Image Cover Sheet

CLASSIFICATION	SYSTEM NUMBER 10. .90
UNCLASSIFIED	

TITLE

SUPERCONDUCTING MOTORS AND LITHIUM-WATER BATTERIES FOR TORPEDO PROPULSION

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to: JR

RESEARCH AND DEVELOPMENT BRANCH

DEPARTMENT OF NATIONAL DEFENCE
CANADA

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE NO. 76-18

SUPERCONDUCTING MOTORS AND LITHIUM-WATER BATTERIES FOR TORPEDO PROPULSION*

by

A.W. Johnson

Primary Power Sources Section
Electrical Power Sources Division

PROJECT NO.
54-80-08

RECEIVED JUNE 1976
PUBLISHED JULY 1976
OTTAWA

* The major part of this report was presented at a briefing on Future Torpedo Propulsion Systems, Ottawa, 21 January 1976.

76-102

ABSTRACT

Presently-available information suggests that the performance of the MK 37 torpedo could be improved by the use of a superconducting electric motor powered by a lithium-seawater battery. Details are given and recommendations for future work are described.

RÉSUMÉ

Les informations présentement disponibles indiquent que le rendement de la torpille MK 37 pourrait être amélioré par un bobinage supraconducteur du moteur électrique et par une pile électrique du type lithium-eau de mer. Quelques détails de ces sources de force motrice sont présentés dans ce rapport ainsi que des recommandations pour des travaux ultérieurs.

INTRODUCTION

The range of torpedoes is limited by the capacity of the energy source used to drive the motor or engine, and the speed of torpedoes is limited by the power developed by the motor, assuming that the battery or fuel supply can deliver the energy required at a fast enough rate. Thus, if a battery of the same weight as is used in the MK 37 torpedo, for example, could be produced, but possessing a larger ampere-hour capacity, then the range would be correspondingly increased. On the other hand, if the power output of the motor could be increased without an accompanying weight penalty, then the speed could be increased, but at the expense of range, unless a battery of larger capacity were also employed.

It should be possible to obtain the best of both of these situations by improving the battery and the motor at the same time. The indications are that this improvement is possible if the conventional electric motor in the MK 37 torpedo were replaced by a superconducting motor and if the Ag-Zn battery were replaced by a lithium-seawater battery. This combination of high-energy-density battery and high-power motor could improve torpedo performance markedly. (It is understood that redesign of the torpedo and of its launcher would be necessary to accommodate these changes and modification of the guidance system would be required to account for changes in the operating parameters. The justification for these improvements has yet to be established).

SUPERCONDUCTING MOTORS

There is great interest in superconductivity and machinery with superconducting windings because the materials used possess zero electrical resistance below some critical temperature. The attractions of using a zero resistance conductor are obvious, however, the drawback is the necessary low operating temperature. This temperature depends upon the superconductor used and is in the range of 4-18 K. Cooling by liquid helium (BP 4.2 K) is thus necessary with the added complexities of refrigeration, insulation, vacuum jackets, etc. In the case of air-launched torpedoes, the motor system would probably be pre-cooled on the ground prior to take-off and would be kept cool by the flow, through an umbilical cord, of liquid helium stored in a reservoir on the plane. Before torpedoes with superconducting motors could be air-dropped, however, the effects of shock and vibration on materials at cryogenic temperature would have to be investigated and any problems resolved. Superconducting windings would have to be adequately protected from shock since they may revert to the normal (resistive) state if subjected to shock energy above a maximum level. Ship-or submarine-launched torpedoes would likely be cooled by an on-board, closed-cycle helium liquefier/refrigerator. These devices can now be made relatively compact and more reliable than older machines and a single unit, when conveniently located, could service any number of torpedoes in their launchers.

