Centre for International Relations Occasional Paper no. 43

NON-NUCLEAR AIR INDEPENDENT PROPULSION (NNAIP)

By Bernard Goulard

Laboratory of Nuclear Physics
University of Montreal
Montreal, Quebec

March 1992

The author gratefully acknowledges the research support accorded him for this study by the Canadian Institute for International Peace and Security.

Introduction

In a recent document, entitled "Anti-submarine Warfare: Meeting the Challenge," the US Navy (USN) elaborated on the problems of antisubmarine warfare (ASW) in an era of rapidly changing threat.[1] Contrary to similar earlier brochures, all dedicated to the Soviet threat, a great deal of concern is expressed in this one about the emergence of Third World submarine forces and the possible threat to US national security. Relatively low-cost and very quiet submarines (compared with nuclear-propelled attack submarines [SSN]) can be equipped with modern cruise missile and torpedoes, and should in the near future be able to remain submerged for weeks without schnorkel operations by using air independent propulsion (AIP). My aim in this paper is to introduce the reader to these new propulsion technologies.

The first section is dedicated to an historical outline of submarine propulsion. I will show how submersibles of World War II underwent a mutation to "real" submarines with the emergence of the SSN, while more traditional diesel-electric subs kept their utility and their status, especially in Europe. Following that, I give a brief review of the last 20 years to highlight the technical obstacles facing diesel-electric propulsion today. With the goal of obtaining greater endurance at depth, designers have been working with AIP systems capable of operating for extended periods. On the basis of recently revived old technologies (e.g. the Stirling engine, and fuel-cells), research and development of a hybrid concept has occurred since the early 1980s: a conventional propulsion system, which provides high speeds for short periods, is coupled with an auxiliary AIP system that could maintain slower speeds over an extended period. The constraints and criteria of hybrid propulsion I assess in my third section. Following that discussion, I explore the principles and realizations of specific hybrid technologies, notably chemical storage with reducing agent and oxydizing agent coupled with conversion of that thermal energy into mechanical and electrical energy. My final section is dedicated to a comparison between relative technologies.

An additional word is in order here. It would be useful to recall a few elementary notions. The submerged range of a submarine (X) is equal to the product of its submerged endurance time (t) and its corresponding average submerged velocity (V). Time necessary to recharge batteries is another important consideration. Finally, the "indiscretion rate" is the time during which the submarine is back at the surface recharging batteries divided by the battery discharge period. In modern submarines, the indiscretion rate is around 10 percent at 5 knots, 25 percent at 10 knots, and so on. Furthermore, the propulsion of a submarine is characterized by: i) the power acting on the propeller shaft (kw), related to the power of the engine, i.e. to the power density of the fuel and oxydant; ii) the energy density, which has to do with how long an amount of power is acting on the propeller shaft (kwh). While the maximal speed of a submarine is related to its power, its submerged endurance is related to its stored energy. For example, a modern diesel-electric submarine has about 16 Mwh of submerged endurance. At 20 kts, a 3,000 ton submarine needs a propulsion power on the order of 4 Mw.

The Mutation

Since they are no longer in contact with the atmosphere, all submarines must carry their own source of energy in order to operate and travel while submerged. On the eve of the Second World War, the only practical energy source under these conditions was electrical energy, supplied by a series of bulky batteries, which limited deep-dive endurance and speed. On the surface and able to take in the oxygen necessary for combustion, submarines were powered by a diesel engine, which made them fully independent and fast enough to intercept and overtake enemy convoys.

The Germans made the first move toward converting submersibles into true submarines by introducing the schnorkel, which allowed the vessel to operate on diesel power at periscope depth, with an air intake and exhaust system at wave-top level. On the eve of World War II, the German type XXI submarine represented the first wide step toward the true submarine, one capable of high and durable underwater speed.[2] The construction of experimental boats derived from the type XXI led to the development of the first kinds of air independent propulsion systems (a closed-cycle diesel engine with oxygen highly pressurized in air containers, and the Walter turbine with oxygen provided by the decomposition of hydrogen peroxyde, commonly called high-test peroxyde [HTP]). These systems, first to deserve the AIP label, had not reached the operational level by war's end. During the first few years of the postwar period, British and US navies placed hopes in the future of HTP plant propulsion. By 1957, when the Royal Navy definitely opted for nuclear propulsion, it had accumulated several thousands of running hours of HTP systems, aboard the submarines <u>Excalibur</u> and <u>Explorer</u> (the latter was nicknamed "Exploder" in acknowledgement of the power plant's dangerous instability). The USN, using ideas implemented in type XXI U-boats in the design of Tang class submarines, worked for a while on AIP projects based on closed-cycled systems technology.[3] Finally, US intelligence reports in the 1950s suggested that one Soviet experimental submarine may have been powered by a closed-cycled diesel engine, the overall experiment meeting with failure.[4]

