MHDS '91

REPORT ON THE FIRST MAGNETO-HYDRODYNAMIC SHIP SYMPOSIUM

BY

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Introduction

Organized by the Japanese Ship and Ocean Foundation and sponsored by the Sasakawa Foundation, MHDS '91, entitled 'International Symposium on Superconducting Magnetohydrodynamic Ship Propulsion (MHDS '91)', was held in Kobe, 28 to 31 October 1991, to mark the completion of the first MHD-driven experimental ship, *Yamato 1* (FIG. 1) ('Yamato' is an old word for Japan). It also presented the results of related research and development in Japan and other countries. A visit to the experimental ship was also included.

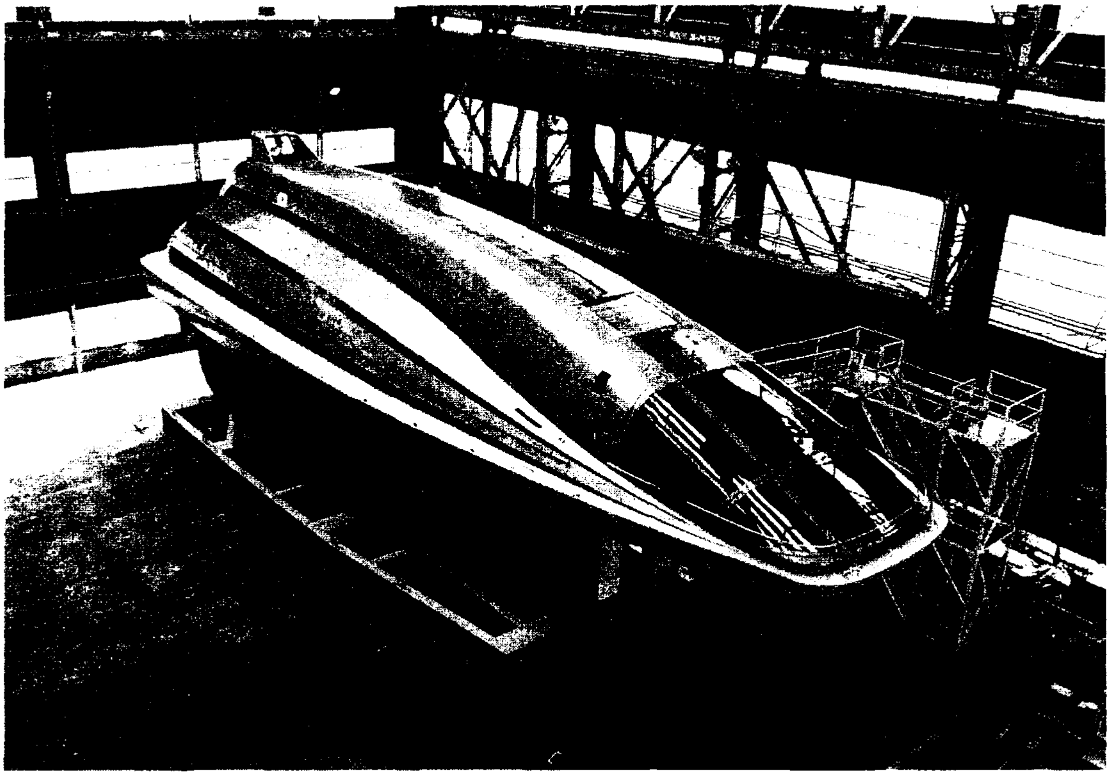

FIG. 1—'YAMATO 1'

MHD propulsion differs from that for conventional ships in that no screw propellers are involved. The thrusters use the Lorentz force acting upon sea water in a duct to produce a water jet. The water in the duct carries a direct electrical current (d.c.) at right angles to the flow and the force is provided by a magnetic field mutually at right angles to the d.c. and the flow. Losses in the propulsor are due to Joule heating, electrolytic action, hydraulic losses and end effects, which can be reduced by optimizing the design.

