HIGH TEMPERATURE SUPERCONDUCTORS AND MARINE POWER APPLICATIONS

BY

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(*Sea Systems Controllerate*)

ABSTRACT

This article introduces high temperature superconductors and then reviews the implications for possible marine power applications, assuming that the future development of materials with the required properties is possible. Except for a d.c. fault current limiter, the applications derive from the use of superconductors to provide high magnetic fields and would require materials to operate at high current densities in high ambient magnetic fields. Other important applications in the electronics field, involving films, are not included.

Introduction

> It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts. ('A Scandal in Bohemia', from *The Adventures of Sherlock Holmes*, by Sir Arthur Conan Doyle[2])

Notwithstanding the lack of data for practicable systems, the desire to speculate on potential applications of a new discovery is almost overwhelming. The discovery in 1986[1] of new high temperature superconducting copper oxides, for which the discoverers received a Nobel Prize in 1987, started a world-wide search for related compounds with higher critical temperatures than known hitherto, and many speculations on potential applications. Since then, thousands of papers have been written in this rapidly developing field. For the stout-hearted with a bent for physical chemistry, the recent book by Phillips[2] is the first 'to cut a well-marked path through this jungle . . . by highlighting . . . the most important experiments'. The history of progress in raising the critical temperature (T_c), at which the onset of superconductivity or zero electrical resistance occurs in materials is indicated in FIG. 1 and poses the question 'Where next?'. The accepted theory for superconductivity in elements and binary compounds and many alternative theoretical mechanisms proposed so far for quaternary and higher compounds are unable to explain critical temperatures of the order 100 K.[2] Hence, on theoretical grounds an upper critical temperature for superconductivity has yet to be determined.

In practice the superconducting state of materials is bounded by three parameters, a critical temperature (T_c), a critical current density (J_c) and a critical magnetic field (H_c), below which the material is superconducting (see FIG. 2). The superconducting state is characterized by zero electrical resistance and perfect diamagnetism, i.e. a magnetic field is totally excluded from the bulk of the material as the result of the opposing field generated by the superconducting current.

A review of known superconducting materials[2] lists 575 superconductors, including elements, with $1 \text{ K} < T_c < 10 \text{ K}$ and 60 compounds with $T_c > 10$ K. There are now many compounds with T_c above liquid nitrogen temperature (77 K), most being substitutional variants of the Y Ba Cu O and Bi Sr Ca Cu O materials where the first constituent has been replaced by another element.