Despite these complexities, superconducting motors, above a minimum power size, present real weight advantages. Compared to conventional electric motors, superconducting motors have the advantage of higher torque, higher efficiency and lower weight for a given power rating. Conversely, weight-for-weight, superconducting motors are 6-8 times more powerful than conventional electric motors (1). The reason is that superconducting windings can support high currents without the need for iron. The usual iron stator can, therefore, be dispensed with and there is more space for a larger field winding. In addition, the I^2R losses in such motors are very low since the winding resistance is negligible.

Superconducting motors can also be designed to operate at slow speed and could be directly connected to the propellers, thus obviating the need for a speed-reducing gear box and its attendant power losses, weight, vibration and mechanical noise. In small torpedoes with insufficient room for a motor with counter-rotating armatures, a one-to-one direction-changing gearbox would still be needed to drive both propellers from the single armature, but the low rotational speed would result in less noise than with the conventional speed-reducing gearbox.

One other property of superconducting windings, and this is due to their zero resistance, is that the circulating current can be made to be persistent by shorting the terminals of the winding when it achieves operating temperature. This is the usual mode of operation of superconducting solenoids and is significant in this context in that the field winding could be fully energized before the torpedo was launched. Suitable provision for electrical connection to an external power supply and control would have to be made in the launcher in this case; however, a further advantage of this system is that all of the battery power would be available to drive the armature.

There are two basic types of superconducting motor with several possible configurations for each. The simplest design is the homopolar machine and is based upon the Faraday disc. The first commercial application of superconductivity to a rotating machine was of this type. It consists essentially of a solenoid in the form of an annulus surrounding a metal disc mounted on a shaft (Fig. 1). Current-carrying brushes contact the disc at the edge and centre. Since the magnetic field is perpendicular to the disc, there is no reaction on the winding from motor loading and a simple dewar arrangement can be constructed around the winding.

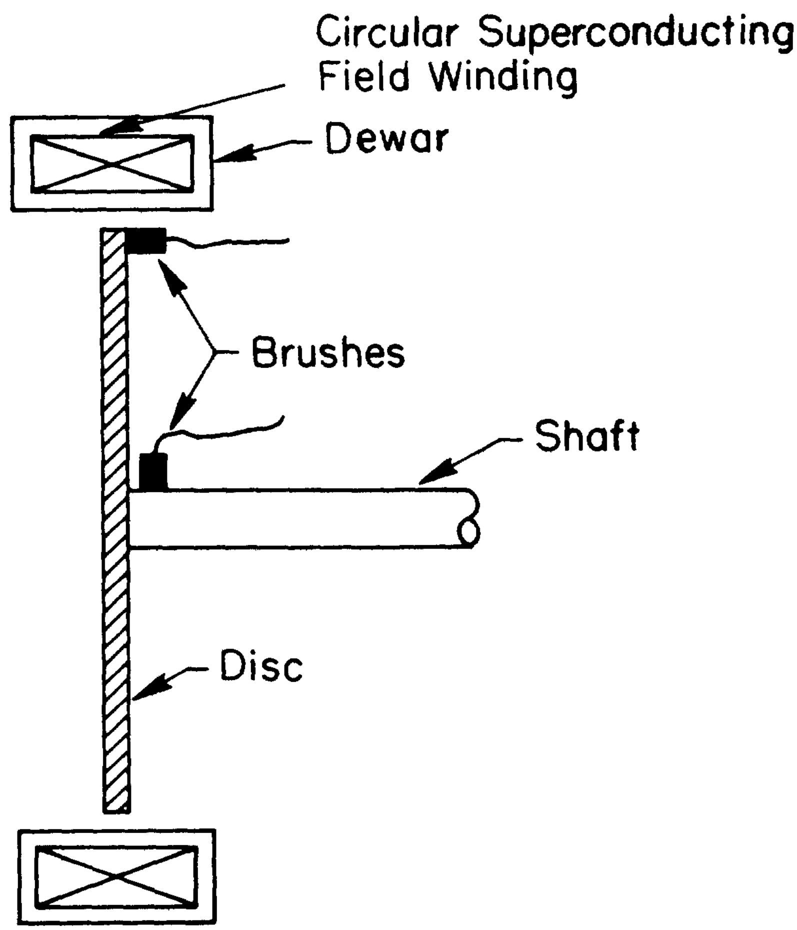

Fig. 1: Simplified cross-section of homopolar electric motor with superconducting field winding.