Summary of the Symposium

The commercial application of MHD propulsion requires large magnetic fields and is still some years away, but the future development of high temperature superconductors would significantly advance the prospects. Fuel cells, for the quiet, pollution-free and direct conversion of fuel to d.c. with high efficiency (50% to 60%) would also be advantageous. Estimates at the Symposium for the minimum applied magnetic field required for commercial viability varied from 6 to 20 Tesla, idealized theoretical propulsor efficiencies were high, and optimized designs were claimed to have potential efficiencies up to at least 60%. Comparisons of key parameters for the experimental ship *Yamato 1*, a test thruster at the Argonne National Laboratory USA (ANL), a test thruster of different design at the Institute for High Temperatures (Academy of Science USSR), and an AVCO USA design/performance optimization MHD concept for a submarine, are summarized in TABLE I.

TABLE I—*Comparison of key parameters*

		Yamato 1	*AVCO*	*ANL*	*USSR*
Max. Magnetic Flux Density, B	Tesla	4	6	6	5·9
Electric Field	V/m	674	160	9 to 270	500
Current Density	A/m^2	3000	350	350	1000
Flow Velocity	m/s	4·4	17	1 to 9	9
Load Factor (K): (Electric Field/Flow Velocity × B)		38	1·57	1·5 to 5	9·4
Electrical Efficiency (1/K)		0·026	0·64	0·2 to 0·6	0·11

Note: The USSR paper referred to a 'relative' (?) efficiency of 0·82 to 0·86 as being the most important, but this was not understood, unless it referred to the hydrodynamic efficiency of the water jet (?). If this efficiency is used for the MHD thrusters, then the calculated flow velocity is 59 to 68 m/s!

About 150 delegates from Japan, China, Korea, Taiwan, USA (26), France (2), Germany (2), Italy (2), Yugoslavia (2), USSR (8) and the UK (3) heard opening keynote papers from Japan, USA, UK and Germany, followed by sessions on the experimental ship *Yamato 1* (4 sessions), MHD Thruster, Efficiency, System Design, Performance, Magnet, Refrigerator and Shield, Electrodes and Conductivity, and State of the Art and Future Scope. Papers from the USA and the USSR summarized the programmes underway in these countries. When questioned, Soviet delegates maintained that there was no interest in submarine applications but later, during the USSR presentation, one of the slides contained a reference to submarines.

The Experimental Ship—'Yamato 1'

More than one third of the symposium was devoted to fourteen Japanese papers on all aspects of the experimental ship, *Yamato 1*. These papers are not summarized here individually. The principal details of the ship are shown in FIG. 2 and TABLE II. There are two thrusters arranged port and starboard at the after part of the bottom of the hull, each water jet operating around a rudder for manoeuvring. Each thruster consists of six ambient temperature sea water ducts, with their associated electrodes and dipole superconducting magnet coils, arranged in a circle, aptly described by the Japanese as a 'lotus-like ring', and contained in a single liquid helium cryostat. It is noteworthy that this design reduces stray magnetic fields to very low values. At the sea water inlet and outlet, single ducts branch into six ports for connection through the MHD ducts. Careful design of these branched ducts is required to reduce hydrodynamic losses, and in *Yamato 1* the design is based on results from model experiments.