In 1954, the United States launched the nuclear-powered submarine Nautilus, thus ushering in the era of true submarines. Energy is provided by uranium which, pound for pound, produces about a hundred thousand times more accessible energy than chemical fuel. Since this fuel also requires no oxygenating agent, propulsion no longer requires contact with the atmosphere. This energy independence, and the conditioning system that regenerates air in the nuclear-powered submarine, give it deep-dive endurance limited only by the crew's stamina.[5] In the following decades, five powers (the United States, Soviet Union, United Kingdom, France, and China) embarked their navies upon a massive long-term commitment to nuclear-powered submarines, leaving aside research and development in the non-nuclear air independent propulsion (NNAIP) technologies pioneered by Germany during WWII.

Some other countries, such as Germany, Sweden, the Netherlands, and Italy--all of whose navies operated in a more restricted geographical context--concentrated their efforts upon conventional diesel-electric submarines, without pursuing NNAIP technologies. The diesel-electric boats are less expensive, easier to manoeuvre, and require a fairly small crew. However, diesel-electric propulsion restricts the ability of the submarine to remain submerged. The battery charge capacity is limited and an oxygenating agent is needed for combustion. On the surface, or schnorkeling at periscope depth, diesel-electric boats are both detectable and less capable of accomplishing their mission. This is why, by the end of the 1970s, demands to achieve a more sustained endurance for submarines triggered a rebirth of studies on AIP in West European countries.

Diesel-Electric Propulsion: Progress and Limitations

In diesel engines, mechanical energy is furnished by the motion of pistons generated by the pressure variations resulting from the air-gas mix combustion. This type of combustion, labelled as internal, is discontinuous and generally incomplete. The diesel engine has the huge advantage of a very mature and worldwide technology. Also, its energy density (12.7 kwh/kg of oil) is high, but its combustion requires oxygen. Batteries do not need oxygen, but their energy density is much smaller. In a battery, which consists in a positive and a negative electrode separated by an electrolyte, the current-causing chemical action alters the electrodes and the electrolyte. The most common battery in use in submarines is the lead-acid battery, characterized by lead-peroxide at the cathode (PbO) and lead at the anode, immersed in an electrolyte made of a solution of sulfuric acid (diluted to about 40 percent). At discharge, both cathode and anode are converted to water. At charge, the battery tends to be restored to its original condition by forcing an electrical current through it. The specific capacity of lead-acid batteries for a 100-hours lifetime has progressed from .003 kwh/kg at the end of WWII to .005 kwh/kg today.[6] Because of the renewal of research and development of batteries technology following a growing demand for autonomous electrical energy, other batteries, more capable of storing large amounts of energy, are being considered and tested with a view to their application to submarines. For example, silver-zinc and sulfur-sodium batteries hold higher energy densities, but each is plagued by specific weaknesses; lithium batteries are being investigated by several groups in the West and teams in the US and UK have been working on a lithium-aluminum-iron-sulfide (LAIS) system for submarine propulsion, which might supersede lead-acid batteries in the future. Beside an energy density as high as possible, qualities expected from batteries are to be durable, inexpensive, and easy to maintain. Shock resistance also is an important criterion. Charging lead-acid batteries increases their temperature and releases hydrogen gas, so that maintenance of these systems requires special precautions.

To illustrate the evolution of diesel-electric submarines, endurances at various speeds of the Oberon-class submarine (obtained by Canada during the 1960s and now discontinued by the UK) and of the Type 209 (one of the most recent diesel-electric submarines) are compared in Table 1.[7]

TABLE 1

Speed (knots)	Endurance (hours)	
	Type 209	Oberon
22	1.0	---
20	1.55	---
16	3.75	1.00
14	6.3	1.66
10	8.2	7.0
8	32.7	11.0
6	60.00	17.0

For periods of time indicated in the right-hand column, the submarine can navigate at the speeds indicated at the corresponding left-hand one without snorting to recharge the batteries, provided that no operation at higher speed takes place during that time. After that period, batteries are down and the boat must snort to recharge. Inspection of the table shows that:

i) Endurance quickly decreases with speed. It is well-known indeed that the thrust power developed at the propeller shaft (Ps) is proportional to the cube of the corresponding velocity (V^3), so that the boat will exhaust its power much more quickly as speed grows. Furthermore, the efficiency at discharge decreases as the discharge rate gets faster.

ii) More recent submarines have a higher performance measured both in endurance and maximal speed. The double-hulled <u>Oberon</u>, compared with the sleek shaped Type 209, has a higher underwater drag coefficient: at a given speed, the power at the propeller shaft is a linear function of that coefficient.

Thus, although significant progress was made in the technology of diesel-electric submarines during the 1970s, for the most part refinements to the traditional propulsion technologies have today reached a kind of plateau, and are unlikely to produce any great steps toward high-submerged endurance.