The major disadvantage of this design is the inherent low voltage of the armature. This voltage is given by the expression (2)

$$V = \frac{\Phi N}{60},$$

where Φ is the useful flux in Webers and N is the speed in rpm. The useful flux is the fraction of the total flux intercepted by the disc between the inner and outer slip-rings or brush contacts and is simply

$$\Phi = \pi \left(r_2^2 - r_1^2\right) B,$$

where B is the flux density in Teslas.

The voltage can be increased by segmenting the disc or by increasing its diameter which suggests that a flat, large diameter machine would have the preferred shape. For a motor small enough to fit in the MK 37, the armature voltage for a double slip-ring pair or drum configuration would be about 3 V ($B \sim 4$ T, $N \sim 1000$) and, for a 150 HP motor for example, the current would have to be in the tens of thousands of amperes. This high current, although possibly attainable from a high-energy-density battery, could not be supported by the brushes in a small homopolar motor. This type of superconducting motor is, therefore, not suitable for powering torpedoes.

The second basic type of superconducting motor is the common heteropolar machine with a wound, repulsion armature (Fig. 2). The field winding is superconducting and the rotor may or may not have superconducting coils depending upon the power requirements, cost, complexity and other considerations. Again the superconducting field provides a very high magnetic flux, but the full reaction of motor loading is now transmitted directly to the winding and it must be securely anchored to the frame. This need for increased support raises the refrigeration load markedly; however, more power can be developed in a smaller rotor of this type than in the homopolar machine.

A superconducting motor for torpedo propulsion would very likely have a conventional resistive armature, carbon brushes with a high metal content and a superconducting field winding. Some of the original superconductors would become suddenly normal when subjected to a changing magnetic field, but type II superconductors when operated within their ratings can tolerate the varying flux from armature rotation without losing their superconducting properties. The conductors most frequently used are alloys or compounds of niobium and titanium or tin in the form of micron-size filaments in a copper matrix; Nb_3Sn is often vapour deposited onto thin ribbons of stainless steel (3). The actual composition and configuration employed depend upon the application.

