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SUPERCONDUCTIVE D-C SHIP DRIVE SYSTEMS,(U)
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by
T. J. Doyle

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Naval Ship Research and Development Center
Annapolis, Maryland 21402

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SUPERCONDUCTIVE D-C SHIP DRIVE SYSTEMS

T. J. Doyle

Naval Ship Research and Development Center

ABSTRACT

Superconductors are materials which exhibit zero electrical resistance at temperatures near absolute zero, supporting current densities in the order of 100,000 amperes per cm^{2*} in the filamentary wire form. When wound into magnets, helium cooled superconductors provide the compact, high flux source necessary for small, efficient electric machines. In ship drive applications, the use of high-power density superconductive generators and motors provide great flexibility of arrangement and of operation. These advantages are illustrated in advanced displacement and surface effect ship hulls with size and performance estimates based on NSRDC d-c machine developments. A recently completed acyclic machine, with a unique magnet-shield configuration designed to maximize flux utilization and power density, is described. The 51 cm (20 inch) diameter unit, now under evaluation, is expected to demonstrate more than 5000 hp per cubic meter at propulsion motor speeds. The machine includes a stationary, niobium titanium wire, solenoidal magnet surrounded by a 1010 steel magnetic shield. Rotor and stator copper drum conductors, series connected through liquid metal brushes, operate in the magnet/shield annulus. Initial motor operation indicated that

*Abbreviations used in this paper are from the GPO Style Manual, 1973, unless otherwise noted.

the high-efficiency, high-power density, low stray magnetic field, and small diameter requirements of full-scale naval ship drives can be achieved.

INTRODUCTION

A ship drive system provides the power transmission path between the prime mover, which may be a gas or steam turbine, diesel engine, or other source of rotary power, and a propeller, fan, jet pump, or other propulsor generally operating at much lower speed. When multiple prime movers or propulsors are used the drive system should also permit power-combining and cross-connection.

If the full potential of advanced hull forms now under consideration is to be realized several additional drive system features must be available.[1] Advanced gas turbine powered catamarans, hydrofoil craft, and surface effects ships are characterized by large turbine-propeller separations, constrictive machinery spaces, and demanding take off loadings. In addition to speed reduction and power distribution functions, therefore, drive machinery must be compact, easily located, reversible, and capable of variable torque ratios.

Many of the features required in advanced ship drives are inherent in electric transmissions which include motor-driven propellers powered by turbogenerators. The alignment free electric linkage provides great machinery arrangement flexibility

[1] Superscripts refer to similarly numbered entries in the References at the end of the paper.

A 400 to 1000-hp motor has been designed and constructed to verify the predicted size and performance advantages of the shaped field configuration. At publication time the laboratory machine is undergoing no-load evaluation. Load testing up to the 400-hp level will be conducted with a rectifier power supply and a water-brake load. Subsequently, system performance will be determined when the rectifier is replaced by a laboratory-built, superconductive generator (of different design) powered by a 1000-hp gas turbine. Successful motor-generator operation in the laboratory will be followed by shipboard evaluation in a small test vehicle.

This paper describes the design and construction of the shaped field laboratory motor. Loss mechanisms are treated and machine performance estimated. The advantages superconductive d-c drive can provide future high performance ships are illustrated in a hypothetical 80,000-hp small water area twin hull (SWATH) ship and 40,000-hp hydrofoil (HF) craft.

SHAPED FIELD CONCEPT

The size and efficiency advantages of the shaped field acyclic machine accrue directly from the unique magnet/rotor arrangement, illustrated conceptually in figure 1. The superconducting solenoidal magnet and helium vessel, or dewar, are the innermost machine elements. The intense magnetic flux generated in the bore of the solenoid is attracted by the ferromagnetic shield forcing virtually all of the magnetic flux to radially transverse the rotor twice. When current is passed through brushes and axially down the copper rotor drums the resulting Lorentz interaction provides motor action. Conventional arrangements of superconducting d-c machines include the same magnet/rotor/shield elements, but the rotor is located in the magnet bore and a lesser portion of the generated flux is utilized in the power production process.