Hybrid Propulsion: Constraints and Criteria

The "hybrid" systems presently under investigation consist in one AIP system added to a conventional diesel-electric plant. The AIP plant maintains the charge in the batteries while the sub is running submerged. Due to its currently modest power, an AIP plant is mainly effective at low speed. At high speeds, the submerged endurance is governed more by the batteries' capacity. Such a dual system can provide a good engine efficiency covering the entire speed range and can give better range performance, despite its somewhat greater weight.* Thus, the crucial improvement in submarine performance arising from AIP incorporation is a <u>significantly extended submerged endurance and indiscretion rate</u> over a wide range of speed.

i) For <u>speeds lower than Vb</u> (balance speed, corresponding to the maximum power rating of the AIP system, keeping the batteries at their initial charge): the low-speed endurance is tremendously improved over the conventional diesel-electric submarine; the energy stored in the batteries can contribute to the obtention of a maximal low-speed endurance (corresponding to the complete consumption of the oxygen and the battery charge). Furthermore, the submarine batteries can be recharged by the AIP system while the boat is hovering below the sea level.

ii) For <u>speeds higher than Vb</u> (here both the AIP system and the batteries give off power, the shortage of AIP-available power being furnished by the batteries): the speed Vh corresponds to the speed at which both the oxygen and the battery charge are completely consumed.

iii) For <u>speeds higher than Vh</u>: the submerged endurance decreases rapidly with speed but remains higher than for the conventional boat over a wide range; at still higher speeds, the endurance curve tends to merge with the submerged endurance curve corresponding to the batteries, because the contribution of the AIP system to the power becomes negligible.

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*With further improvements, some AIP technologies might prove able to provide demands of submarine propulsion for a full range of speeds and entirely replace diesel generators.

Those improvements of the submarine performance yield much more flexibility to the decision concerning the independent running period of the boat in response to a mission. Operational scenarios (transit to patrol area, submerged surveillance, intercept, trail, attack, and battery recharging) taking advantage of the AIP-related capacities of submarines have been reported in the literature. Among requirements on AIP systems performance, the reduction of the submarine indiscretion rate during transit from its base to the area of operations is more demanding, in both power and range, than the increase of its patrol range in diving conditions at low speed, especially if area of operations is far from the base and if the desired increase of range at low speed in the area of operation is modest. Expectations of navies dedicated to limited operational theatres such as the Baltic are different from those of navies dealing with longer coastlines, such as Australia or Canada.

AIP systems consist in two components, each associated with a set of parameters: i) the <u>energy storage</u>, e.g., mass density and consumption of the reactants: oxygen or, more generally, an oxidizing agent, and hydrogen or, more generally, a reducing agent (a mix of carbon and hydrogen); and ii) the <u>conversion system</u> (transmission efficiency, etc.), which transforms the heat originating from the combination of reactants into electrical or mechanical energy.[8] Electrochemical conversion is carried by fuel-cells of various types, while in thermal conversion, combustion processes convert chemical energy into heat, which then is transformed into mechanical energy, e.g., closed-cycle diesel, Stirling engine, steam or gas turbine. Such an hybrid system is not expected to cover all energy needs of the submarine, especially at high speed. It does <u>not</u>, for instance, provide unlimited underwater endurance, yield the same maximum speed as a SSN or provide the same hotel power as does nuclear propulsion. Requirement to snort is not eliminated.

In their effort to improve the performances of conventional submarines (in other words to close the gap between SSN and SS), designers must use an AIP system based on a mature technology and able to be incorporated into the hull. Then, several constraints must be considered: i) the efficiency of the AIP system must be high enough to limit the growth of displacement due to the extra engine and storage of fuel and oxidant; ii) the detectability of the boat should not be raised by the incorporation of the auxiliary system: the engine mode should not add significantly to the low-frequency machinery noise, nor should the combustion reaction products leave a detectable wake; iii) the operating reliability and safety hazards should be maintained without an excessive manning requirement; iv) logistics (infrastructure, fuel storage on land, and boat landing) should be less demanding than would be the case for a full-nuclear sub[9]; v) the energy conversion leading to waste products must be managed within the small space of the boat, or disposed of in outer sea. In the next section, the various conversion systems will be assessed relative to these criteria.

The development of such systems requires several phases, from the birth of a new concept until its operational use in a navy. A prototype of reduced power is built, then land-based tests are carried on within simulation of a submarine environment, following which sea trials occur. This sequence may require several years, and is marked by uncertainties of technical, political, and financial nature. As a consequence, AIP systems can be retrofitted into an existing submarine, once they are available; however, the distribution of such items as batteries and tanks of the SSK design is probably not optimal for the lengthened submarine. Also a submarine can be designed for delivery as a SSK with arrangements made so as to enable it to incorporate, when the time comes, auxiliary systems to be defined later. A somewhat duplicate design has to be formulated to optimize its performance both as a conventional and a hybrid submarine.