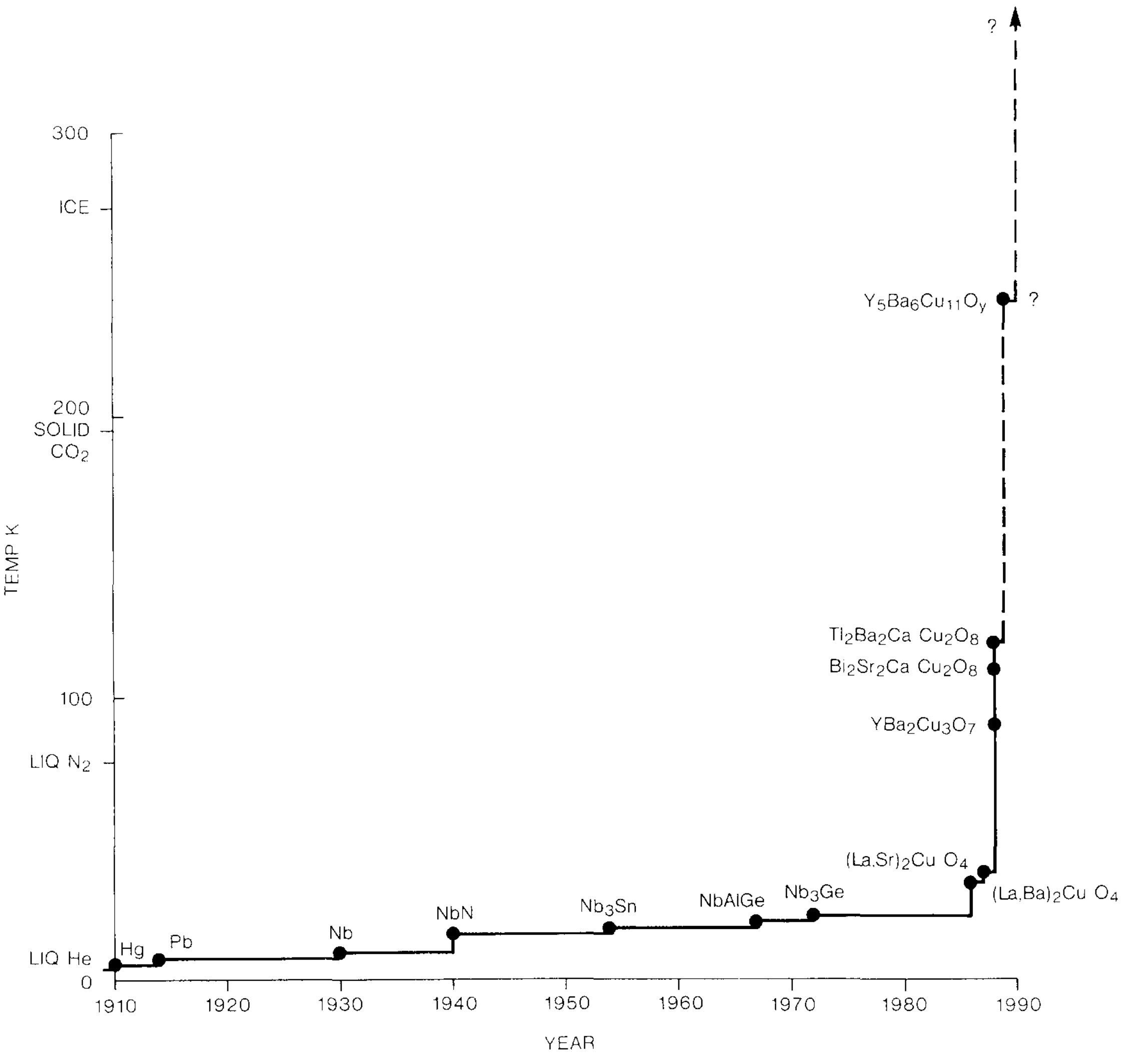

FIG. 1—MILESTONES IN SUPERCONDUCTOR CRITICAL TEMPERATURE

Phillips[2] notes that there are three widely observed general patterns in superconductors:

(*a*) The critical temperatures of elements or compounds containing transition elements are generally higher than those with non-transition metals.

(*b*) Binary compounds can have significantly higher critical temperatures than elements. A simple explanation for this is that there are more binary compounds than elements. If this is correct then still higher temperatures should be found in ternary, quaternary and higher compounds, which until recently (see FIG. 1) had not appeared to be the case. However, since only 7200 true ternary compounds are yet known compared to 15 000 binaries, this second supposition may be correct. In practice, the higher the T_c, the more unstable the material, and among 100 000 possible ternaries and higher the ones made so far have been preferentially prepared[2]. The material with the highest claimed T_c to date (240 K for $Y_5Ba_6Cu_{11}O_Y$ (see FIG. 1) requires, unlike the other high T_c superconducting copper oxides, maintenance of an oxygen atmosphere to sustain the zero resistance transition[3]. It should be noted that this result has yet to be reproduced elsewhere*. The authors claim

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*As of March 1990 this situation still persists and consequently the validity of this result has been doubted.

that, since the observed effect is from a minor phase, the conditions must be right and that samples can be easily damaged by rapid changes in electrical current or rapid cooling.

(*c*) High T_c materials have high symmetry, especially cubic symmetry. However, this principle may be less useful in the search for materials because it is much easier to test for superconductivity than it is to determine crystal structure[2].