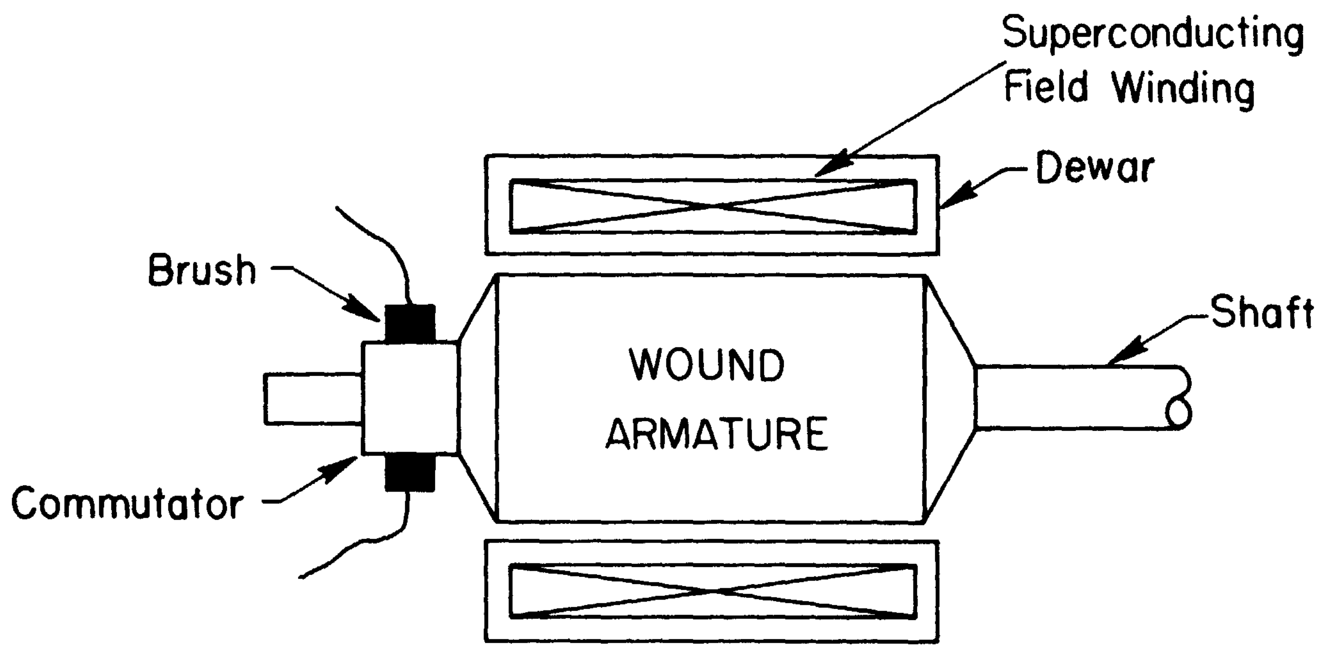

Fig. 2: Simplified cross-section of heteropolar electric motor with superconducting field windings.

The field which may be obtained from an air-core winding may be calculated approximately from the expression for a solenoid. At the end of the coil (4,5)

$$H = \frac{4\pi}{10} \cdot \frac{NI}{2L} ,$$

where N/L is the number of turns per cm and I is the current. In general terms, NI/L may be replaced by the product of the thickness, S, of the coil and the current density, j, yielding

$$H = \frac{\pi j S}{5} .$$

With a current density of 30,000 Acm^{-2} (6) in a coil 2 cm thick it is possible to obtain a field of about 40 kOe which is four times higher than the field obtainable from a normal winding of the same size (7). Although iron is not needed in the magnetic circuit to achieve this high field, some external shielding would be required to reduce the stray field. Compensating windings could possibly by used, but they are probably impractical in a motor of this relatively small size. The external iron would also help to focus the flux lines and increase the interacting field somewhat but at the expense of added weight.

The use of a conventional resistive armature would allow more realistic terminal voltages than with the homopolar machine. The values would likely be in the 30-300 V range and the current requirements would be correspondly reduced. Power losses in the brushes and in resistive connections would also be lower.

If a 150 HP superconducting motor were installed in the existing MK 37 torpedo, its speed would be increased by about 50% without enlarging the engine compartment. However, the advantage of using superconducting motors is not fully realized at this horsepower rating; maximum benefits begin to appear at $\gtrsim$ 500 HP. A 500 HP heteropolar superconducting motor would not be much larger than one of 150 HP and its use in the MK 37 would result in a speed increase of about 100%, although the greater electrical power required (375 kW) would necessitate the use of a larger, more efficient battery.

LITHIUM-SEAWATER BATTERIES

In electric motor-powered torpedoes, the limitations of size and weight necessitate the use of a high-energy-density battery. The Mg-AgCl battery used in some torpedoes employs seawater as the electrolyte and has an energy density of 26-40 Wh/lb depending upon the configuration. In the MK 37 torpedo, the Zn-AgO battery used develops ∿ 80 V at 450 A and has an energy density of about 35 Wh/lb. The figure for the lithium-seawater battery is 3-4 times higher and the energy per unit volume can be four times greater depending upon battery size. In addition, the cost/kW is much lower since no silver is used and lithium is in abundant supply. This battery is an excellent candidate for use in torpedoes.