At the present, no AIP system is fully operational aboard a submarine. Research and development generally only started during the 1980s, thus some of these systems should be put into operation by the mid-1990s. Three NNAIPs that have reached the phase of on-board sea trials seem to be near to some technological maturity. One technology is based on the Stirling engine (Sweden); a second is based on fuel-cells (Germany); the third, based on the closed-cycle diesel, is being developed in Germany, the Netherlands, and Italy. Options including an auxiliary nuclear reactor are not treated in the current work.

Storage Systems

A common feature of AIP technologies resides in the storage of oxydising and reducing agents aboard. Volumes and masses associated with such storage are important criteria for the assessment of AIP technologies. These agents are held inside the confined space of submarines and should be resistant to shocks.

Oxydants: Oxygen is generally stored in the liquid state (LOX). This method, which is usually preferred, renders the oxygen into a very compact form but requires a strict thermal insulation to keep liquid oxygen at a temperature a little bit lower than its boiling point (minus $183^{o}C$), i.e. about minus $200^{o}C$. Some companies put the liquid oxygen tanks outside the main pressure hull, others put them inside. The first solution, adopted in

Germany, offers more safety if a leak occurs underwater but leaves tanks exposed to shock waves originating from possible underwater explosions. Further, in the oil-polluted environment of a port, leaks from external tanks might induce explosive consequences. The second solution, adopted in Sweden, yields more complications in the case of a leak occurring in diving conditions. An approach, proposed by the French, is internal storage with a suspended tank, itself located inside a wall of containment; this arrangement, inspired by safety regulations originating from the nuclear industry, presumably increases the cost of storage in a significant way.

Storage of oxygen in a gaseous form is practiced by the Maritalia company, which develops small diesel closed-cycle submarines. Oxygen is stored (at a pressure of 280 bars) in circular pipes welded together and shaping up the hull into a short of "Michelin-man" configuration. Such a system, labelled as GST (Gaseous Storage in a Toroïdal hull), is said to favour internal noise muffling and to hold a much stronger configuration against sea pressure. However, its resistance to shock is seriously questioned by submariners. The prospect of extending these configurations to larger boats imposes the handling and storage of large quantities of highly pressured oxygen in an extremely clean environment.

Use of metal power cells avoids liquid oxygen storage. Hydrogen peroxyde is the oxydizing agent. Even under favourable conditions, H_2O_2 is unstable and tends to be prone to detonating under certain conditions, e.g., impurities, temperature variations, and shock. Its maintenance in the confined atmosphere of a submarine will necessitate the strictest discipline.

Reducing agent: Hydrocarbon fuels, which exist in a large variety, contain about 85 percent carbon and 15 percent hydrogen. The most common types are diesel oil and methanol, and are relatively easy to handle and inexpensive. After combustion, hydrogen yields water (H_2O) and carbon yields carbon dioxyde (CO_2) which will have to be disposed of one way or the other. We shall see later that some conversion systems need reformers to pick up hydrogen from the hydrocarbon fuel.

Hydrogen is a very attractive fuel because its density of energy per unit of weight is higher than that of any chemical fuel. However, storage of hydrogen for application to submarine propulsion presents special requirements: large and heavy vessels, necessary for the storage of compressed gaseous hydrogen, are unfit for submarines. Liquid hydrogen, boiling at minus 253°C, is very cold and extremely volatile;[*] furthermore, the liquefaction process consumes a significant fraction of the energy delivered by the combustion process itself. Metal hydrides have been proposed because they accommodate a high density of hydrogen by volume in a safe way at ambient temperature. The metal-hydrogen system is the chemical analog of a battery, with hydrogen playing the role of electricity. The weak point of metal hydrides resides in a low density of energy by weight imposed by the weight of the associated metal.

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[*] Successive launch postponements by NASA of the Columbia shuttle (May and September 1990) were due to hydrogen leaks noticed during launch preparation. The occurrence of fuel leaks in such a highly careful enterprise illustrates the difficulties associated with the presence of liquid hydrogen in a propulsion system.