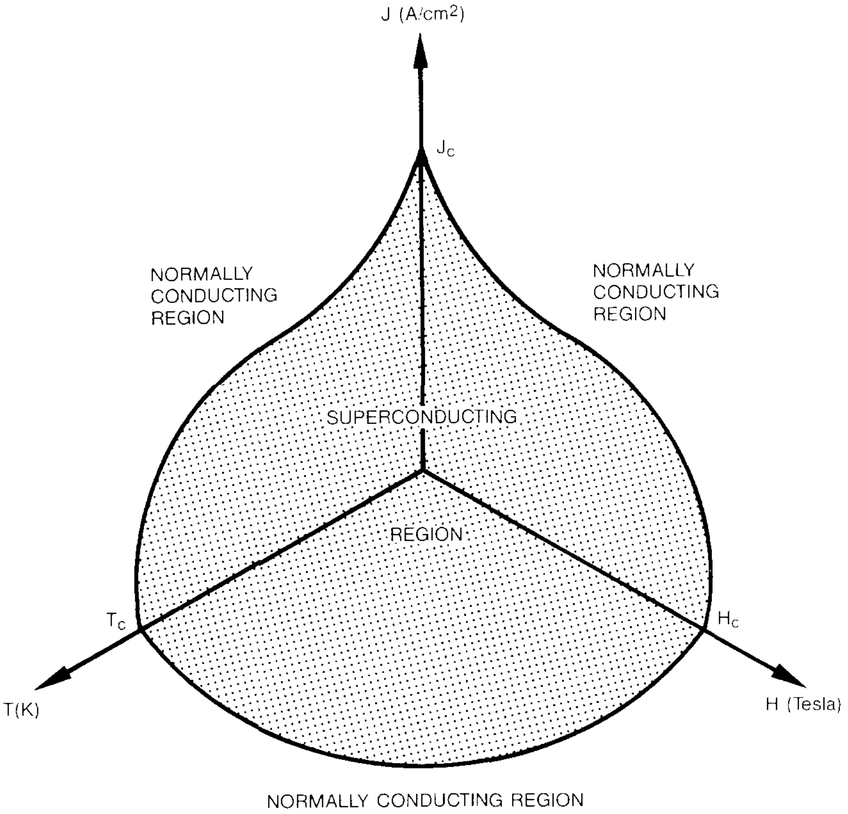

FIG. 2—CRITICAL TEMPERATURE, CURRENT DENSITY AND MAGNETIC FIELD FOR SUPERCONDUCTORS

Superconducting Copper Oxides

The new class of superconducting copper oxides, some of which are shown in FIG. 1, are ceramics and are prepared by annealing in oxygen. Historically, they have evolved from materials related to the perovskite (a mineral) family, ABO_3, which can have a cubic, tetragonal or orthorhombic crystalline structure. It is the presence of planes and chains containing the copper oxides CuO_2 and CuO in the structure which is believed to contribute to their superconducting properties, which are anisotropic. The problems of manufacturing forms suitable for practical applications from materials with a crystalline structure, which form grains, are actively being pursued world-wide.

Thin films with aligned layers of crystals have been produced and the first practical application is likely to be in SQUIDs (Superconducting Quantum Interference Devices) which are extremely sensitive magnetometers. If these are to compete with conventional magnetometers then a low intrinsic magnetic flux is necessary; recently a $Y\ Ba_2Cu_3O_7$ thin film device has been shown to exhibit such an intrinsic low noise[4].

Most power applications require the development of materials capable of carrying 15 000 to 20 000 amps/cm^2 in magnetic fields of 5 to 10 Tesla. Recently [2,p.263] $Y\ Ba_2Cu_3O_7$ materials capable of greater than 1000 amps/cm^2 in a field of 1 Tesla have been made in small quantities. Single crystals and thin films are capable of current densities of about 1 000 000 amps/cm^2 in high magnetic fields, but with the obvious disadvantage of small total critical currents due to the small dimensions involved. In the U.K.[5], ICI have produced wires, sheets, tubes and small coils from the Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O materials aimed mainly at r.f. and microwave frequency components. Critical current densities in excess of 7000 amps/cm^2 are reported but no mention is made of the critical magnetic field[5]. Hence, there is a long way to go before materials are available for the types of application considered here. However, the large effort being spent world-wide on their development provides confidence for the future.

The recent discoveries in high T_c materials have prompted speculation on potential power applications[6,etc.], and the Ministry of Defence has carried out preliminary studies on the implications for marine engineering applications, assuming that materials suitable for magnetic field windings would be available in the future. These studies have included the comparison of motor types[7], the consideration of new applications in marine engineering[8] and of magneto-hydrodynamic (MHD) propulsion for ships[7,9].

MARINE APPLICATIONS

Most power applications derive from the application of high magnetic fields, and superconducting windings provide the possibility of smaller systems than could be achieved by conventional methods. In some cases the application of superconductivity is the only way of producing sufficiently high fields.

The following marine power applications have been identified at the present time and their future development is dependent upon the development of high temperature superconducting bulk materials or those suitable for magnetic field windings:

(*a*) d.c. fault current limiters;
(*b*) electromagnetic bearings;
(*c*) electromagnetic anti-vibration mounts;
(*d*) generators and motors for ship propulsion;
(*e*) MHD ship propulsion;
(*f*) weapons and launchers.

Electromagnetic energy storage and superconducting busbars have also been considered for direct current application but, at liquid nitrogen temperature of operation, they were found to have no advantages compared with conventional systems[8]. In terms of the space required, the net energy density of a magnetic storage system is over an order of magnitude less than that for a currently available lead acid battery system. Conventional high direct current (5000 A) cable runs are smaller than equivalent projected liquid nitrogen superconducting d.c. cables plus their refrigeration support plant. Although the net cross section of the superconducting cable would need to be 0.6 of that for conventional cable runs the associated refrigeration plant would need to be large (about 3 m^3) with a power consumption of about 30 kW[8].

Fault Current Limiters

One application for fault current limiters is to limit the current surge in a submarine battery following a short circuit fault. A limiting device based on an inductor in series with the battery is a possibility but unsatisfactory because the ultimate level of the fault current is not limited and the device simply slows down the rate of rise.

An alternative is to use a device consisting of a superconductor in parallel with a normal conducting shunt[8] where the superconductor is designed to switch to the normally conducting state, by exceeding its critical current density, when a fault occurs. The device is placed in series with the battery, thus limiting the magnitude of the fault current and reducing the demand on the circuit breakers (FIG. 3). In principle it is possible to construct a limiter of this type using presently available high temperature superconducting material, since a high current density and high ductility are not essential for the superconductor. However, there are problems in manufacturing a bulk material of sufficient size for large current application and in reducing the resistance of joints between the superconducting material and external leads at room temperature.