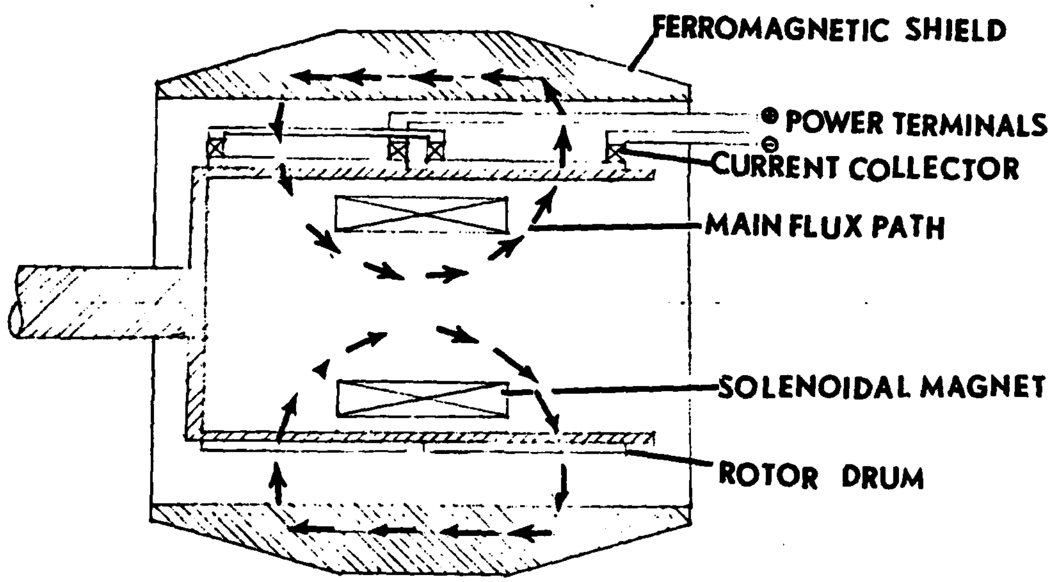

Figure 1

Shaped Field Machine Concept

Similarly, high flux utilizations are possible with internal magnet disk rotor machines which incorporate current collectors at inner and outer disk perimeters. The shield is sliced to provide narrow passages for the disk conductors which rotate when the radial current couples with the axial flux. The drum configuration is preferred, however, since it permits the reduced stray fields possible with a nonsegmented shield and is more easily adapted to high conductivity liquid metal current collectors. The improved flux utilization of an internal magnet design, coupled with the high current levels in compact liquid metal brushes, accounts for the attractive power density characteristics of the shaped field arrangement.

The capacity and maintainance benefits possible with liquid metal collectors point up a second desirable feature of the shaped field arrangement, the ability to locate brush sites in low magnetic field regions. In conventional arrangements the collector fluids, located in the magnet bore where the field is most intense, will experience severe field induced torques with correspondingly large viscous drag losses. This major source of inefficiency can be virtually eliminated in the shaped field machine and an improved efficiency characteristic results.

The opportunity to use a small, centrally located magnet-dewar assembly provides additional benefits. The cylindrical dewar, without a warm hole as in previous d-c designs, can be built with a very low heat leak, reducing refrigeration requirements and further improving efficiency. It is also protected by an almost invulnerable set of steel and copper shells and inherently rugged machine construction results.

LABORATORY MACHINE DESIGN

Major design features of the shaped field laboratory machine are shown in figures 2 and 3 in cross-sectional and isometric views. The solenoidal superconducting magnet is enclosed in the double walled, vacuum insulated, helium dewar supported by the rotor at one end through an idler bearing. At the opposite end, the dewar neck, which contains the helium inlet and exhaust lines and power leads, is rigidly attached to one bearing housing.

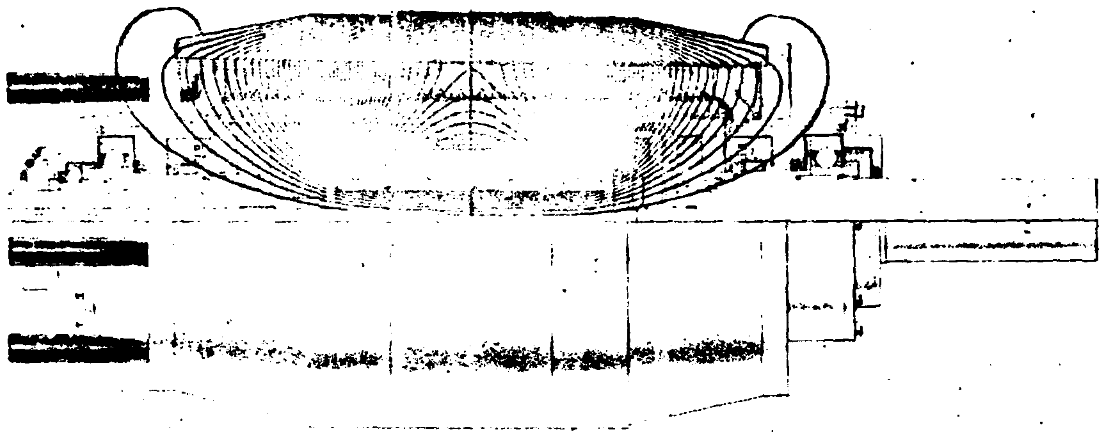

Figure 2

Motor Cross Section with Flux Plot

1 - Input or Output Leads
2 - Stator Drums
3 - Rotor Drums
4 - Magnet and Dewar
5 - Collector Rings
6 - Brush Disks
7 - Input or Output Shaft
8 - Iron Shield
9 - Shaft, Rotor Section
10 - Epoxy
11 - Bearings and Seals