Closed-Cycle Diesel Engine

A normal marine diesel engine is open-cycled in the sense that it is in direct contact with the atmosphere, using oxygen to keep the combustion going and nitrogen as a fluid conducting heat. The idea of using a "closed cycle" for diesel engines in submarines dates back 45 years, as I briefly mentioned above. The necessary oxygen is stored on board and the contact of the engine with the atmosphere is suppressed; exhaust gases are recycled at the entry of the engine, with an oxygen addition that keeps combustion going and some inert gas that plays the role of air nitrogen. This system yields a greater fuel consumption since the combustion of diesel fuel requires oxygen (3.5 kgs for 1 kg of diesel), so that consumption of 1 kg of fuel amounts to 4.5 kgs of fuel and oxygen. Use of diesel engines relies on a well-proven and well-known practice; in this case, development work on underwater power plants had been done in the past to meet the needs of the offshore oil industry. However, in application to military submarines, this noisy mode of combustion gives rise to difficult problems of sound damping; pulsed forces on engine structure are imposed by the discontinuous nature of the combustion process. Furthermore, as already mentioned, exhaust combustion gas (CO_2) is produced by the burning of diesel and has to be taken care of; while a combustion engine normally operates under constant pressure, the ambient sea pressure, which rapidly grows with depth (10 atmospheres for 100 metres depth) requires that this exhaust gas be put under enough pressure to be expelled from the boat (or kept aboard) by some mechanism. This circumstance leads to a limitation of the diving depth of the boat.

Since 1986, the German company Thyssen Nordseewerke (TNSW) and the Dutch company Rotterdamse Droogdon Mij (RDM) have been developing a diesel system that could work alternatively in open and closed cycle. They take advantage of a technological breakthrough realized by Cosworth Engineering and a group at Newcastle University, both in the UK. In this method, carbon dioxide in the exhaust gas is dissolved into seawater with a mechanical scrubber (under three bars) and the scrubbed exhaust is recirculated into the engine after addition of oxygen and argon. A water-management unit exchanges the low- and high-pressure dirty seawater and high-pressure clean seawater circuits into low-pressure clean seawater and high-pressure dirty seawater circuits. Loss of energy due to this process, presently of the order of 15 percent, might be reduced to 10 percent. A diesel so equipped has been named the "Argo diesel."[10] Land-based tests upon a 120-kw system for TNSW and 150-kw system for RDM are carried on. A 500-kw prototype is presently under research and development at the RDM laboratories.[11]

TNSW and RDM are currently working on the applicability of such a system to naval propulsion. Here, one of the most arduous problems is the loss of efficiency resulting from the evacuation system of exhaust gas; another difficulty is the high noise level. These companies assume that the incorporation of such a system would typically yield more than two weeks of submerged endurance, at 7 knots, for a 2,000-ton submarine; these numbers obviously depend on other parameters (the capacity of oxygen containers, for example). As far as we can determine, sea trials are not being considered by TNSW yet. RDM plans to test its system aboard the Zeehond, a submarine recently retired from service by the Dutch Navy.

An endurance limitation of these systems (common to other NNAIP systems) is the amount of oxygen that can be stored aboard. Maritalia

Company, which has adapted several diesel engines to closed cycle, relies upon a very new concept, the storage of oxygen in gaseous form. Diesel fuel is carried in ordinary tanks. As it gets used up, oxygen is replaced in tanks by the newly formed exhaust gases. Not being rejected to sea, this does not form wakes which would make the submarines easily detectable.[12]

Two small submarines have been built as prototypes following these concepts. The first small operational military submarine, the "3 GST9" (3 inches diameter for tores and 9 to 9.99 metres for the boat length), was submitted to sea trials in 1988. This 30-ton midget has a 200-nm range at 8 knots. Maritalia, now associated with Fincantieri, has drawn the design for a larger submarine, the "20 GST 48," which should yield a submerged endurance of 4,000 nm at 8 knots, or 8,000 nm at 5 knots, according to those companies. The Maritalia concept has been advertised as a revolutionary step in AIP technology; however, technical documentation is somewhat scarce. Considerations on the scaling up of these submarines from midget to oceanic size yield very optimistic expectations that require substantiation. In particular, the capacity bestowed upon some of these submarines--being able to navigate at a 30-knots immersed velocity for 3,000 miles--implies the availability of 10Mw closed-cycle diesels. Further, oxygen under pressure presents significant fire hazards. The USN plans to undertake technical evaluations and testing of the hull design developed by Maritalia.[13]

The first boat equipped with a closed-cycle diesel engine to go on sea trials may be an ex-Soviet submarine completed in February 1987. The Beluga (as labelled by western navies) looks like the Kilo-class diesel-electric Soviet submarine. If sea trials are successful, the Kilo submarines would adopt this propulsion design.[14] Of course, the recent breakup of the Soviet Union will almost certainly retard, if not terminate, development of the Beluga.