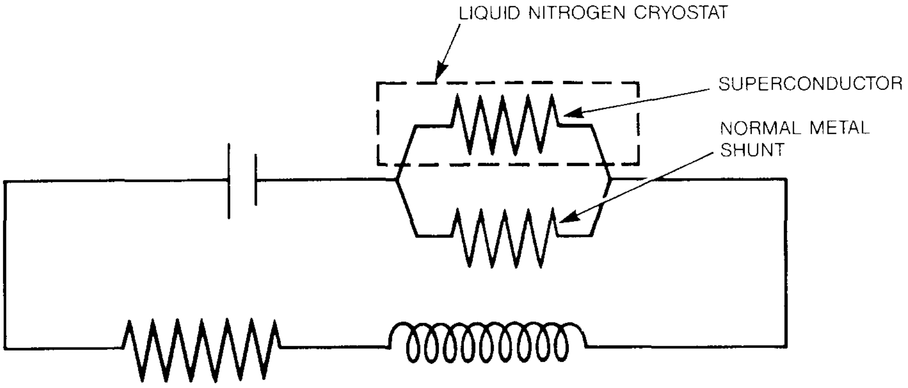

FIG. 3—RESISTIVE CURRENT LIMITER

Electromagnetic Bearings and Anti-Vibration Mounts

Electromagnetic bearings have been studied to reduce noise in both main shaft and auxiliary machinery bearings for submarines. The application of high temperature superconductors could reduce the overall size and weight of the bearings and may foster interest in development for main shaft bearings. However the added complication of a refrigeration cooling system would need to be considered agains the benefits.

The active control of vibration isolation mounts for both submarine and surface ship machinery using electromagnetic mounts has been studied.[10]. In such systems a load is basically supported by magnetic attraction between a magnet and a reaction plate. Superconducting magnets are ideal for suspension systems because they oppose change to the magnetic field produced. The control placed around a resistive magnet, where instrumentation monitors the magnet gap and the load movement to control the magnet current, mimics this property. Additional monitoring of the magnetic circuit is required for the control of the complete system.

For resistive magnetic mounts the lift to weight ratio can be as high as 10 to 1 and the power requirement 0.6 kW per tonne supported[10]. Thus, for large machinery such as diesel generators, the weight, size and power consumption of the suspension magnets become significant. Also the magnet gaps have to be small to achieve a sufficiently intense field to create the attractive force. The use of superconducting magnets would significantly alleviate these problems.

Generators and Motors for Ship Propulsion

The Ministry of Defence has supported research and development work on liquid helium cooled superconducting d.c. motors from the early 1960s to the early 1980s[11,12], culminating in a full scale demonstration programme during which the cryostat and field system for a 25 MW 200 rev/min motor was built and successfully tested in 1983[12]. However shortage of funds, coupled with no foreseen applications at the time, resulted in cancellation of the programme.

Recently, there has been renewed interest in electric propulsion for conventional and unconventional ships[13]. Electric propulsion eliminates the need for gearboxes and permits flexibility of layout of prime movers. It also offers integrated power generation for propulsion and other loads, and reduced cost, size, weight, vulnerability and noise signatures. Suggested requirements for various application are shown in TABLE I, where possible ranges of the maximum outputs for electrical machines are given.

TABLE I-*Suggested power ranges for electrical machines*

Type of Vessel	*Motors Power* MW	*Generators Power* MW
FF/DD (Frigate/ Destroyer)	15 to 20	5 to 15
AOR (Aux Oiler Replenishment)	9	5
CVS (Aircraft Carrier)	40 to 50	5 to 20
SWATH (Small Water Plane Area Twin Hull)	5 to 40	3 to 20
SSV (Sonar Support Vessel)	1·5	1
SSN	30	15
SSK	2 to 4	1

The choice of motor and generator type for a particular application depends upon such parameters as the power and torque required and the rotational speed of the prime mover. For the higher powers and torques the d.c. homopolar motor has many attractions but the disadvantage is that electrical brushes are required. The assumptions made for the properties of liquid nitrogen superconductors in assessing parameters for electrical machines[7,8] are given in TABLE II.

TABLE II-*Assumptions for high T_c superconductors*

Type of Machine	*Current Density* A/cm^2	*Max Flux Density* Tesla
a.c. motors	15 000	5
d.c. motors	18 000 to 20 000	6

Superconducting a.c. generators for civil power stations have been under study for over 20 years and prototypes have been constructed[6]. The existing liquid helium technology could be used to design machines with the ratings required for marine propulsion, and the benefits to be derived from using liquid nitrogen or higher temperature refrigeration instead of liquid helium are substantial. Such benefits are simplification of the rotating field winding, the use of superconducting stator windings, and a superconducting screen to contain the magnetic flux. With these benefits the size and weight may be reduced. However, preliminary studies[8] have indicated that at 20 MW 200 rev/min and 3600 rev/min, water-cooled conventional and liquid nitrogen temperature machines would be fairly closely matched in terms of their output per unit volume.

