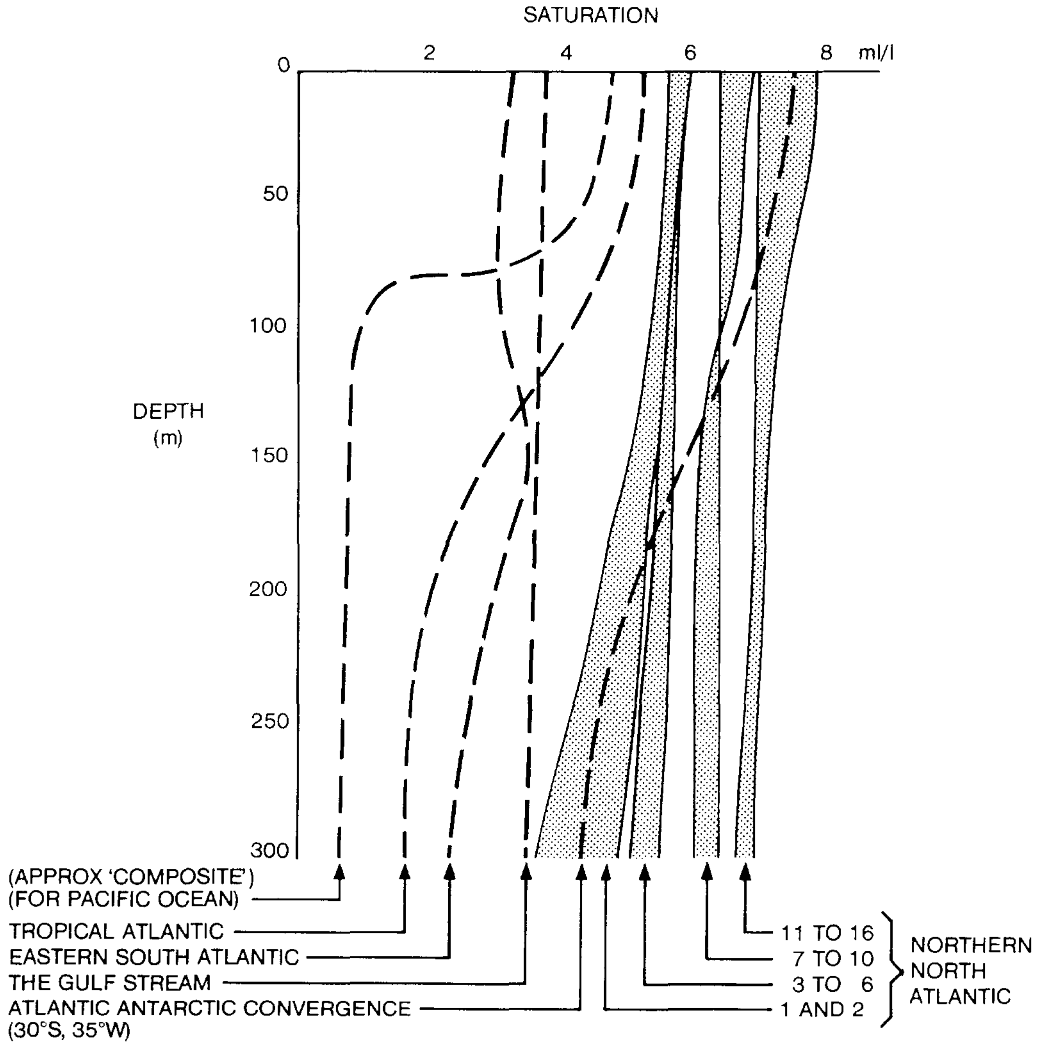

Fig. 1—Average dissolved oxygen in the oceans. The North Atlantic numbered bands relate to areas shown in Fig. 2

based on published information[5,6,7]

FIG. 2—NORTH ATLANTIC, SHOWING LOCATION OF THE AREAS RELATING TO THE NUMBERED BANDS IN FIG. 1

characteristics. Consequently, it is theoretically possible to separate the dissolved oxygen in seawater using an artificial gill constructed of an assembly of microtubes and with a liquid oxygen-carrier. Small systems have been demonstrated in the laboratory.

