Prospects for Superconducting Systems in Military Submarines

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What follows is a summary of proposals for the building of deep-diving, nuclear gas turbine powered, electrically driven submarine embodying an all integrated superconducting system, ranging from generators and motors to electronics, computers, navigation and air-purification systems. All systems are critically reviewed from the points of efficiency, weight, volume, noise and heat emission, with special reference to other prominent characteristics. Finally, a suggested deep-diving configuration of a small missile submarine is presented in view of the prevailing strategic requirements.

Introduction

THE need for an effective defense in lieu of expensive ABM options dictates the use of many, small, deep-diving and quiet-running submarines. A defense system has to be mobile, silent and inaccessible to the attacker. The following discussion blends and outlines strategy and deep-submarine possibilities by approaching the topic from the unusual angle of the very promising superconducting-state technology, always bearing in mind that the abyss challenge has to be taken on early enough to yield returns when mostly needed, in the future. There is a strategic requirement for the control of the ocean bed. Deep-diving military submarines have to be developed with advanced outer-space methodology employed from their design conception. Performance priority is given over cost, with sole criterion the weapon delivery capability for equal destruction potential. MIRV warheads, second stage of development, should be adopted for these vehicles, with an eye on the stringent payload and volume limitations.

The importance of strategic submarine technology has been the subject of many ariticles in recent years.[1–9] 1) Attention has been focused on their weapon carrying capability and the U.S.'s intention of replacing the Polaris missiles with Poseidon. 2) Major naval powers are developing more effective Antisubmarine Warfare (ASW) techniques. Now, the constant surveillance of the submarine's technological parameters, and the threat imposed by the Soviet navy [including a Nuclear Submarine (NS) build-up of around eight per annum] have encouraged the exploration of the possibilities for adoption of advanced types of powerplants and review the intersubmarine systems.

This short paper will state these new possibilities, namely the adoption of High Temperature Gas Cooled Reactors (HTGCR's); the integration of the Gas Turbine (GT) within the reactor pressure vessel; and lastly develop at some length the advantages of an excessively integrated Superconducting Electric System (SES) within the submarine.

Currently, the most common reactors employed in the NS's are of the Pressurized Water Reactor (PWR) type which offer good reliability and were the first to be developed for naval use.[10,11] Their practical efficiency lies between fifteen and twenty-eight percent with maximum expected in the near future of thirty percent. By comparison the HTGCR's of today, with their better powers for electrical generation, allow efficiencies approaching forty-two percent.[12–18] A HTGCR can use its coolant to directly drive three to six or more GT's integrated within its pressure vessel circumference, and therefore do away with the need for two heat-exchanger groups and the duplication of other bulky equipment currently used in the PWR designs. Rolls-Royce has already studied and proposed this configuration, while various U.S. and European companies are well advanced in its development.[19,20] Helium and Carbon Dioxide gases are currently favored by the majority of producers.[21]

Major NS design considerations met by the HTGCR's are: a) much higher power to volume and power to weight ratios; b) simplicity, particularly in maintenance and inter-changeability and c) cost, which for a given rating will be initially comparable to the naval steam turbine geared PWR's, but should subsequently fall because the HTGCR's have an inherent capability for improvement in capacity, as their operational temperatures rise, which is not matched by these PWR designs. Other important advantages of this type of reactor include: low inertia/high response to the reactor load variations, damage resistance capability, (individual Nuclear Gas Turbines, NGT's, can be isolated, in event of a failure, the reactor remaining operational) a fail safe characteristic, reactor load stability in all axes of movement and the ability to attain close to maximum efficiencies at part load levels. The last property will substantially improve the operational economics of the NS.[22–24] Figure 1 shows a section of a 90 mw max continuous power marine HTGCR arrangement suitable for the deep-diving submarine proposed later. The NGT's are contained in the periphery of the reactor pressure vessel and it is possible to remove and service them separately from the top without affecting the operation of the reactor. The upper part of the NGT is the HP section, while the lower part, the LP, close to which the power output is located where an emerging shaft will be coupled to a Superconducting Electric Generator (SEG) sited directly underneath. A small auxiliary cryogenic inverter compartment could be conveniently located directly underneath the reactor main base. The pressure vessel is firmly secured against violent motion circumferentially along x_1x_1 which is in turn connected to the upper floor of the reactor compartment. Figure 2 shows the reactor plan along section x_1x_1, here the 6 NGT's each rated at 15 Mw cont. power, can be seen along with their auxiliary systems all independently coupled to the reactor core. Finally Fig. 3 illustrates a section x_2x_2, along the reactor base, the six 15 Mw cont. rating SEG's are seen along with the auxiliary cryogenic inverter compartment and the fixed circumferential base supports allowing easy SEG