Stirling Engine

In the Stirling engine, the fluid that moves the pistons (helium is generally chosen for its thermal conductibility) is not subject to combustion and stays in a closed volume, divided into hot and cold regions; compression and expansion are accomplished by periodically varying the size of the volume, heating and cooling are accomplished by periodically transferring working gas between the hot and cold region. This accounts for the "external" qualification given to this engine. Absence of admission and exhaust valves makes the Stirling engine extremely silent. Since combustion takes place under high pressure, it is not so difficult to compress exhaust gases before their expulsion from the boat, unlike with the closed-cycle diesel. Stirling engines, equipped with a heat source based on liquid oxygen (LOX) and diesel oil, lead to a high energy density, which compares favourably with that of diesel engines. However, since a Stirling cycle requires both high operating temperature and pressure of the working gas, oil tightness between crankcase and cylinders is difficult to establish, meaning that regenerators, very sensitive to impurities, get less effective after a while. Further, helium, being of a very "leakish" nature, tends to sneak out of the engine. Lastly, the external combustion feature of the Stirling mode requires a combustion chamber surrounding the space of evolution of the working fluid, something that imposes complex thermal exchanges between the hot source and the working gas. The main problem in the development of high-power engines seems to lie in the availability of adequate seals.[15]

Kockums Marine AB, in Sweden, seeks to develop, on behalf of the Swedish government, an underwater propulsion system constituted of a diesel engine recharging the batteries at surface, a lead-acid battery for submerged high speed, and a low-powered and high-endurance Stirling engine (with LOX and diesel oil). In September 1988, Kockums started sea trials involving a complete Stirling system (100 kw) on a 1,100-ton Näcken submarine, originally launched in 1978 and relaunched in 1988, extended by an 8-metre section. Trials, carried on over a one-year period, have shown that the Näcken's submerged endurance was passing from about two days to two weeks; furthermore, engine vibration levels were much lower than those in diesel engines of similar size. The Stirling system will be adapted to the next submarine of the Swedish Navy, the A-19, which is now ordered. Also, the contract of the Australian Navy with Kockums contains the Stirling system as an option for the acquisition of two of the Type 471 submarines. As in the case of closed systems, a scaling up to 600-1,000 kw of the power plant is necessary to sustain an ocean-going submarine propulsion. Kockums is working to develop a 600-kw engine, in collaboration with the German company, MAN ; RDM, which has obtained the Cosworth license for application to the Stirling engine, considers adoption of the Stirling technology as a second step of its R&D program on AIP activities, beyond closed-cycle diesel plants.[16] Mechanical Technology Inc. (MTI), located at Latham, N.Y., claims capacity to offer a 1 Mw (4 cylinders) Stirling.

Turbines

These systems convert the heat gained from an oxygen-fuel mix combustion into mechanical energy acting on a turbine. The high-pressure steam (gas) strikes the blades of the turbine and makes them rotate, and in so doing, expands and lowers its pressure and temperature; the art of turbine design is to get the maximum amount of heat turned into mechanical power. In a gas turbine, the work is made by the thrust of a fluid that never condenses during the transformations making up the gas turbine cycle. Thus, a gas turbine submits a gas to a compression and a thrust, with a reheating between the two operations with the help of the heat furnished by a fuel. In a steam engine, the combustion products do not undergo a thermodynamic cycle; they instead yield most of their heat to the water and its vapor, which constitute the working fluid. That heat transfer is realized by heat exchangers: the separation of the two components--heating fluid and heated fluid--in the steam engine does not hold in the gas turbine.

These two technologies are well known and proven in aeronautics and in surface ship engineering; their reliability is comparable to that of diesels. Further, turbines, which rotate, hold a better acoustical discretion; their main disadvantage resides in low efficiency at low speed.

The German company Mortoren und Turbinen Union (MTU) works on the development of a closed-cycle gas turbine and plans to reach both high efficiency and power (600 kw). Unfortunately, documentation is, to our knowledge, not available and does not enable us to assess the state of advancement of the project. For example, efficiencies are known to depend upon the turbine inlet temperature; however, it is not known when the proper materials (generally, ceramics) necessary to reach those temperatures will become available. At the beginning of 1990, the French company Bertin, associated with the Direction des Chantiers Navals (DCN), started research and development of an underwater autonomous energy module based on a steam turbine named MESMA. The O_2 and H_2 mixture takes place in a small size burner and the combustion products (CO_2 and H_2O) are condensed and separately stored in the liquid state, i.e., in small volumes. Tests on the heating production loop and its coupling with the secondary loop should be completed by mid-1992.

Fuel-Cells

The fuel-cell essentially is a device that generates electric current from a combination of hydrogen and oxygen, or more generally from fuel and oxydiser; fuel goes to anode while oxidiser goes to cathode. Electric current is realized by the electron stream created by reactions inside electrodes. The concept, 140 years old, was implemented in space-propulsion systems in 1958. Since its use in the Gemini and Apollo spacecrafts, fuel-cell technology has been subject to many attempts at use in large-scale earthly applications. It is now expected that in the next decades, fuel cells will take an important part in energy production.[17] Not until the 1980s were naval applications considered. Their efficiency exceeds that of batteries, they work silently, and they do not require rotating pieces or exhaust gases; however, the two reactants of the reaction must be stored in the submarine.