The overall chemical reaction of the lithium-water cell is

$$Li + H_2O \rightarrow Li^+ + OH^- + \tfrac{1}{2}H_2 \ .$$

The hydrogen is evolved at a nickel or iron cathode. The theoretical energy density is 3830 Wh/lb of lithium and practical systems can develop ∿ 1500 Wh/lb of reactants in a marine environment, where the weight of water consumed is not included. The need for a heat exchanger, circulation pump and associated plumbing reduces this figure by a factor of ten when the entire system is considered. Littauer and Redlien (8) have described the operation, manufacture and use of this cell in marine applications.

An example of the capabilities of the Li-water battery has been reported by Halberstadt et al. (9). A cylindrical battery weighing 946 lb and measuring 20 inches in diameter and 72 inches long had a capacity of 1200 Ah at 80 V. Compared to the Ag-Zn battery of the MK 37 torpedo, this lithium battery had 12 times the output but only 4 times the weight and 3 times the volume. If installed in a torpedo, it would be able to power a 120 HP motor for 1 hour, assuming that the superconducting field winding was in the persistent mode and armature losses were 5% (low bearing and windage losses because of low speed and independently-energized field). Higher power applications would not result in a proportionate increase in battery size and weight as the plumbing need only be upgraded, not repeated and the required increase in electrode area would mainly involve lightweight lithium.

CONCLUSION

It has been shown that it is possible to increase the speed of the MK 37 torpedo by a factor of two or more by the use of a superconducting motor powered by a lithium-water battery. Lower noise and vibration are additional benefits. The combination might be considered as an alternative propulsion system in other torpedoes if high-speed turbines plus speed-reducing gearbox are considered too noisy.

RECOMMENDATIONS

It has not been possible to present specific information on torpedo-size superconducting motors as the required development work has either not been done or has not been published. The same situation exists in the case of suitable, compact, high-power lithium-water batteries, although it appears that such systems are not far from reality.

It is recommended that

1. A survey be conducted of the state-of-the-art of small superconducting motors;

2. a contract be awarded for the development of a superconducting motor suitable for use in a torpedo, if it is discovered in the survey that no such motors have already been developed;

3. a survey be conducted to determine the state-of-the-art of compact, high-power lithium-seawater batteries;

4. a contract be awarded for the development of a lithium-water battery suitable for powering a superconducting motor in a torpedo if no such battery already exists.

The recommendation for the awarding of development contracts is made in anticipation of the expected future use of superconducting motors in torpedoes.

REFERENCES

1. C.J. Mole, W.C. Brenner and H.E. Haller, Proc. IEEE 61, 95 (1973).
2. A.D. Appleton, Proc. IEEE 61, 106 (1973).
3. R.A. Hein, Science 185, 211 (1974).
4. R.P. Winch, Electricity and Magnetism, Prentice-Hall Inc., Englewood Cliffs, N.J. 1955.
5. J.K. Hulm, D.J. Kasun and E. Mullan, Physics Today 24, No. 8, 48 (1971).
6. Z.J.J. Stekly and R.J. Thome. Proc. IEEE 61, 85 (1973).
7. A.D. Appleton, Superconducting Machines and Devices, ed. S. Foner and B.B. Schwartz. Plenum Press, New York, 1974.
8. E.L. Littauer and J.J. Redlien. Proc. 9th Intersociety Energy Conversion Engineering Conf. p. 615, 1974.
9. H.J. Halberstadt, E.L. Littauer and E.S. Schaller. Proc. 10th Intersociety Energy Conversion Engineering Conf. p. 1120, 1975.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA – R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1 ORIGINATING ACTIVITY Defence Research Establishment Ottawa National Defence Headquarters Ottawa, Ontario, Canada K1A 0Z4	2a DOCUMENT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 DOCUMENT TITLE

SUPERCONDUCTING MOTORS AND LITHIUM-WATER BATTERIES FOR TORPEDO PROPULSION

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

TECHNICAL NOTE

5 AUTHOR(S) (Last name, first name middle initial)

JOHNSON, Arthur W.