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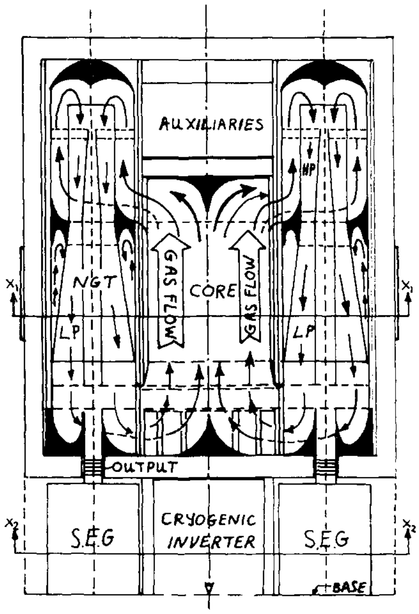

Fig. 1 Section of 90 Mw gas cooled reactor with integrated gas turbines to drive six superconducting electricity generators positioned below its base.

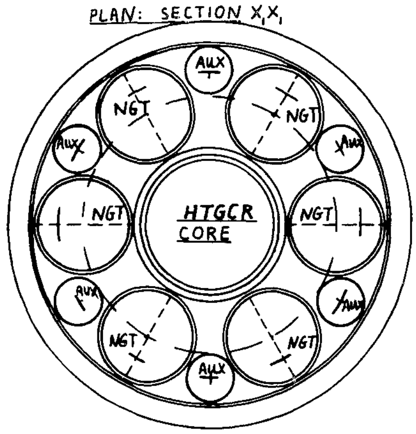

Fig. 2 Gas cooled reactor plan along section x_1x_1 showing the gas turbines and auxiliary arrangement.

access for maintenance purposes. Leaving now the reactor proposals, let us examine the electric systems of a conventional submarine and then extrapolate our conclusions in the field of the advanced nuclear types.

Superconductive Electric Systems in Perspective

Most of the conventional submarines of today are of the diesel electric type. As a consequence, they characteristically suffer from insufficient speed and endurance as well as inadequate depth penetration. The inability to use air-breathing prime movers under submergence has led to the adoption of electric powerplants driven by rechargeable batteries which could be replenished when the submarine was surfaced. Traditionally, electric drives offer advantages such as small shaft length, elimination of reduction/reversing gearboxes or need for a variable pitch propeller and very low noise emission. However these are accompanied by setbacks such as power inadequacy, high weight and cost, low efficiency (up to 93%) and increased heat emission,[25] but were accepted for naval submarine powerplants for lack of another viable alternative. Present day advances of ASW technology make the above mentioned drawbacks intolerable. The development of the NS has gone a long way towards solving the aforementioned prime mover deficiencies, but subject to a heavy financial penalty, leaving ample scope for developmental effort towards improving the system's effectiveness.

What follows envisages a novel technology of all integrated components, using a very low temperature common circulating medium applied to a deep-diving submarine. Both nuclear and conventional submarines could benefit from this proposal and overcome all present major technological obstacles, although it is appreciated that greater returns can be predicted for sophisticated NS design applications.