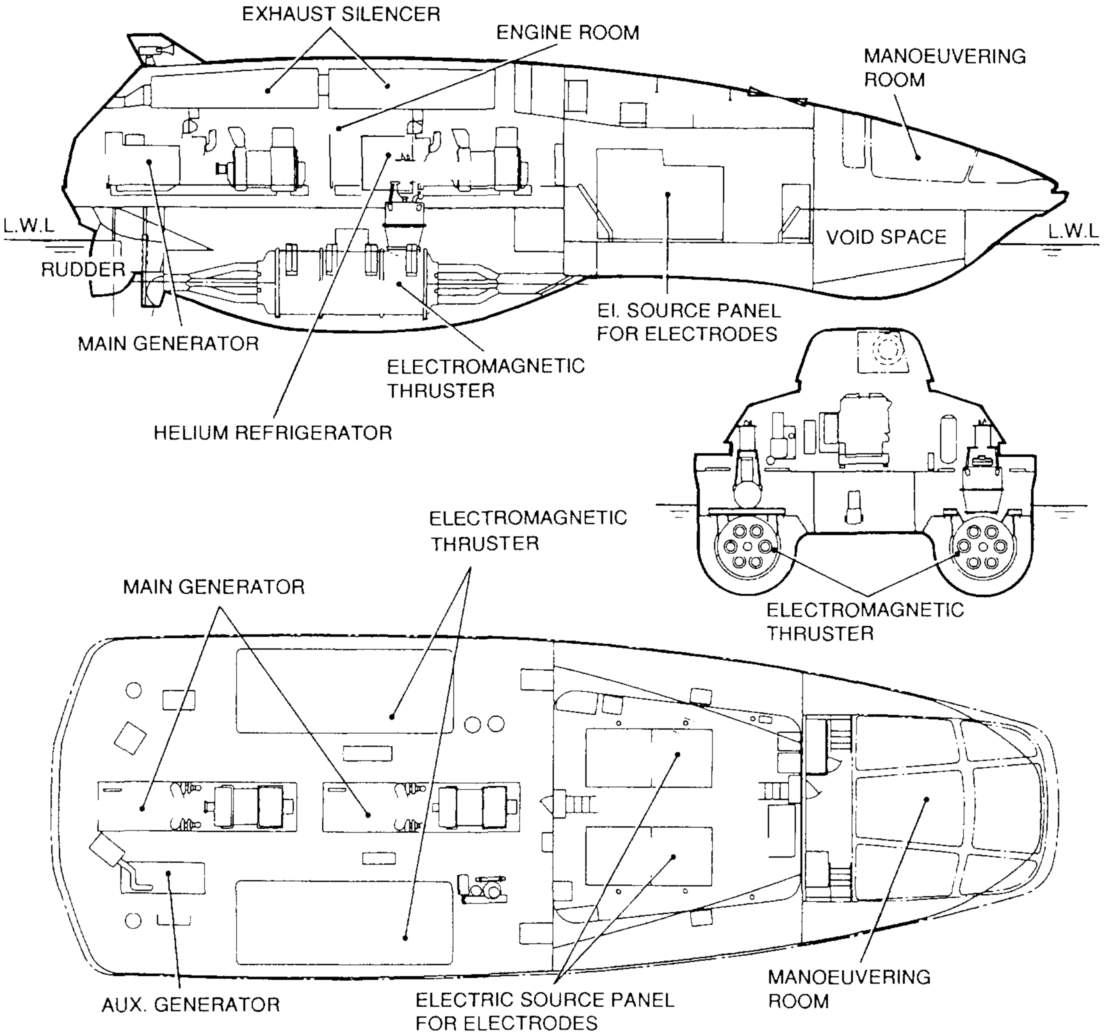

FIG. 2—'YAMATO 1', GENERAL ARRANGEMENT

TABLE II—*Main particulars of 'Yamato 1'*

Length (overall)	m	c.30
Length (B.P.)	m	26·4
Breadth	m	10·39
Depth	m	2·5
Draft	m	1·5
Displacement	tonne	c.185
Gross tonnage	tonne	c.280
Ship speed	knot	c.8
Complement		10

The overall design of the ship is a shallow draft monohull with a delta-shaped waterplane. At the after end of the bottom of the hull are two side-by-side bulges, with maximum distance between them and occupying 60% of the total displacement volume below the waterline, which contain the MHD thrusters. From resistance tests, a planned maximum speed of 8 knots could be achieved, at a maximum effective thrust of 8000 N from each thruster, where the water jet efficiency is assumed to be 50%. Although the electromagnetic efficiency of the thrusters is low (TABLE I), it should be noted that the purpose of the experimental ship is to demonstrate the feasibility of MHD propulsion at sea and is not optimized for maximum overall efficiency.

The on-board equipment includes a small liquid helium reservoir and refrigerator for each thruster cryostat, diesel-driven electric generators to supply the thruster current via a.c. to d.c. rectification, and an auxiliary generator. Shore-based facilities include a liquid helium refrigerator and transfer line to supply the initial fill to the ship's cryostats. The first circular for the Symposium announced the presentation of tentative analysis of sea trials whereas the second circular, produced some months later, made no mention of this. In the event, it was announced that the first sea trials were scheduled for the spring of 1992.