The essence of research and development in fuel-cells technology is to improve the performance of the cell, lower its cost per unit of area, and raise its reliability and endurance. Fuel cells are generally designated by the electrolyte* used in the cell. Alkaline fuel cells (AFC), such as those with potassium hydroxide (KOH), are already commercialized and of possible application in submarines. They operate at about 100°C and can be started in a short time. Because of the electrolyte sensitivity to CO_2, AFC operations require the use of pure hydrogen or fuels from which CO_2 has been extracted; air aspired from schnorkel is not appropriate for bringing oxygen to these fuel cells. Two more types of fuel cells will be operational in the next few years: solid polymer electrolyte fuel cells (SPEFCs) and molten carbonate fuel cells (MCFCs). These fuel cells, which are more compact, accept hydrocarbons (e.g., methanol) for fuel with the help of a reformer that extracts the hydrogen and gets rid of the CO_2. SPEFCs work at about 100°, can be started rapidly, and their reformer is external. They were used for the Gemini program in 1963-65; since then, their membrane reliability and power density have vastly improved and they remain under research and development. MCFCs, which run at 1200°, strip hydrogen from hydrocarbon internally; however, the high temperature would impose a long start-up time to the system. Availability of reformers will

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*Electrolytes can be distinguished by their physical state--liquid or solid--and also by the presence or absence of a solvent. For instance, ordinary salt (sodium chloride, NaCl) can go to the liquid state by dissolution in water at ordinary temperature; each ion Na+, Cl- is surrounded by water molecules, so that electric forces between ions are somewhat screened. Another way of getting a mixture of ions Cl-/Na+ is to heat the salt to high temperature, so that the resulting liquid contains ions. Contrary to the first case, ions are surrounded by similar charge-carrying ions without water-solvating water molecules. Thus, beside diluted electrolytes, molten and solid electrolytes with a higher energy density and a more complex structure are currently under research and development.

eliminate the need for metal hydrides for storage, and consequently of the hydride heating system (which removes gaseous hydrogen from hydrides), as well as of the pipes moving the gas from storage to fuel cells. In any case, implementation of large stacks of those fuel cells--which let hydrogen and oxygen stand close to one another in large spaces--will require a few years of development time in order to design compact reformers based upon a full understanding of heat and mass transfers, and reforming reactions within those systems. In 1989, a German consortium--the SS design firm IKL, the building yard HDW, and the firm FS--started developing a system of fuel cells adapted to an underwater environment; later, in 1983, a system of conventional type coupled with a fuel cell (AFC) was tested on land. The storage of hydrogen was carried through a metal hydride/Ti-Fe-H. In 1987, the U-1 type 205 submarine was equipped with one of those systems during a refit; it has been subject to a ten-month period of sea trials on behalf of the German Navy. Since trials have been considered as positive, a fuel-cell system--a SPEFC designed by Siemens--will be incorporated in the next generation of Type 212 German SS (1,400 tons) which should replace the 205 and 206 SS during the 1990s. In Canada, Ballard Technology develops, in collaboration with VSEL, membrane fuel cells (SPEFC) for adaptation to submarines.[18]

Finally, underwater AIP based on metal power cells might become quite competitive in the coming years if they reach greater efficiencies. Among metals characterized by their capacity to convert chemical into electrical energy, aluminum is especially interesting because of its high energy/mass density. Aluminum batteries were developed by Alcan in 1986 and are used for emergency lighting and for experimental electric vehicles. The tendency of aluminum to form a protective oxide layer was overcome by the use of new alloys that let the current flow. A continuous operation needs a continuous renewal of consumed hydrogen peroxide and a continuous removal of aluminum hydroxide.[19]

Applications to submarine AIP have been recently tackled by Alupower of Canada. Stacks of cells will have to be completed by a system of removal and storage of $Al(OH)_3$ while the reactants to be stored will be hydrogen peroxide and aluminum. For the time being, aluminum power cells are very limited by their power; necessity of hydrogen peroxide storage, which was not so appreciated by submariners of the 1950s, has already been commented upon above.

Comparisons

The previous descriptions of AIP systems have been presented along a specific set of criteria. A recapitulation of those criteria with respective performances of the AIP systems under study would be useful for comparison.

Efficiency: All submarines with an AIP system have to carry the fuel and oxydant required by this auxiliary system operation; this leads to superimposing volume and weight to the boat together with an extra infrastructure, a function of the nature of the added fuel. In other words, beside the energy density of the fuel and oxydant, the energy storage density (which takes into account the storage containers and weight modifications) is a key element in the assessment of a hybrid option. These considerations are basic for comparative studies on the increase of the boat displacement as a function of the submerged endurance for several hybrid options: for NNAIP technologies, the volume of the system (or possibly the weight) depends mainly on the energy to be stored, i.e., the number of kwh. Closed-cycle diesel and Stirling systems hold a better efficiency than fuel cells fed by hydrogen originating from metal hydrides. This results from the very heavy storage imposed by the use of metal hydrides, despite the very high energy density of hydrogen. Use of hydrocarbon improves the performance of fuel cells able to use a reformer.