SES or SElectricS derive from the fact that at very low temperatures electric components exhibit negligible resistance to the flow of current (become superconducting). This property, when applied to the engineering of motors or generators, enables them to work under very high magnetic fields and currents leading to substantial advantages in every aspect of their performance.[26–28] A brief summary of the expected features for a given rating includes the following. 1) Volume reduction by at least 80%. 2) Weight reduction by over 85%. 3) For equal volumes, very high powers are now available with impressive torques at low rpms. 4) Efficiencies topping 98% are now available equalling those of mechanical systems. 5) Noise is further reduced and heat emission eliminated. 6) Initial cost for the machinery is cut by at least 40%. 7) Now, there is ample scope for design innovation.

A design innovation could, for example, incorporate a simple annular Superconducting Electric Motor (SEM), embedded in the submarine's pressure hull, driving two ring contra-rotating propellers through contactless (magnetic bearings) reverse polarity drives following the linear induction motor principle. Such an arrangement will a) completely eliminate shafting and consequently any hull openings; b) the diving limitations are now shifted towards the structural crush-depth capability of the hull; c) substantially improve propeller efficiencies and, d) reduce the propeller noise through lighter loading, a tactical advantage to consider where detectability is of vital importance. Figure 4 shows detail of the Selectric propulsion motor for the proposed submarine described later. The motor windings are immersed in low-temperature helium and are insulated in an arc of 270° via a superconducting shield contained in the same cryostat, which allows the magnetic field to escape only radially outward. The cryostat is mounted on insulating pads which are in turn supported on the reinforced motor casing. The propellers are made out of two 180° segments joined together and allow a small clearance between stator and rotor. This gap will be free-flooding, with seawater acting as lubricant. PTFE bearings are inserted at equal intervals on the thrust blocks to take any sudden propeller

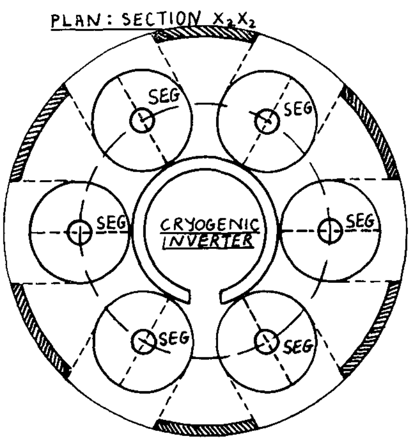

Fig. 3 Gas cooled reactor plan along section x_2x_2 showing the six superconducting electricity generators and the cryogenic inverter.

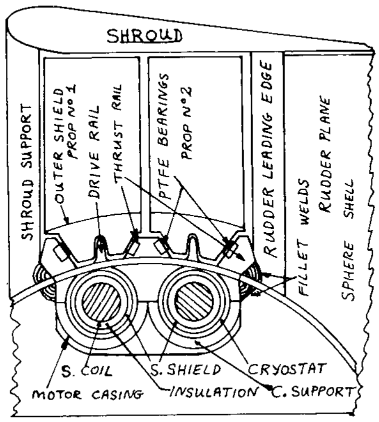

Fig. 4 Detail of the superconducting electric motor rated at 80 Mw to drive two contrarotating propellers.

load fluctuations. The rotor position is maintained by the stator high magnetic field which keeps the rotor under uniform compressive load. The electrically charged drive-rail is located in the middle of each propeller footing and is covered to a considerable depth by an outer shield aimed to reduce the intensity of the remaining escaping magnetic field. The two contra-rotating propellers are masked by a shroud filled with syntactic foam so as to increase their efficiency and reduce noise dissipation. The stator outershell is part of the encasing sphere occupying the area close to the diameter. On fabrication the two "hemispherical" ends are welded on the motor assembly with multipass welds as shown in Fig. 4.