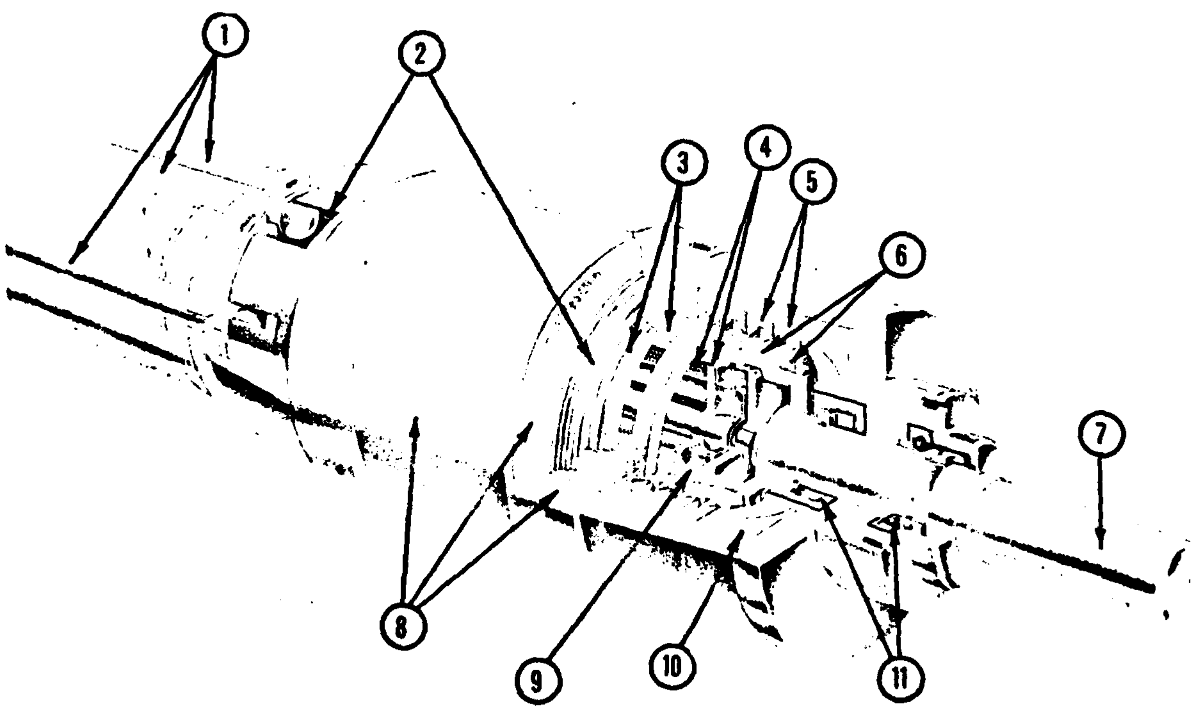

Figure 3

Shaped Field Laboratory Motor Isometric

The winding includes 13,340 turns of 0.030-inch outside diameter filamentary niobium titanium superconductor providing magnetomotive forces approaching 2 million-ampere turns.

Two inline sets of four concentric drum conductors are symmetrically located about the magnet center plane and epoxy bonded to the outer surface of the stainless steel rotor shaft. The eight copper rotor drums are insulated from each other and from the shaft permitting connection in electrical series through liquid metal brushes and a similar arrangement of copper current return drums in the stator. Stator drums and terminal rods are bonded to the ferromagnetic shield.

Flux generated in the solenoid by the circumferential field current is attracted to the steel shielding. Entering the iron radially, flux proceeds axially through the iron to the other end of the machine, returning radially to the magnet bore to complete the path. Although fields of 55,000 to 70,000 gauss exist in the magnet the superimposed flux map in figure 3 indicates extremely effective flux containment, with stray fields outside the shield limited to less than 100 gauss. Field lines are concentrated in the active drum regions and widely spaced at the collector sites, illustrating the flux utilization and loss suppression benefits of the shaped field arrangement.

When voltage is applied at the terminal rods, the resultant axial current flow in each rotor drum interacts with the radial field producing a circumferential torque. The cumulative torque developed in each drum is coupled to the output shafting through the drum-to-drum and drum-to-shaft insulated bonds. Reaction torque produced in the stator drums is transmitted through the shielding to the machine mounting points.

The brush work includes 16 copper rotor disks, two on each drum, each rotating in stator channels with the disk/channel gap bridged by liquid sodium-potassium eutectic (NaK). The collector geometry can be seen in figure 4 which illustrates machine assembly.