6 DOCUMENT DATE JUNE 1976	7a TOTAL NO OF PAGES 9	7b NO OF REFS 9

8a PROJECT OR GRANT NO 54-80-08	9a ORIGINATOR'S DOCUMENT NUMBER(S) DREO TECHNICAL NOTE NO. 76-18
8b CONTRACT NO	9b OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)

10 DISTRIBUTION STATEMENT

UNLIMITED DISTRIBUTION

11 SUPPLEMENTARY NOTES	12 SPONSORING ACTIVITY

13 ABSTRACT

Presently-available information suggests that the performance of the MK 37 torpedo could be improved by the use of a superconducting electric motor powered by a lithium-seawater battery. Details are given and recommendations for future work are described.

UNCLASSIFIED

DSIS

UNCLASSIFIED

Security Classification

KEY WORDS

SUPERCONDUCTING MOTORS

LITHIUM-WATER BATTERIES

TORPEDO PROPULSION

77-00030
101690

INSTRUCTIONS

1 ORIGINATING ACTIVITY Enter the name and address of the organization issuing the document

2a DOCUMENT SECURITY CLASSIFICATION Enter the overall security classification of the document including special warning terms whenever applicable

2b GROUP Enter security reclassification group number The three groups are defined in Appendix 'M' of the DRB Security Regulations

3 DOCUMENT TITLE Enter the complete document title in all capital letters Titles in all cases should be unclassified If a sufficiently descriptive title cannot be selected without classification, show title classification with the usual one-capital-letter abbreviation in parentheses immediately following the title

4 DESCRIPTIVE NOTES Enter the category of document, e g technical report, technical note or technical letter If appropriate, enter the type of document, e g interim, progress, summary, annual or final Give the inclusive dates when a specific reporting period is covered

5 AUTHOR(S) Enter the name(s) of author(s) as shown on or in the document Enter last name, first name, middle initial If military, show rank The name of the principal author is an absolute minimum requirement

6 DOCUMENT DATE Enter the date (month, year) of Establishment approval for publication of the document

7a TOTAL NUMBER OF PAGES The total page count should follow normal pagination procedures, i e , enter the number of pages containing information

7b NUMBER OF REFERENCES Enter the total number of references cited in the document

8a PROJECT OR GRANT NUMBER If appropriate, enter the applicable research and development project or grant number under which the document was written

8b CONTRACT NUMBER If appropriate, enter the applicable number under which the document was written

9a ORIGINATOR'S DOCUMENT NUMBER(S) Enter the official document number by which the document will be identified and controlled by the originating activity This number must be unique to this document

9b OTHER DOCUMENT NUMBER(S) If the document has been assigned any other document numbers (either by the originator or by the sponsor), also enter this number(s)

10 DISTRIBUTION STATEMENT Enter any limitations on further dissemination of the document, other than those imposed by security classification, using standard statements such as

(1) "Qualified requesters may obtain copies of this document from their defence documentation center "

(2) "Announcement and dissemination of this document is not authorized without prior approval from originating activity "

11 SUPPLEMENTARY NOTES Use for additional explanatory notes

12 SPONSORING ACTIVITY Enter the name of the departmental project office or laboratory sponsoring the research and development Include address

13 ABSTRACT Enter an abstract giving a brief and factual summary of the document, even though it may also appear elsewhere in the body of the document itself It is highly desirable that the abstract of classified documents be unclassified Each paragraph of the abstract shall end with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (TS), (S), (C), (R), or (U)

The length of the abstract should be limited to 20 single-spaced standard typewritten lines 7½ inches long

14 KEY WORDS Key words are technically meaningful terms or short phrases that characterize a document and could be helpful in cataloging the document Key words should be selected so that no security classification is required Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context