An alternative propulsion mode is the SElectric Magneto-Hydro-Dynamic (MHD) Liquid Induction Pump (LIP) which has no moving elements. Large powers can be efficiently delivered through a wide speed spectrum at high magnetic fields using d.c. current. Areas where development is necessary are 1) availability of better superconductors to generate higher magnetic fields; 2) variable speed operation control and coil protection; 3) exhaust noise minimization attributed to pulsating ionized water mass; and 4) dewar and cryostat optimization. The MHD–LIP can be mounted axially or on pods following standard aeronautical practices.[29]

Compact SEG's are also conceivable[30] and could be designed to operate at higher rpm's and be directly coupled to either a NGT, or a high speed diesel output. Reference 31 supports this view and suggests that a 13.5 Mw (18,000 shp), SEG could weigh as little as 3050 lb having a volume of 17.2 ft^3. It concludes that for the examined 18,000 shp marine powerplant the weight of the superconducting transmission is 2.72 times lighter than the equivalent geared system.

Electricity transfer throughout the hull is to be affected by the use of cryogenic transmission pipes.[32] Cryogenic equipment efficiency is expected to increase as research in this field is intensified while superconductor operating temperatures will rise from the present useable level of approximately 3.6° K to close to 20° K.[33] Recent research indicates that superconductivity could be induced to take place at higher temperatures through subjection of the superconductor to elevated pressures.[34] Ocean depths can thus be used to a considerable advantage once pressure sensitive superconductors are developed. Any such temperature increases will more than halve operational costs, saving in refrigeration power requirements. Figure 5 shows the evaluated refrigeration cost as a function of temperature. A comparison between the present and future operational temperatures of superconductors with no sacrifice in performance illustrates the drastic reduction of operational costs.[35]

Piping cryo-fluid outside the engine room will have the following applications: 1) All electronic components can be immersed in it, using microminiaturization techniques, with consequent improvement in performance, volume, weight, and cost reduction for a specified capacity.[36] 2) Cryo-computers will benefit also, volumes shrinking to a fraction of today's equipowered units or, given an equal volume, storage capacities could be increased by at least two magnitudes, access times being bettered, with lower initial and running costs per given capacity, while generating no heat at all. Figure 6 allows a comparison between the economics of magnetic and low temperature computer memories.[33] The advantages promised by the cryo-computer technology are striking. Specifically, a 100,000 Kilobit memory with a cycle time of one μsec, at a cost of less than 0.1 pence per bit, is feasible while by employing the newly discovered tunneling cryotron logic device nanosecond logical operation of the circuit could be attained.[33,36] Large capacity computer applications aboard a NS will be of paramount importance and will be used to a) check and monitor equipment performance; b) optimize tactical and routine maneuvers; c) carry out ocean-contour plots and prepare for sonarless, blind, navigation; and d) work in conjunction with cryo-gyros, with drift rates of less than 10^{-2} sec of an arc per year and read-out systems capable of detecting less than 10^{-2} sec of an arc without disturbing the cryo-gyro, to ensure both exact position fixing as well as weapon delivery. The read-out uses an extrasensitive magnetometer which has superconducting inductors and modulator and is capable of detecting 10^{-13} Kgauss.[33] It is also obvious that sonar navigation

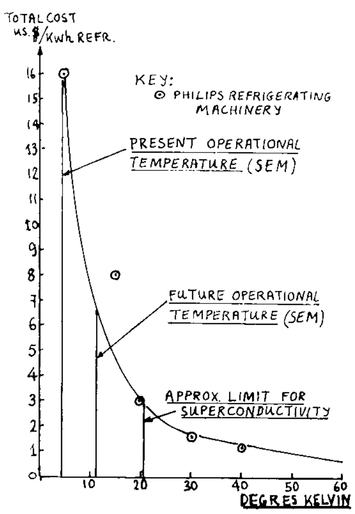

Fig. 5 Cost of superconductor refrigeration with present and future trends.

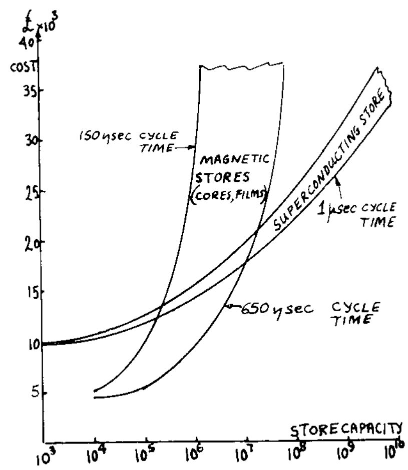

Fig. 6 Comparison between the costs of conventional and low-temperature computer memories, from Ref. 33.