Estimated sizes for artificial gill systems vary from a few hundred litres for one-man life support to at least an order of magnitude larger for a 30kW fuel cell power system. Power requirements are approximately 0·3 W/kW of output power, i.e. 38W for a one-man life support system requiring about 127W for respiration and 9kW for a 30kW fuel cell. This is at least an order of magnitude better than that which could be achieved using electrolysis. There would be sufficient dissolved oxygen to operate an artificial gill and provide the needs for most of the above auxiliary power supplies (including life support) in areas where the concentration is at least 3·5 to 4 ml/l. However, at present estimated artificial gill system sizes limit their practicable application to small power supplies.

Small Nuclear Power Plant

One system which does not need a supply of oxygen is a nuclear power plant. Nuclear systems for small power supplies up to about 400 or 500 kW electrical output and suitable for land and marine application are being considered commercially and have been proposed to meet Canadian submarine requirements[8]. These plants employ light water-cooled reactors with low pressurization, and power conversion technologies such as an organic Rankine engine are proposed. They also have a relatively small fission rate producing up to about 4 MW thermal output and are designed to provide 5 to 7 years of operation between refuelling.

Comparison of Air-Independent Power Systems

FIG. 3 shows the benefit, in comparative terms only, to the submerged patrol endurance that might be obtained by fitting systems which could be developed now. Lead acid batteries and a small nuclear plant are included for comparison. The endurance shown for the small nuclear plant is determined by the amount of other consumables which could be carried on board rather than fuel and oxidant.

Thus, by a suitable choice of fuel and oxidant a significant improvement in low speed submerged endurance is possible, particularly for fuel cells. As a follow-on to the development of an auxiliary system, a hybrid air-independent system/battery submarine with no diesel engines could be envisaged. The air-independent system would be capable of providing the total power requirements during transit, patrol and for battery charging, whilst the batteries would be used mainly for high speed running.

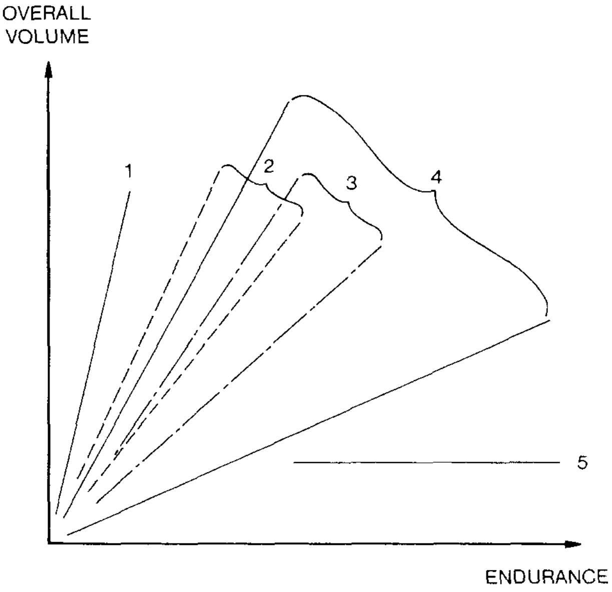

FIG. 3—SUBMARINE ENDURANCE WITH VARIOUS AIR-INDEPENDENT POWER SYSTEMS
1: LEAD ACID BATTERY
2: CLOSED CYCLE DIESEL
3: STIRLING ENGINE
4: FUEL CELL PLANT
5: SMALL NUCLEAR PLANT

Alternative Propulsion

Magnetohydrodynamic (MHD) propulsion systems are being studied commercially, particularly in Japan[9]. Thrust is imparted to seawater in a duct by the electromagnetic force produced by passing current through the water in a transverse magnetic field. Losses due to thermal heating of the seawater, electrolysis, out-gassing, etc., are high and the present overall efficiency is as low as 5% or less. Difficulties may also be encountered in producing a sufficiently large magnetic field over a long length of duct. However, at power levels between, say, 100 and 200 kW the use of high magnetic fields employing superconducting windings operating at a high magnetic flux density might increase the efficiency so that the power could be provided by an air-independent supply such as a fuel cell system.