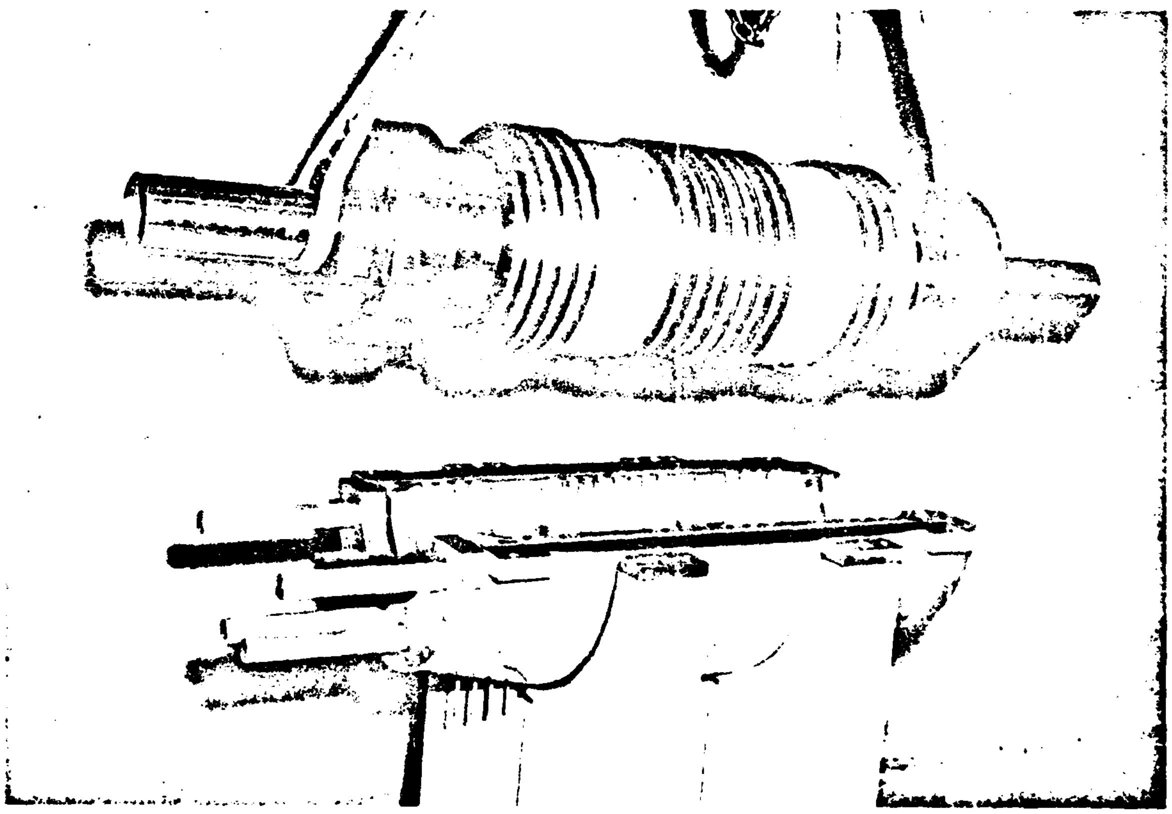

Figure 4

Rotor Placement in Bottom Stator Half

The stator channels are grooves cut into copper stator rings, two annular rings electrically bonded to each stator drum. An unflooded operating mode is employed with no external NaK circulation. Small quantities of liquid metal, sufficient only to assure uniform contact around the disk/channel annulus are injected into each channel with centrifugal and magnetohydrodynamic (MHD) forces providing for NaK distribution. The fluid pools at the bottom of each channel during periods of nonoperation. A dry, oxygen-free cover gas maintains long-term NaK purity.

A nonconducting coolant fluid is circulated through parallel tubes in the stator rings to remove resistance and viscous drag generated heat. Most of the heat originating in the rotor is transferred by conduction to the stator rings across the liquid metal collectors, with a lesser portion radiated and convected to the stator drum assembly and the fluid cooled dewar surface.

The completed machine, shown in figure 5, weighs 1050 kg (2300 pounds) and displaces 0.17 cubic meter (6 cubic feet), with a (maximum) 51 cm (20 inch) diameter at the machine center plane. The shield is 76 cm (30 inches) long and the bearing housings add an additional 10 cm (4 inches) at each end of the machine. Output shafting is 10 cm (4 inches) in diameter. The conventional 25-hp drive motor provides a dramatic size comparison with the 400 to 1000 hp superconductive unit.