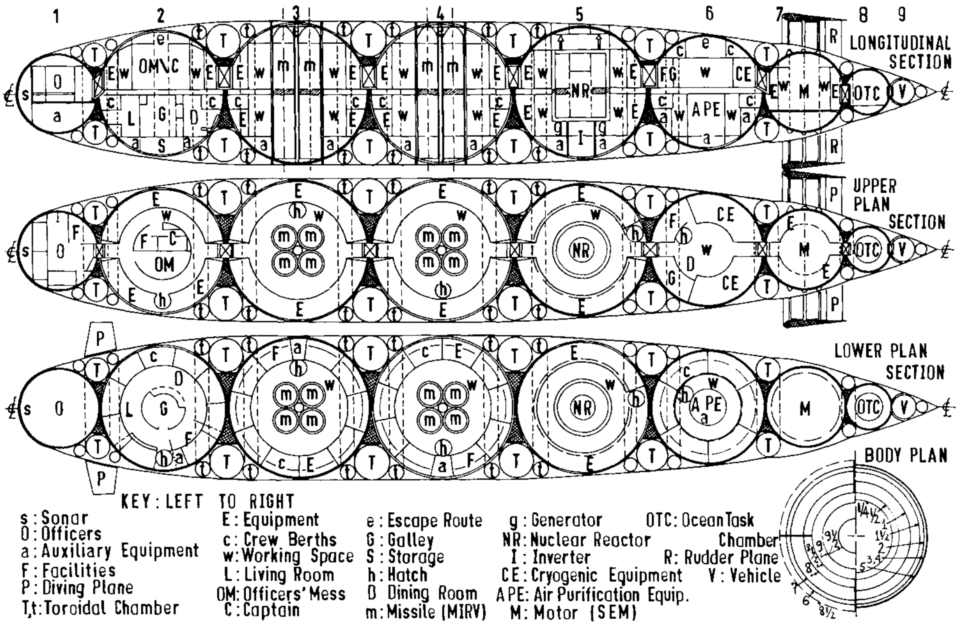

Fig. 7 Schematic outlay of deep-submergence missile submarine employing integrated electric superconductor technology.

could improve in accuracy and range using superconducting components while laser emitters/range finders, working at superconducting temperatures, could supplement their functions.[36] 3) Air purification systems can benefit from the abundancy of cryo-fluid, increase their efficiency and reduce their volume and running cost,[37] while one could anticipate crew reductions to be accomplished through radically increased automation.

The above considerations, if properly exploited, will open up new fields for innovation and advancement in submarine design. If an effort is made to build smaller NS's with equal weapon capability by employing improved or novel materials' combinations in their construction, there is no reason why the military influence of a nation should not extend over the sea-bed. Presently Maraging steels of tensile strength of 180,000 psi have been successfully used in the construction of a submersible,[37] while steels approaching 300,000 psi are thought feasible. Employing these for the construction of the pressure spheres of the deep-diving submarine described below in conjunction with a nonmetallic steamlined body having integral low-density syntactic foam for additional buoyancy as well as giving good thermal/sound insulation will enhance the vehicle's passive defense capability. On the other hand, physical and structural behavior of these materials under service conditions has yet to be determined.[38]