NOTES ON OTHER PAPERS

Applications of Superconducting Technology in Japan by Y. Kyotani of Technova Inc described activities for present (High Speed Vehicle with Magnetic Levitation, Linear Motor Vehicles and MHD Ship Propulsion) and proposed (Linear Elevators, Submerged MHD Freight Ships and Levitated Motor Assisted Take-off for space Rockets) applications.

W. J. Andahazy, from the US House of Representatives and a member of the Armed Services Committee presented *US Policy, Goals and Objectives in MHD.* The inspection of MHD facilities and model experiments in Japan in 1988 had overcome sceptics in the USA who made claims of low efficiency, immature technology and potentially superior alternatives as reasons for sidestepping investigation. A unique opportunity was seen to advance MHD propulsion through international collaboration, particularly in submarines for acoustic silencing and stealth, and a small test programme was started under the auspices of the Defense Advanced Research Project Agency (DARPA). Recently, an additional $5M has been added to advance the technology for naval applications.

United States Activities in MHD Ship Propulsion, presented by R. E. Metrey of the David Taylor Research Center Annapolis. The USA has several interrelated projects aimed at power applications of superconductivity, including electric propulsion, and some are concerned with both theoretical and experimental work on MHD thrusters (see TABLE I). It is not clear which technology will eventually be used for advanced ship propulsion; the economic, performance and risk trade-offs together with future requirements will determine future developments.

A review of *Superconductivity in Propulsion* was given by A. D. Appleton of International Research and Development Ltd. Design criteria and some of the technologies of superconducting homopolar motors and generators for ship propulsion were given. Reference was made to machines produced in the 1970s and 1980s and the improvements which may be expected when high temperature superconductors become available. Comments on power supplies included reference to the possibility of fuel cells in marine applications and their applicability in providing the direct current for MHD propulsion.

H. Weh from the Technische Universität Braunschweig, Germany, presented a detailed paper on *Ship Propulsion with Electromagnetic Direct Drives* and concluded that there are limited possibilities for improvements of the conversion efficiency in d.c. MHD drives. Typically, calculated efficiencies of 10% to 20% with an excitation field of 5 Tesla can be increased by using higher fields (10 to 15 Tesla may be possible). Optimization of the shape of the sea water channel could provide an increase of 10%. An a.c. MHD concept offered the potential of higher electrical efficiencies but depended upon the availability of superconductors capable of operating in a varying high magnetic field and the requirement for 16 MA/m to excite a magnetic field of 10 Tesla. Direct drive with an oscillating membrane where the propulsive forces are established by an alternating magnetic field was, in contrast to the a.c. MHD concept, practicable with conventional windings and the conversion efficiency can match optimistic results typically obtained with d.c. MHD using high magnetic flux densities and superconducting windings.

Progress of High Temperature Superconductivity was presented by S. Tanaka from the Superconductivity Research Laboratory, International Superconductivity Centre, Japan. The maximum critical temperature obtained to date was 127°K for the Thallium based material. Critical current densities against magnetic fields were shown, and it was noted that in order to increase these for potential wire applications, there was a need to produce more uniformly distributed and uniformly sized flux pinning centres in bulk materials. One important aspect of high T_c materials was the very high current density in high magnetic fields at 4°K (10^6 A/cm^2 in 10 Tesla for YBaCuO material compared with 2400 A/cm^2 at 70°K. To date 30 m lengths of high T_c material multifilament wire had been manufactured. BiSrCaCuO material had also been produced in a tape form with 10^4 to 10^5 A/cm^2 current density in fields up to 25 Tesla at 4°K.

Magnetohydrodynamic Sea Water Propulsion was presented by M. Petrick of Argonne National Laboratory, USA, and included both theoretical and experimental investigations of a large scale MHD propulsor (see TABLE I). Main objectives were to investigate the transient and steady state performance, quantify the principal loss mechanisms and obtain preliminary hydrodynamic data. A research programme was being pursued which was aimed at:

- Fundamental understanding of generic MHD- and electrolysis-related phenomena that affect performance.
- Validated analytical capability (models, scaling factors, etc.) to predict performance of full-scale MHD thrusters over ranges of interest.
- Data base of the critical loss mechanisms to support the design and evaluation of thruster configurations.
- Preliminary data base of acoustic performance to develop data on noise mechanisms.
- Demonstration of steady state and transient phenomena of large scale thrusters.