A small liquid nitrogen superconducting field winding has been used in a small a.c. generator[14], the world's first power engineering demonstration of a high temperature superconductor, which was in part financially supported by MOD. In this demonstration the copper d.c. excitation winding (7500 turns) of a generator was replaced by a 10 cm diameter coil with 15 turns of yttrium barium copper oxide ($Y\ B_2Cu_3O_7$) wire of diameter 0·25 cm, manufactured by ICI. The coil, which carried a maximum current of 19·1 amps, was cooled to 77 K in a cryostat and the generator produced a three phase RMS, 50 Hz voltage of 2·5 volts on open circuit at 1500 rev/min.

Superconducting a.c. motors, in which there is no need for iron and slotted windings, have also been studied but preliminary results[8] indicate that at 20 MW 200 rev/min, water-cooled conventional and liquid nitrogen temperature machines would be fairly closely matched in terms of weight and volume. However, a comparative study of synchronous machines for application in electric power generating stations for boiler feed pumps and fan drives[15], shows that for a 10 000 HP (7·46 MW) size it would be advantageous to employ a liquid nitrogen superconducting field winding. This would provide fewer losses, calculated as 40% of a conventional machine[15], and for the continuous duty requirement of these machines would justify the overhead of a liquid nitrogen cooling system.

Superconducting homopolar d.c. generator studies[8] have indicated that for a rating of 20 MW the design requires a large number of stages and limited diameter because of rotationally induced stresses. The brushgear for the large number of stages is difficult to accommodate in the motor size.

Homopolar d.c. motors with superconducting field windings require high performance current collection and the number of stages varies with the power output[8,11,12]. For 4 MW machines two stages are adequate whereas for 20 MW machines 8 stages are required at 200 rev/min and 16 stages at 100 rev/min. Preliminary studies[7] indicate that liquid nitrogen superconducting homopolar d.c. motors would give benefits in terms of torque/unit volume when compared with other types. This assumes 18 000 to 20 000 amps/cm^2 at a maximum flux density of 6 Tesla for the superconducting windings, but further improvements could be made if higher values could be achieved. DC motors eliminate the need for cyclo- or synchro-convertors which are required for the speed control of a.c. machines[13].

Comparison of Motors

In a previous paper[7] the criterion adopted to compare drive motors was the ratio of torque to unit volume in the form of power/speed/volume, expressed in kW/rpm/m^3. An update of the plot of torque/volume against power on a log/linear scale in reference 7 is shown in FIG. 4, using sketch design values from Prothero & Cullen[8] for machines with liquid nitrogen superconducting field windings. Full symbols in this figure represent motors already built and open symbols motor design. Thus in terms of torque/volume, it is seen that conventional machines are not competitive with machines employing high temperature superconducting field windings operating at liquid nitrogen temperature. A log/linear plot of the same motor weights, where known, against power is shown in FIG. 5, and again it is seen that benefits are obtained with motors employing superconducting field windings.