Studies are being undertaken on both a.c. and d.c. water-cooled machines for ship propulsion to take advantage of possible space and weight savings. Water-cooled motors are already used in some classes of submarines in Europe. Permanent magnet motors, particularly multiphase machines with the magnets mounted circumferentially on the rotor and stator windings supplied from converters, are also a possibility.

Propulsion motors employing superconducting magnetic field windings operating at liquid helium temperature have been studied in the past in both the U.K.[10] and the U.S.A.[11]. The possibility of superconductors operating at liquid nitrogen or even higher temperatures would increase reliability and simplify design both of the machines and of the associated plant for liquid nitrogen, as well as reducing the power level at which such machines might be competitive with conventional designs[10].

Comparison of Motors

Any marine electrical transmission system which avoids gear reduction must achieve torque at relatively low speeds. A criterion which can therefore be adopted is to compare alternative drive motor systems on the basis of their torque/volume ratio. This has been plotted in FIG. 4 in the form of motor power/speed × volume, expressed in kW/rpm.m^3, against power on a log/linear plot for the above motor types plus conventional a.c. and d.c. motors. In terms of torque/power it is seen that conventional machines are not competitive with liquid-cooled or permanent magnet designs, or with machines employing superconducting field windings.

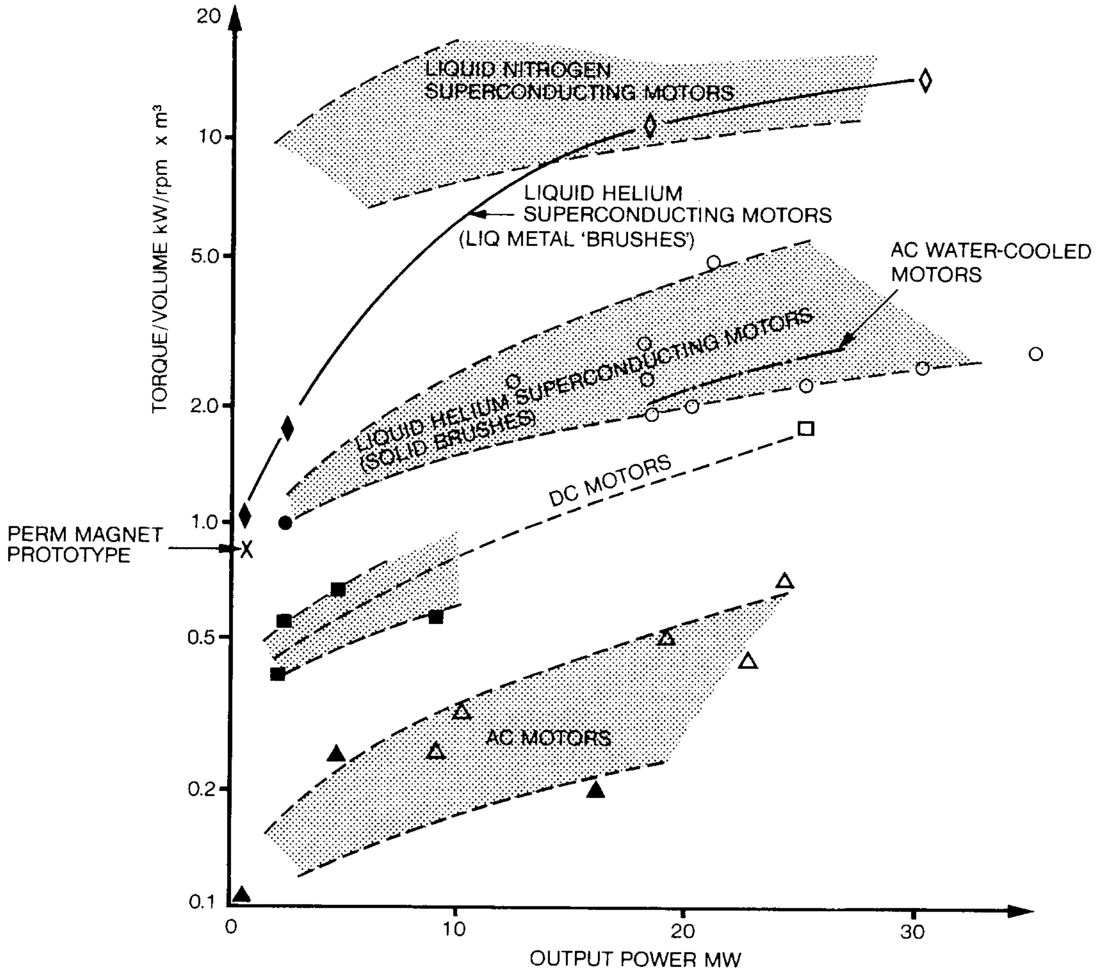

FIG. 4—MOTOR TORQUE/VOLUME RATIO

Closed symbols represent motors already built
Open symbols represent motors designed but not built

Conclusions

Depending on the operational requirements, there are several air-independent power systems that could be developed for future submarine use, e.g. closed cycle diesel and Stirling engine generators, fuel cell systems and small nuclear power plants. All but the last need a supply of oxidant and fuel and would clearly benefit in the