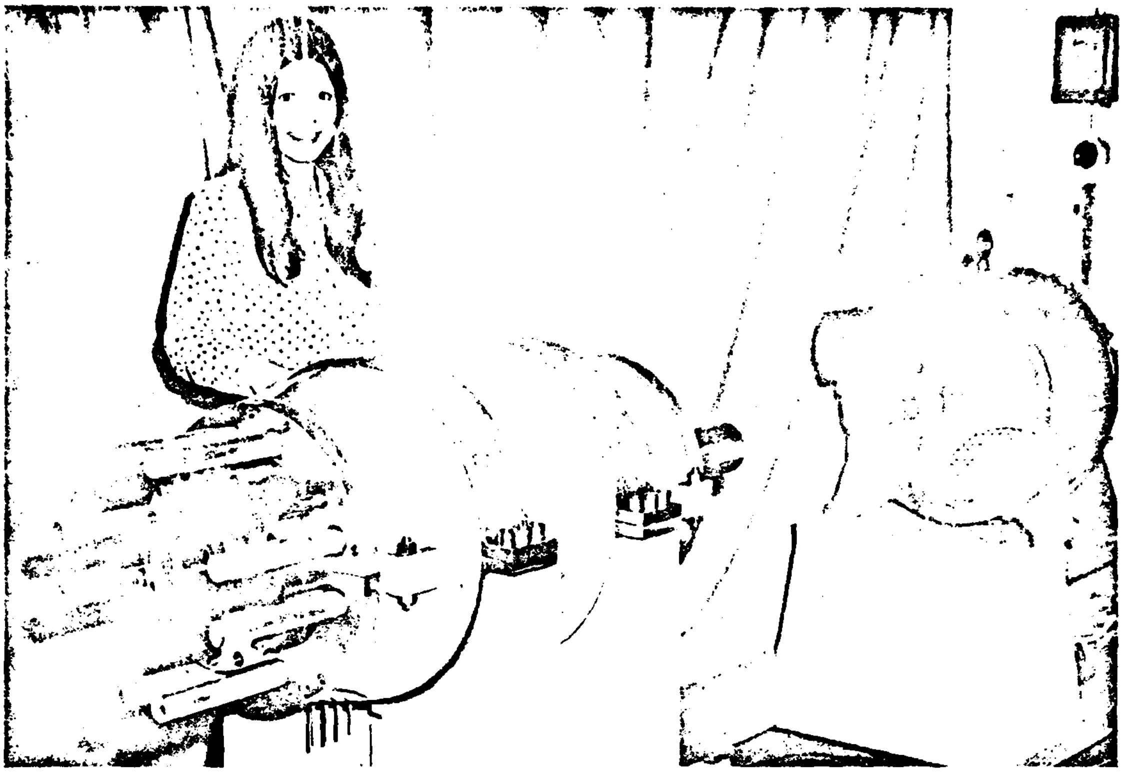

Figure 5

Assembled Machine Being Readied for No Load Testing

MACHINE LOSSES

Loss mechanisms in the laboratory acyclic motor can be conveniently divided into two categories: ohmic losses in the armature circuit and drag losses from collector, windage, and bearing effects reducing output torque.

Ohmic losses are proportional to circuit resistance, estimated at 30 micro-ohms in the laboratory motor. This extremely low resistance results from the use of large copper cross sections (30 to 35 cm^2) and NaK collectors, whose contact drops can be rendered unmeasurable by proper surface preparation.

The preponderance of drag losses are attributable to the liquid metal collectors where three separate and distinct loss mechanisms can be identified. The normal viscous shear loss becomes a cubic function of rotor speed since the relatively narrow collector gap assures turbulent flow, these will not exceed a few kilowatts in the 1800 to 2400 r/m range appropriate to motor operation.

The two remaining losses result from the presence of axial and radial magnetic fields in the collector regions. The axial field component interacts with the radial transport current with a consequent tangential (MHD) body force experienced in the collector fluid. The resulting acceleration of the NaK provides an additional fluid shear loss proportional to the square of the local axial field. This axial field in the motor configuration, however, is in the order of 1000 gauss and the predicted losses of a few watts per site can be safely neglected. In contrast, similar collectors operating in the 40,000 to 60,000 gauss fields present in a conventionally arranged superconductive machine could generate Lorentz losses of 200 to 400 kilowatts.

The final collector loss mechanism considered results from the radial magnetic field in the collector region. The radial field component generates an axial voltage differential across the brush tip in the same manner as in the drum conductors. This collector disk voltage, however, is shorted to the stator ring through the liquid metal, and an entropy-generating current loop is established across the collector gap. In the laboratory motor the radial fields in the collectors are also quite low, in the order of 3000 gauss. With proper disk insulation these circulating current losses are limited to a few kilowatts.

OPERATING POINT PERFORMANCE

Two operating points have been selected for motor load testing, one dictated by rectifier current limits and the other consistent with turbogenerator capacity and propeller speed requirements in the test bed vehicle system. Estimates of machine performance at these two points are summarized in table 1, with significant electric and magnetic circuit parameters included. Losses, discussed above, appear quite manageable permitting efficient operation at high-power density. The predicted motor performance over a wider range of power, speed, and efficiency conditions is included in figure 6.

TABLE 1

SHAPED FIELD MOTOR OPERATING POINT PERFORMANCE ESTIMATES

			Powered	
			Rectifier	Turbo-generator
Machine Performance	Input	: Terminal Voltage	31.74	30.11
		Load Current, A	10,000	25,000
		Power, kw	317.4	752.6
	Output	: Rotor Speed, r/m	2,400	1,800
		Torque, N-m	1,215	3,865
		Power, hp	410.2	976.5
	Power Den	: hp/m^3	2,400	5,750
		hp/kg	0.39	0.93
	Efficiency	: %	96.4	96.8
Magnetic Circuit Data	Magnet	: Field Current, A	121	150
		Generated Flux, webers	0.139	0.172
	Rotor	: Effective Flux, webers	0.098	0.120
		Flux Utilization, %	70	70
	Shield	: Maximum Field, gauss	14,400	18,000
		Stray Field at 6 inches, gauss	15	19
Electric Circuit Data	Curr Den	: Rotor Drum, A/cm^2	320	805
		Stator Drum, A/cm^2	280	695
		Terminal Drum, A/cm^2	275	685
		NaK Brush, A/cm^2	515	1,290
	Circuit	: Resistance, 10^{-6} ohms	30.3	30.3
		Back EMF, volts	31.35	29.25
Machine Losses	Elect Circ	: Ohmic, kw	3.03	18.94
	Collector	: Viscous, kw	4.29	1.81
		MHD, kw	0.02	0.21
		Circ Curr, kw	3.27	2.85
	Windage	: kw	0.07	0.04
	Bearings and Seals	: kw	0.70	0.52
	TOTAL	kw	11.64	24.37