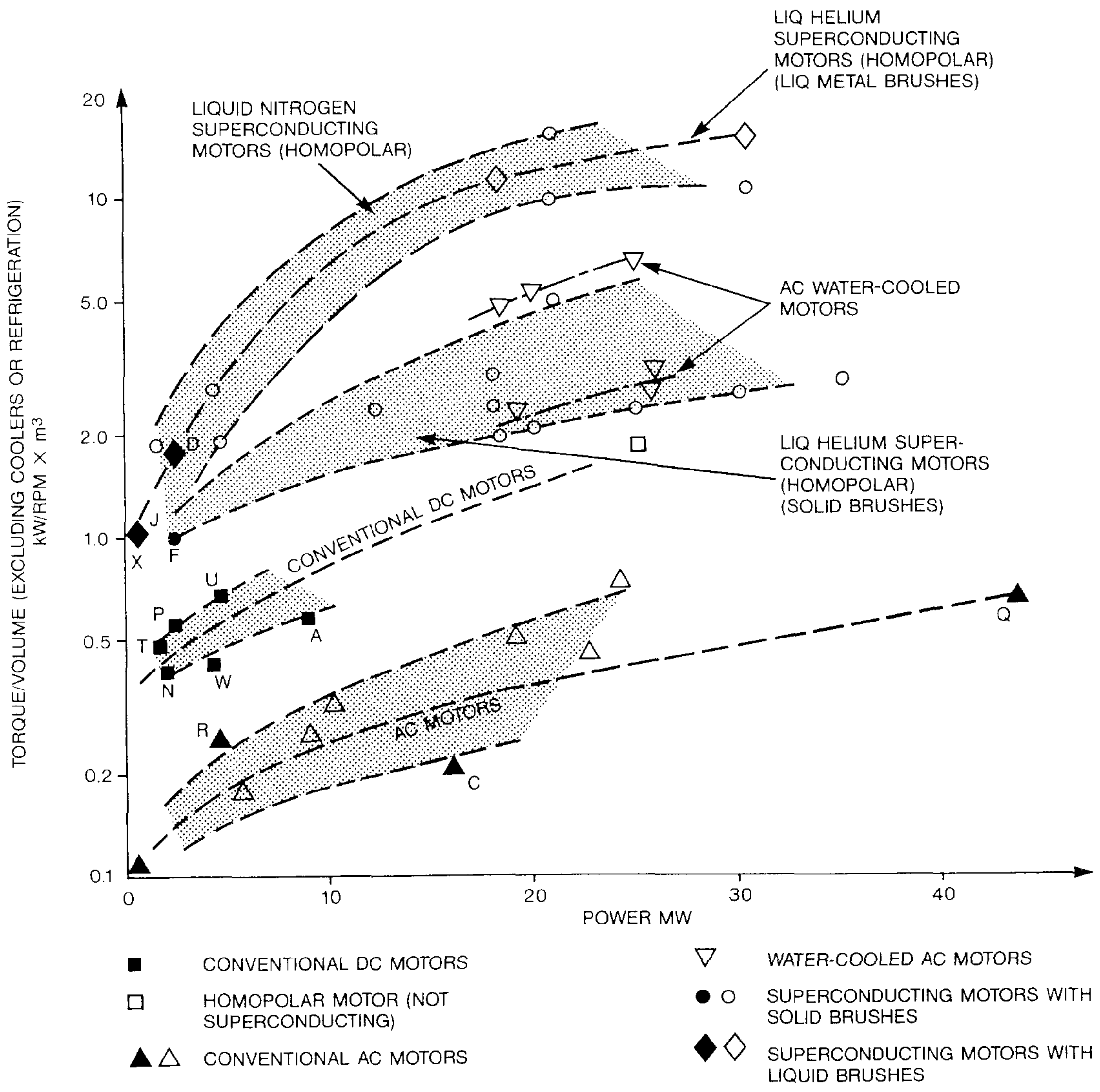

Fig. 4—Propulsion motors: torque/volume against output power

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

A	*Arktika*
C	*Canberra*
D	DTNRC M/C
F	Fawley motor
J	DTNRC 'Jupiter II'
N	*Newton*
P	P Class
Q	*Queen Elizabeth 2*
R	Ro-Ro ferry
T	Type 23
U	*Upholder*
W	Westinghouse tanker
X	permanent magnet prototype

MHD Ship Propulsion

For a number of years the Japanese have been publishing papers on MHD ship propulsion using a magnet[16,17]. This is not a new concept and papers go back to the early 1960s[18]. Studies in both the U.K. and the U.S.A. indicate that the efficiency of the system is unlikely to be better than 10%[9].

The concept is to provide a high magnetic field using a superconducting magnet and then pass a d.c. current through the sea water between electrodes at right angles to the magnetic field so that the water experiences a Lorentz