long term by the development of membrane technology for the extraction of the dissolved oxygen in seawater. A fuel cell system would give the greatest benefit in terms of reduced noise, highest efficiency and energy density. A small nuclear power plant might be considered as a strong contender but requires an engine for conversion of heat to useful energy.

Savings in space and weight in propulsion motors may be achieved by employing liquid cooling. Further benefits might be obtained by employing liquid nitrogen cooled superconducting machines when materials suitable for power applications become available.

References

1. Macnair, E. J.: The recycle diesel engine for submarines; *Journal of Naval Engineering*, vol. 29, no. 2, Dec. 1985, pp. 398 – 403.
2. Stenberg, P. A.: Stirling power systems for submarines; *Maritime Defence*, vol. 11, Jan. 1985, p. 17.
3. Adams, V. W.: Fuel cells and possible naval applications; *Journal of Naval Engineering*, vol. 29, no. 3, June 1986, pp. 519 – 527.
4. Knaak, K.: A new German hybrid propulsion system: *Maritime Defence*, vol. 11, Sept. 1986, pp. 333 – 339.
5. Friedrich, H.: *Marine biology*. Sidgwick & Jackson, 1969.
6. Riley, P. J. and Chester, R.: *Introduction to marine chemistry*; Academic Press, 1971.
7. Dietrich, G.: *Atlas of hydrography of the northern North Atlantic Ocean*; 1969.
8. Sligl, V. R., Kastner, G. A., and MacDonald, A. G.: An air-independent hybrid nuclear/diesel-electric submarine; *Maritime Defence*, vol. 12, Dec. 1987, pp. 421 – 423.
9. Takezawa, S.: Japanese project for electromagnetic propulsion of ships; *World Congress on Superconductivity, Houston, Texas, Feb. 20 – 24, 1988* (to be published).
10. Appleton, A. D.: The impact of high Tc superconductors upon applications in electrical power equipment; *Proc. of European Workshop on High Tc Superconductors and Potential Applications, Genoa, Italy, July 1988*, pp. 145 – 176.
11. Stevens, H.: The US Navy superconducting ship propulsion motor programme; *World Congress on Superconductivity, Houston, Texas, Feb. 20 – 24, 1988* (to be published).