Experimental Studies of a Superconducting Electromagnetic Thruster for Seawater Propulsion described a test facility with a 3.3 Tesla superconducting magnet and initial tests carried at the Naval Underwater Systems Center, USA. Good agreement between analytical predictions and test results were obtained. Future requirements are the manufacture of light-weight, compact high field superconducting magnets, seawater electrode systems which produce an environmentally friendly neutral electrochemical end product and no bubble trails and enhancement of the seawater conductivity.

Reactive Forces in Magnetohydrodynamics and their Applications for MHD-Jet Propulsive Ocean Ships was presented by V. A. Bashkatov of the Institute for High Temperatures, USSR Academy of Sciences. A highlight was the description of a novel model MHD thruster with a helical insulator which separated an external tubular anode from an internal tubular cathode, thus providing a sea water thruster with a screw-like motion (shades of Red October!) which used the magnetic field from a superconducting solenoidal magnet (see TABLE I). A rough sketch of a viewgraph schematically depicting the sea water test facility indicated two 3 m length MHD test sections; this was the viewgraph mentioned earlier in the Summary which had a Soviet reference to submarines in one corner.

J.-P. Thibault of Institut de Mécanique de Grenoble, France presented *Some Aspects of Sea water Thrusters*. Performance predictions in terms of efficiency (net useful thrust power/electrical input power), taking into account propulsion, viscous, electrochemical and Joule losses, were shown to vary from 0·3 to 0·55 at a ship velocity of 20 m/s and from 0·65 to 0·78 at 3 m/s, but with magnetic fields from 12 to 21 Tesla. However, the asymptotic tendency of efficiency against magnetic field indicated that fields above 12 to 15 Tesla were of little interest. At the relatively low field of 3 Tesla, efficiencies varied from about 0·18 at 3 m/s to less than 0·05 at 20 m/s. Interpolation of the data presented gave efficiencies of about 0·4 at 3 m/s to 0·1 at 20 m/s for a magnetic field of 5 to 6 Tesla. An experimental programme was proposed in which electrochemical and gas production measurements were included.

A paper entitled *Basic Study on Application of MHD System to Marine Water Jet* by K. Imaichi of Osaka University, Japan, discussed the characteristics of basic MHD devices with rectangular ducts. The performance of devices was characterized by the dimensionless velocity parameter, $X = (w \times v \times B)/V$, where w is the inter-electrode distance, v is the fluid velocity, V is the external voltage and B is the magnetic flux density. Values of X between 0·4 and 0·8 were shown to be realistic, where the device acted as a pump. Efficiencies both for a theoretical MHD pump and for real fluid MHD pump were presented. The practical range for X gave theoretical efficiencies between about 0·4 and 0·8 and actual efficiencies (taking into account the hydraulic losses of a real fluid) of about 0·4 to 0·5. However, when seawater was used as a working fluid in an experimental duct, the release of considerable Joule heating and of fine gas bubbles due to electrolysis made the flow strongly turbulent.

Propulsive Efficiencies of Magnetohydrodynamic Propulsors considering Electrical and Magnetic End Effects, presented by H. O. Stevens of David Taylor Research Center, USA, represented work by DTRC and others from the University of Vermont and Carnegie Mellon University. The mathematical performance for a d.c. rectangular duct MHD propulsion system was presented, which accounted for effects due to spatially non-uniform magnetic fields and current distributions at the ends of the duct. Estimates of propulsive efficiency and electrical power requirements were made for five duct configurations. It was shown that the fringe magnetic fields and electric currents could significantly reduce propulsive efficiency. Experimental data for MHD duct flows using NaK fluid were quoted, and calculated drive efficiencies shown (0·2 to 0·5 for a centre field of 6 Tesla and 0·25 to 0·7 for a field of 10 Tesla, both for speeds above 5 m/s).