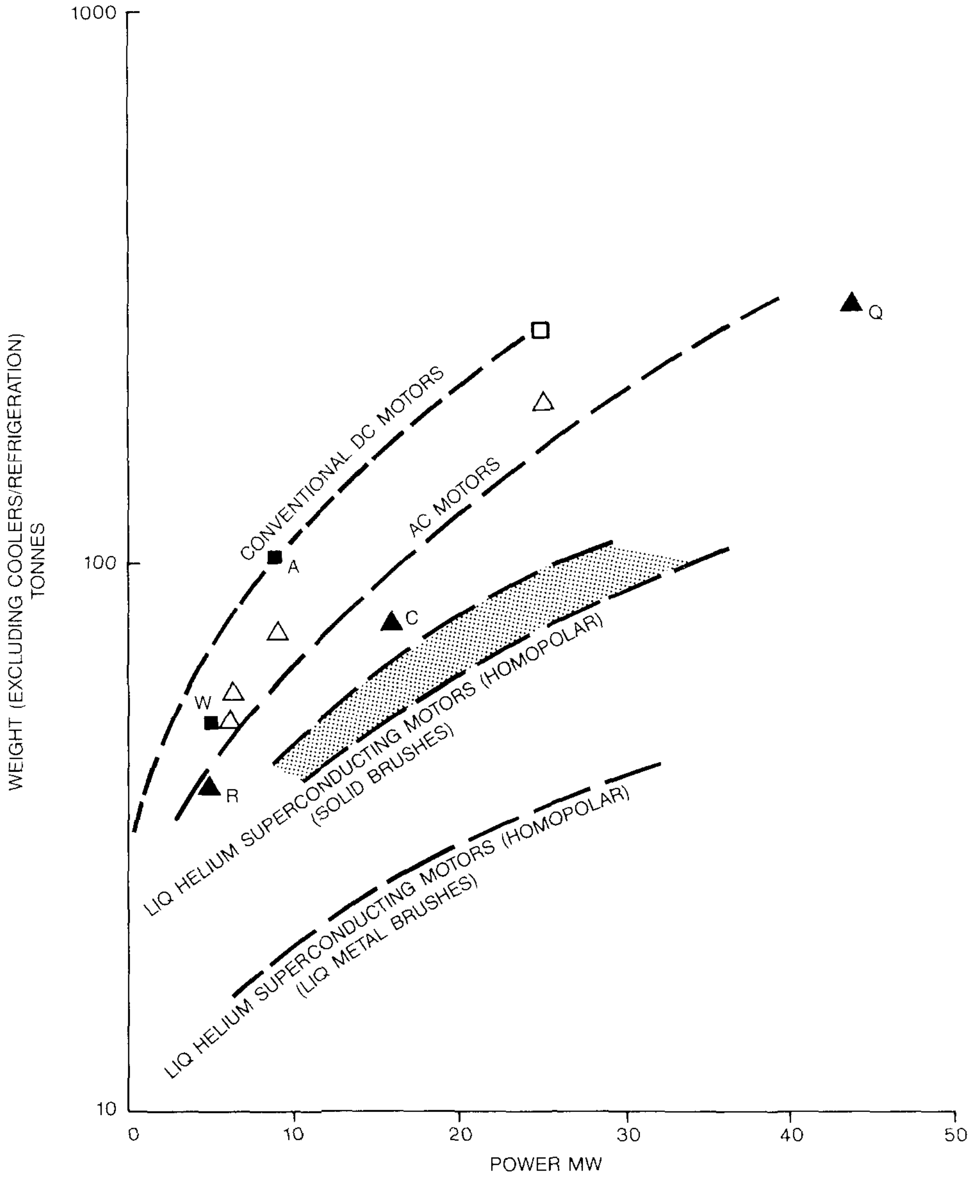

FIG. 5—PROPULSION MOTORS: WEIGHT AGAINST OUTPUT POWER
Symbols as in Fig. 4

force. In practice the preferred system consists of a cylindrical duct with internal electrodes along its length. Superconducting coils are arranged to produce a uniform magnetic field in the duct mutually at right angles to the current between the electrodes and the induced sea-water flow (FIG. 6). Several of these ducts are enclosed circumferentially in a cylindrical pod with an outer magnetic shield to eliminate flux leakage. Details are discussed by Freeman[9]. Scale model MHD drives using liquid helium superconducting field windings have been built and tested in Japan[17,19].

The main problem is that most of the energy goes into heating the sea water and, unless the electrical conductivity of this can be significantly increased, such losses will always be high. In addition, an electrochemical reaction produces hydrogen and chlorine gases. The Japanese have suggested seeding the water with acid but many problems remain and it is unlikely that an MHD system would be the main propulsion for a ship, although a proposal has been made to build a demonsrator in a 150 tonne ship[19]. However, a main propulsion system for a commercial vessel would require a high magnetic flux density, of about 20 Tesla, to obtain a sufficiently high thrust efficiency. Currently, it is possible to generate a field of only(!) about 10 Tesla using superconductors operating at liquid helium temperature. A practical application would also require high electrical conductivitiy of the sea water and the necessity for support structures to contain the high electromagnetic forces on the coils. These problems would still remain with liquid nitrogen or higher temperature superconducting magnets.

With regard to naval applications it is possible that the concept could be used as a low power drive, e.g. to provide the thrust for a submarine at low speed. Although this might provide an ultra-quiet propulsion system, assuming the problems can be solved, the noise signature of the power generation plant may become more significant.

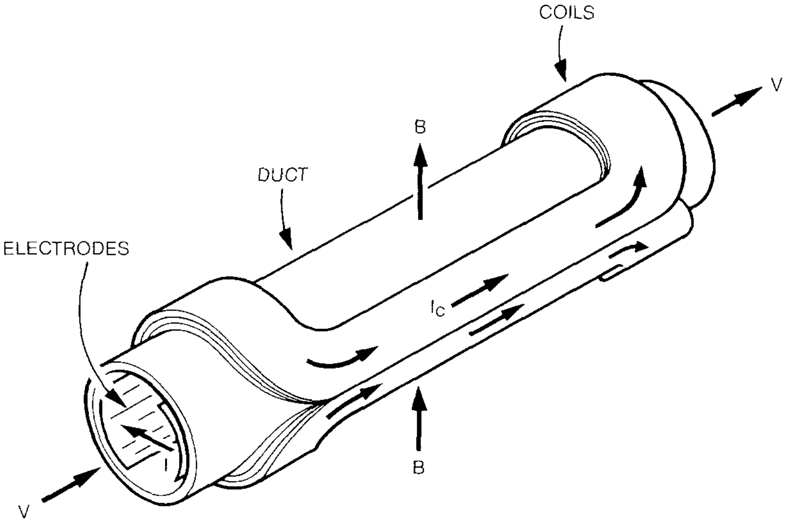

FIG. 6—MHD PROPULSION DUCT
B magnetic field
I sea water current
I_c coil current
V sea water motion

Weapons and Launchers

Electromagnetic launchers and MHD thrusters employing gases have been explored intermittently for many years and applications have ranged from launching aircraft from ships to speculative space launchers and thrusters. In addition, a projectile could be electromagnetically accelerated to act as a weapon for purposes such as close-in ship defence against cruise missiles. The projectiles in these systems are either conducting and experience a Lorentz force in a magnetic field, or are propelled by some other conducting medium which receives the Lorentz force.