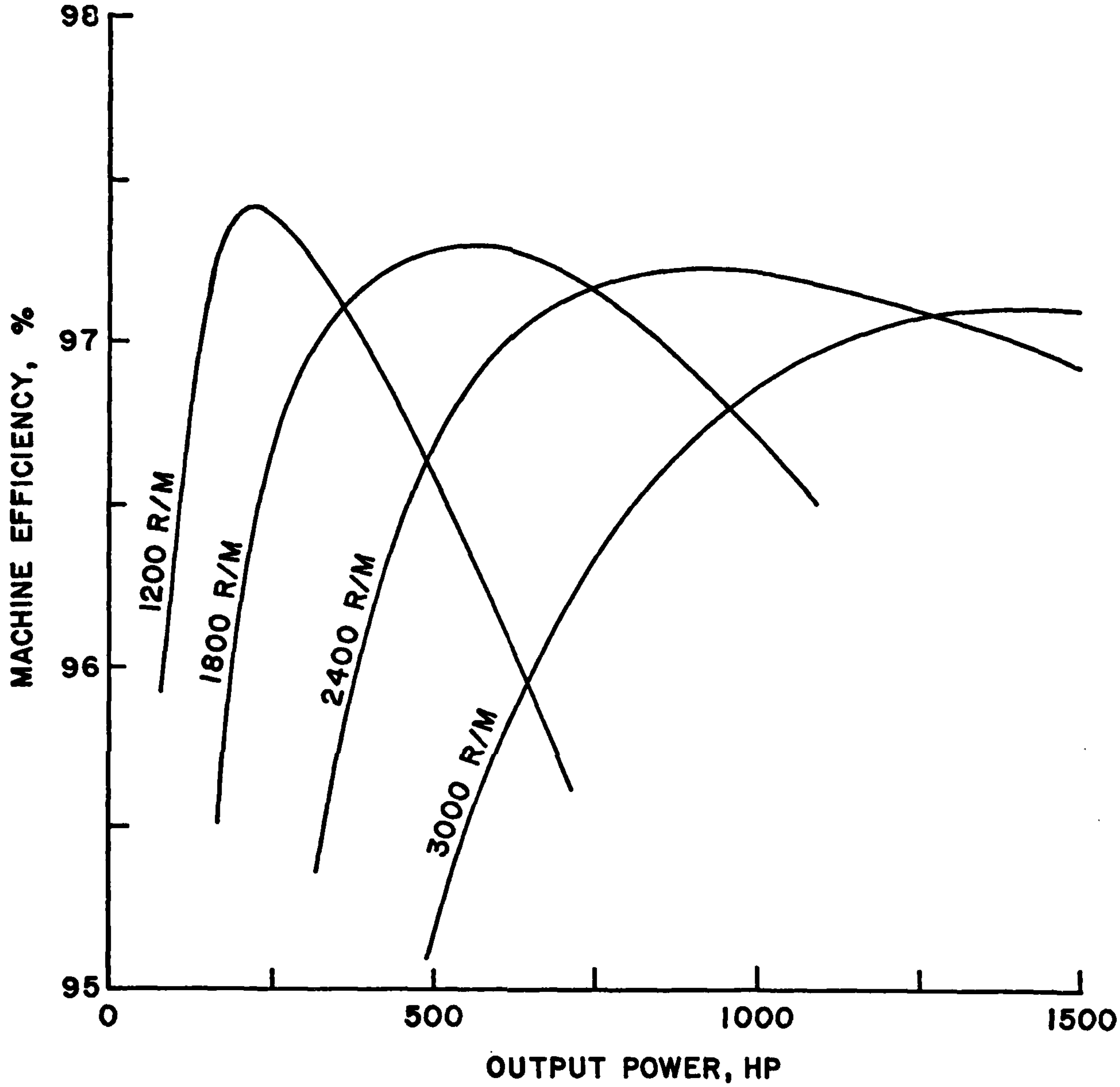

Figure 6

Estimated Motor Performance

(140-Ampere Field Current)

ADVANCED HULL APPLICATIONS

Two advanced vehicle types were conceptually fitted with superconductive d-c machinery to assess the size and performance potential of full-scale drive systems. The first vehicle considered was a 4000-ton SWATH ship equipped with 40,000-hp contrarotating screws in each hull driven by twin 5000 hp cruise turbines and four 20,000-hp boost turbines for high-speed operation. The SWATH can be described as a football field, strut supported on two submarine hulls. Wave action along the relatively thin struts provide minimal pitching and rolling moments and consequent high platform stability. The difficulty of efficiently coupling the high-speed turbine prime movers to remote, low-speed contrarotating propellers is apparent.

One possible solution is illustrated in figure 7.