Reliability: Diesel closed-cycle systems and steam and gas turbine systems as well enjoy a high reliability because of the well-proven nature of diesel technology. Stirling engines, because of tightness problems, are reliable on operations of relatively short duration, to the exclusion of long-distance operations. Fuel cells equipped with reformers pay for their better efficiency by a lesser reliability imposed by the overall complexity of the MCFC and even more the SPFC. These problems might be subject to improvement coming from the various R&D efforts around the world.

Safety: Storage of oxygen, hydrogen, and H_2O_2, in a confined system, always calls for precautions, whatever the energy conversion system, as mentioned earlier. Good marks are bestowed to storage-conversion systems based on hydrocarbon fuels and small burning subsystems, in other words, those where oxygen and hydrogen hold a minimal probability of getting mixed. Thus, development of reformers and spread of hydrogen-moving conduits should be looked after in the coming years.

Brief Comparison with Hybrid Nuclear Options: Nuclear naval propulsion does not necessarily mean high power (several Mw). Hybrid nuclear options presently under research and development are correlated with a small auxiliary reactor (less than 2 Mw) and draw practically unlimited endurance (many Mwh) from the extremely high energy density of U-235. In such hybrids, the increase in displacement comes from shielding and not from the quantity of nuclear fuel. This nuclear option might supersede NNAIP options if introduction of nuclear technology at a lower power output carries much milder requirements (e.g., safety, manning, and logistics) than those attached to full nuclear submarines.

Future

Review of the domain of chemical AIP technologies seems to distinguish two families of submarines:

i) Coastal submarine: its submerged displacement lies between 1,000 and 1,500 tons. Its expected performances, about 200-300 kw, make transits only possible at very low speed and increase range in the operational area provided patrol speed keeps low. The Näcken, endowed with two 75-kw Stirling engines, providing a 5-knots speed and hotel load for a three-weeks submerged mission, is a successful example. The Baltic has a very limited area, which makes snorting submarines easy to locate and so constitutes a well adapted theatre for such subs.

ii) Ocean-going submarine: oceanic submarines with a higher auxiliary power (around 1 Mw) and with a 10-12 knots transit speed. Realization of such boats is more remote. The above-reviewed chemical AIP technologies are still subject to too many uncertainties to provide a high level of performance in this submarine environment. Despite these uncertainties, NNAIP technologies are likely to become increasingly important.

Indeed, NNAIP technologies are not limited to auxiliary systems for diesel-electric submarines. In the military domain, diesel-emergency propulsion systems aboard SSNs could be advantageously replaced by an NNAIP system, either a closed-cycle diesel engine or fuel cell. In case of a breakdown of the nuclear reactor, such emergency systems could take over while the boat remained submerged. Also, underwater vehicles (AUV) that need an underwater endurance in the order of 2 to 10 Mwh--much more than a torpedo--for a power range of 20 to 50 kw, are expected to play a significant role in future naval operations. Extensive R&D programs on these propulsion systems are being conducted, particularly in the United States. In the civilian domain, scientific operations that involve long underwater operations can benefit from the endurance brought by AIP systems. For example, Saga 1, a 500-ton manned submersible being developed by a French-Swedish collaboration, is powered during submersion by two Stirling engines of power up to 75 kw. Oxygen (LOX) storage allows the submersible to remain under the surface for up to 14 days. AIP would also give large submarine tankers the capability of shipping extensive loads of merchandise between the Northeast Asian coast and North Atlantic ocean ports, via the Arctic Ocean under the ice. Technological perspectives look attractive enough to justify commercial feasibility studies.[20]

To conclude, emerging NNAIP technologies are bringing diesel-electric submarine-endurance capabilities closer to those of the SSN, at a comparatively low cost. This evolution is associated with: i) advances in other key technologies, such as weapons systems (e.g., antiship cruise missiles and modern mines);[21] and ii) the growing capability of submarine acquisition and production by Third World countries.[22] As a consequence, the navies of regional powers should be able in future to conduct quiet submarine operations for extended periods of time. Emergence of the post-Cold War era, which blurs the traditional East-West polarization, will enhance concerns of Western countries about these newly acquired capacities of regional powers. The US Department of Defense has already referred to AIP proliferation as similar in nature to the more "traditional" nuclear, missile, and chemical proliferation threats.[23] Finally, and on the positive side, it is hoped that thanks to the easing of East-West tensions, AIP technologies might play a new role in both scientific and commercial ventures in a more peaceful world.

Notes

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