Such weapons are envisaged as being of several types[20]: pulsed rail guns, where the projectile carries an electrical current and is accelerated in the self magnetic field formed by the current in the rails and projectile (FIG. 7), or a combination of the self field and an

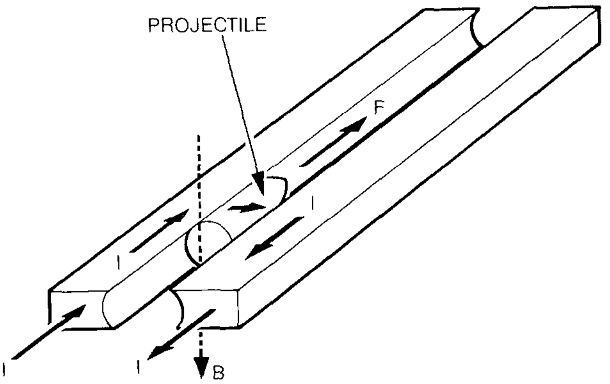

FIG. 7—PRINCIPLE OF RAIL GUN
B magnetic field
F force on projectile
I pulsed electric current

externally applied magnetic field using superconducting coils; alternatively, a rail gun where the projectile is propelled by an electromagnetically driven plasma or electric arc discharge, which behaves aerodynamically like a solid body[21], and which is produced by a high energy pulse. Other systems[20], where there is no contact between the projectile and launchers, are known as superconducting quench guns, where the projectile is effectively a coil which is accelerated by the magnetic field in a multi-section solenoid barrel. The magnetic field of each section is tightly coupled to its neighbour and the projectile 'coil', and as the projectile passes the centre of each solenoid section the current in that section is quenched[20].

Superconducting materials, both at liquid helium and higher temperatures, increase the feasibility of electromagnetic launchers for weapons. Materials operating at the higher temperatures would give benefits as stated previously for other applications; lower volume and weight, and possibly higher efficiency.

Conclusions

The following marine applications would benefit, in terms of lower volume, lower weight and higher overall efficiency, from the application of high temperature superconductors. Comments relate to the use of liquid nitrogen cooled superconductors:

(*a*) d.c. fault current limiters.

(*b*) magnetic bearings and antivibration mounts.

(*c*) a.c. motors for very large power ship propulsion (the lower limit has yet to be determined but is probably greater than 20 MW if water cooling is to be considered as an alternative; otherwise the lower limit is probably about 10 MW).

(*d*) d.c. motors and generators with low power ratings (0·4 MW has been considered).

(*e*) d.c. motors with large power ratings (the lower limit has yet to be determined but is probably greater than 10 MW).

The feasibility of the following applications would be increased with the use of high temperature superconductors:

(*f*) low power MHD propulsion for slow speed ultra-quiet drives; however, the noise signature of the power generation plant may be of greater significance.

(*g*) electromagnetic weapon launchers.

Except for fault current limiters, the benefits obtained for all the above applications depend upon the development of high temperature superconducting bulk materials capable of carrying a high current density (15 000 to 20 000 amps/cm^2) in high magnetic fields (5 to 10 Tesla).

The use of currently available high T_c materials for large (10 000s amps) d.c. fault current limiting depends upon the cost and ability to manufacture large sizes (several square cm in cross-section). This difficulty would be overcome when materials with higher current densities are developed.

The highest current densities to date in bulk materials* vary from >1000 amps/cm^2 in a magnetic field of 1 Tesla [2,p.263] to >7000 amps/cm^2 with no mention of a magnetic field[5]. Single crystals and thin films are capable of about one million amps/cm^2, but with the obvious disadvantage of small total current.

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*Since this article was written, results obtained at the Argonne National Laboratory and A.T. & T. Bell Laboratory, using magnetization measurements, have claimed 10 000 to 100 000 amps/cm^2 for Y Ba Cu O materials[23, 24] in magnetic fields of 1 Tesla at 77 K.

Estimates of the development time for materials have varied from five to twenty years, the most pessimistic being in a recent short report[22] which states that it could be at least ten years before simple devices made with high temperature superconductors are available commercially and more like twenty years for more ambitious power applications. Although there is a long way to go before practical machines can be built, the large effort being spent world-wide on the development of high T_c materials provides confidence for the future.

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