Refer to Fig. 7 now. As seen in the longitudinal and plan sections the proposed submarine is a series of interconnected spheres or compartments allocated specific functions and numbered from one to nine. Spheres 1,7,8 and 9 have only one level the rest having twin. Access between compartments is through double, valve-type, airtight, pressure compensating doors. In an emergency each sphere is capable of being self-sustaining and has its own escape route. All wiring and cryo-fluid is piped along the middeck in pressure resistant pipes. Triple circuitry is thought necessary for safety. The crew is best accommodated in the lower segments of the spheres numbers 2,3,4 and 6, close to the major diameter, with space reserved underneath for various functions. Single hatchways connect upper and lower sphere segments. The sphere connections are engulfed by large, reinforced plastic, toroidal chambers T, each segmented into two halves; upper and lower, with spherical, pressure resistant, separations between them. The upper halves act as variable buoyancy chambers while the lower segments are free-flooding and contain equipment of low access bility requirements; this arrangement ensures inherent stability and good maneuvering characteristics. The smaller toroidal chambers t are employed similarly as necessary. Inspecting the vessel from nose to tail the following points can be raised. Chamber number one can accommodate six officers O with facilities F; it contains an obstacle avoidance, vertical and horizontal clearance sonar s mounted at the nose, with ample space reserved for supplementary auxiliaries a at below floor level. Chamber two constitutes the command section. The upper part contains all superconducting electronic equipment E relating to navigation, control and communications as well as cryo-computer installation. The captain's quarters C and officers' mess OM occupy the central sector. The lower part is used for crew accommodation c with facilities, living and dining rooms L and D, and catering G, for the whole crew. Storage S and auxiliaries' space is provided at below floor level. Spheres three and four constitute the missile section; eight MIRV warhead missiles m are contained in separate casings. The majority of electronic equipment is mounted on the upper floor, the auxiliary and launching gear being distributed on the lower, under the crew berths. Eight crew and two officers are allocated in each sphere. Rearmament under submergence is specified as necessary. Sphere five contains the reactor shown in Figs. 1–3 with all the associated equipment for control, maintenance and routine repairs, the lower segment having the six SEG's, g, surrounding the cryogenic inverter I. Sphere six contains the cryogenic and purification equipment, CE and APE, in the upper and lower sections; additionally the upper hemisphere has a small galley and dining space plus facilities, for the six engineering crew accommodated below. Three officers occupy the space above the upper floor working area. Sphere seven contains the SEM described in Fig. 4 with all ancillary equipment. Sphere eight is the Ocean Task Chamber, OTC; it is essentially a decompression chamber equipped with tools for carrying out ocean engineering military tasks in conjunction with the vehicle V, number nine, which is electromagnetically mating with the OTC. Its functions range from inspection/repairs of the mother ship to scouting new territory. Additional submarine particulars are: length over-all 64.0 m, maximum sphere diameter 10.0 m, displacement 3600 tons, appendage maximum diameter 11.0 m and design diving depth 4500 m.

It will be possible, at the preliminary stages of the systems, performance evaluation, to convert conventional submarines to carry SES. This will simplify the introductory step while improvising for the essential initial elimination of any minor problems.

It is known that the United States Navy has already embarked upon the building of the costly deep-diving silent submarine employing novel technology, while the U.K. Department of Defence is reported to be sponsoring the International Research and Development, Ltd. effort towards developing the SEM with all its evident advantages and follow-ups. Already a 3250 hp SEM has been installed at the Fawley power station for continuous evaluation.[39] The proposed concept of the NGT powered, completely integrated, SES, deep-diving, cheap submarine should be highly effective both in operational and defense fields if it is seen in the context of potential development and subsequent returns. Due to demands imposed by technological lead-time, not only insight, but advanced forecasting is vital to facilitate successful policies for the future. The procurement of advanced systems demands mastery of the principles involved, as much as good coordination of effort and sharing of common knowledge among designers and potential customers. The drive for control of the ocean bed was slow to start because the means for exploitation was lacking, although in the close foreseeable future, technology will provide wider opportunities. Commercial concerns are becoming increasingly aware of the offshore prospects and governments are bound to step in. Underwater conflict is not altogether a remote possibility[2,9] given the present loose legislation prevailing among the nations of the world. The deep-diving submarines are a must for the navies now, and these will generate the security and know-how for the commercial large scale utilization. The above proposals express the author's opinion and it is believed are within our present technological capabilities supported by deep-submersible operational experience. The cost of materializing such projects is undeniably enormous; but aren't the other options costlier and their returns potentially lesser in value? This is the issue.

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