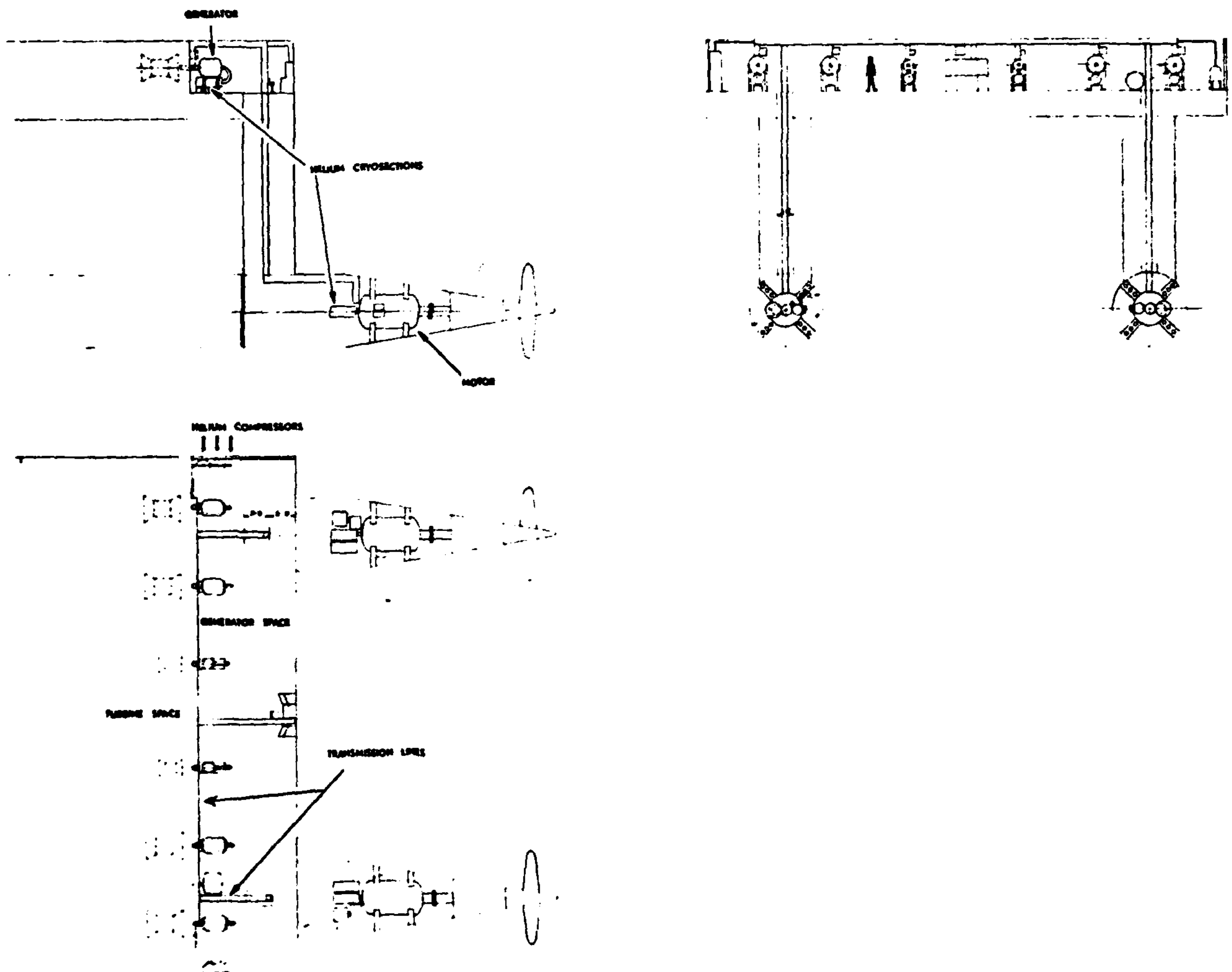

Figure 7

80,000-HP SWATH Ship Superconductive Drive Arrangement

Motors and generators, sized at the same current and flux densities and tip speeds as the laboratory machines, are quite compact, permitting close coupling. Each 1.7 meter outside diameter motor includes concentric contrarotating rotors designed for 2,400,000 nt-m of torque. Motor and generator unit efficiencies, including refrigeration, exceed 98% and low loss, highly maneuverable systems with minimal machinery space requirements are predicted. The total drive system weight, including superconductive machinery, coaxial transmission lines, helium refrigerators, controls, and auxiliaries is estimated at 150,000 kilograms.

Hydrofoil craft with submerged, strut-supported propellers and dynamic lift foils provide platform stability similar to that of the SWATH and high-speed capability. Requirements for pivotable struts make an electric linkage an attractive alternative to geared drives, with the additional variable reduction ratio capability of d-c machinery well suited to the demanding take off torque schedule. One machinery arrangement for a 750-ton, 40,000 hp hydrofoil is illustrated in figure 8. The compactness and modest helium requirements of the shaped field design permit location of the motor and its cryosections in small diameter, hydraulically efficient pods. The 1.0 meter diameter motor illustrated is designed for 20,000 hp at 1200 r/m and an efficiency of 98.5%, including refrigeration. The drive train with all auxiliaries, is estimated to weigh 42,000 gm.

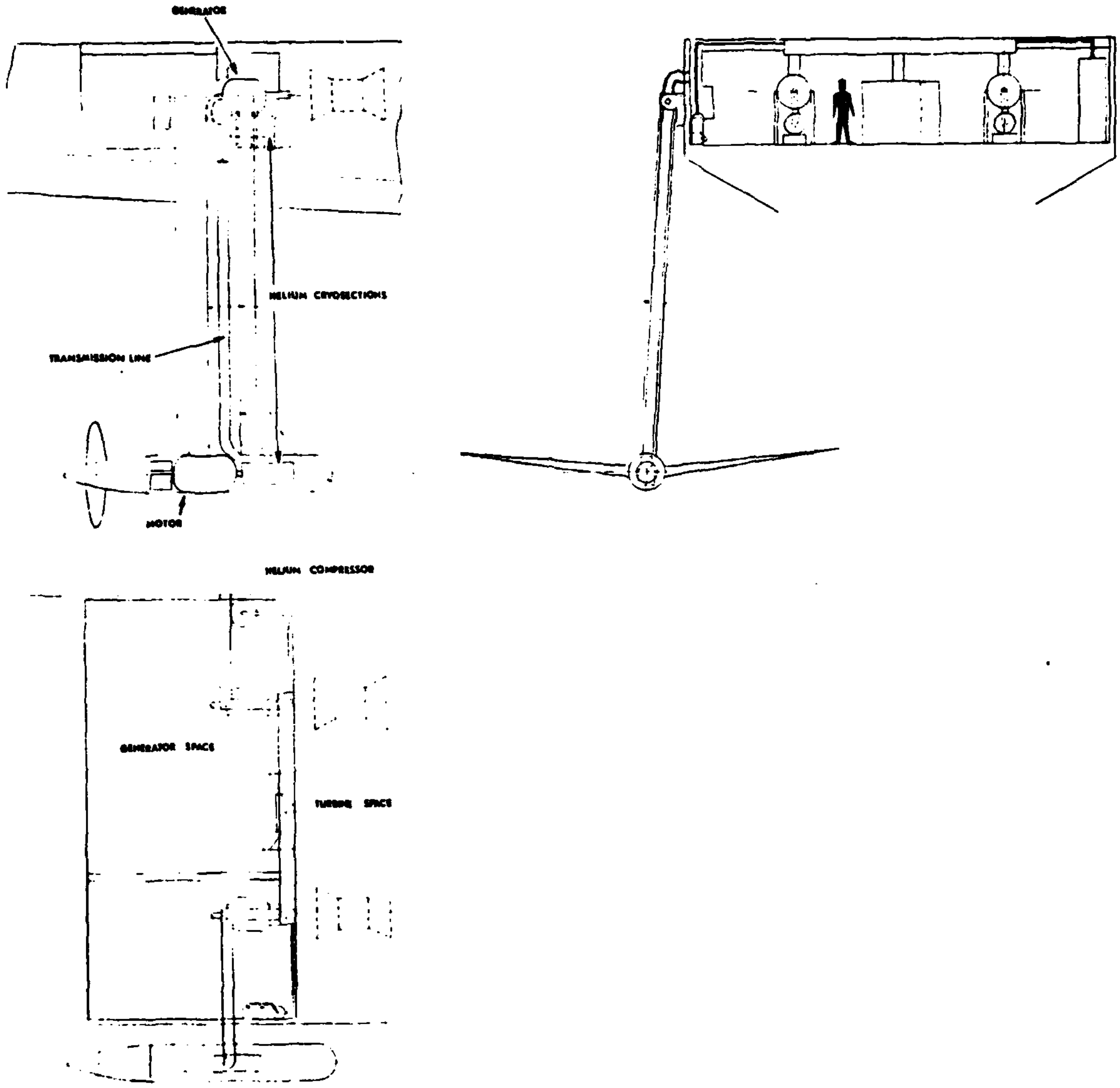

Figure 8

40,000-HP Hydrofoil Craft Superconductive Drive Arrangement

REFERENCES

1. Levedahl, W. J., "Superconducting Naval Propulsion System," NSRDC/A, presented to Applied Superconductivity Conference (ASC), 1 May 1972

2. Appleton, A. D., "Status of Superconducting Machines at IRD," IRD Co. Ltd, England, presented to ASC, 1 May 1972

3. Fox, G. R., and B. D. Hatch, "Superconductive Ship Propulsion Systems," GE Co., presented to ASC, 1 May 1972

4. McCann, E. F., and C. J. Mole, "Superconducting Electric Propulsion Systems for Advanced Ship Concepts", Westinghouse Electric Corp., presented at the Advanced Marine Vehicles Meeting, Annapolis, Md., July 17-19, 1972

5. Levedahl, W. J., and T. J. Doyle, "Superconductive Machinery for Naval Propulsion Systems", presented at the 1972 IECEC, 5 Sep 1972

6. Doyle, T. J., "Magnetically Shielded Electric Machine with Superconductive Field Windings," US Patent No 3,657,580, 18 Apr 1972