A paper from L. Huisheng of Shanghai Jiao Tong University, China, entitled *A Study of Efficiency of MHDS Propulsion* analysed the various components of efficiency including the considerable effects of magnetic and electric fringe effects. The paper considered that the practical application of MHD could only be realized when magnetic flux densities of at least 20 Tesla are practicable. Thus, the potential use of high temperature superconductors, which have the ability to produce fields of 100 Tesla, was envisaged. Propulsive efficiencies were shown to vary considerably with vehicle velocity, magnetic field and duct diameter. Examples were from 0·05 to 0·44 with magnetic fields from 4 to 30 Tesla, 0·02 to 0·05 for duct diameters from 0·24 to 0·52 metres (*Yamato 1*), 0·11 to 0·69 with magnetic fields from 10 Tesla to 80 Tesla (proposed for a ferry), and 0·32 to 0·47 for vehicle speeds from 5 to 50 knots (proposed for a submarine).

Ship Integration and System Configuration by H. O. Stevens of DTRC Annapolis, USA, identified the components for powering and providing services to an MHD propulsor. Options for prime movers were Gas turbine, Diesel, Fossil Fuel Steam Turbine, Nuclear Steam Turbine, and Fuel Cell. In terms of fuel rate, power density and volume (and minimum noise) the fuel cell had the greatest advantages but with high cost. Two 'natural' candidates for the electrical generators (editor's note: except for fuel cells) to supply power to the propulsor were chosen: homopolar and rotary multiphase rectified alternators, either making use of conventional or with superconducting excitation and water-cooled armatures, if required.

Ship Integration and Construction Considerations by R. F. Ranellone of Newport News Shipbuilding and Dry Dock Co Virginia, USA, gave an overview of MHD propulsion plant integration and production from a ship designer/shipbuilder viewpoint. Analytical models for design optimization of MHD systems are being developed which will be validated on a test loop at Argonne National Laboratory.

B. Bilen of the Institute of Technical Sciences Belgrade, presented *Some Results of the MHD Propulsion Research in Yugoslavia*, which reported the results of a research group formed about two years ago. This was a largely mathematical paper which showed the interaction of the magnetic and electric fields with the viscous boundary layer and the ship's waves. Theoretical results showed that there were significant possibilities for reducing the wave-inducing resistance and the frictional resistance of a MHD propelled ship with an external type of thruster (Editor's note: problems with stray magnetic fields?), where an electromagnetically produced wave system was induced on the water surface.

Magnetohydrodynamic Submarine Propulsion System Performance Analysis Results, presented by D. Swallom of Textron Defence Systems, Everett, Mass., USA, represented work by Swallom and others at Textron and at General Dynamics Space Systems San Diego. Significant points were the establishment of a mathematical mode for a 35 MW system capable of propelling an SSN at 30 knots, no net mass impact on the submarine (buoyancy, etc.) and improved signature reduction (see TABLE I).

D. Brady of Advanced Technology Inc, USA, presented *MHD Propulsion for High Speed Vessels*, which discussed the current performance characteristics of conventional propulsors against which MHD systems need to compete, and possible future goals. It concluded that significant improvements are required in efficiency, specific power, and enabling technologies before MHD can compete against conventional high speed propulsion systems. (editorial Note: The potential future application of high temperature superconductors operating at 4°K could be advantageous).

MHD Magnet Technology included work from both MIT and the Naval Underwater Systems Center, USA. The impact of performances of up to 10 Tesla for magnetic flux density and support structures stressed to 800 MPa were discussed. A new cable-in-conduit conductor configuration, where the liquid helium was contained in the conduit, thus eliminating the pressure vessel and enabling rapid quench to occur which eased protection problems was also described.

Magnet Development for MHD Ship Propulsion was by Z. J. J. Stekly of Intermagnetics General Corp, USA, and reviewed examples of magnets built and under development. The maximum steady state field achieved with a small coil to date was about 20 Tesla using Nb_3Sn cable. However, large magnets were needed to produce fields transverse to the flow in MHD thrusters and also were required to operate under severe mechanical conditions. For a transverse field single dipole type winding, the maximum radial compressive stresses could be reduced by subdividing the winding. The design of the magnets in *Yamato 1* was an improvement on the simplest configuration, a dipole magnet, and used a cluster of several dipoles which considerably reduced the stray external field. Another configuration from US Navy studies had a toroidal magnetic field produced in an annular duct between outer and inner windings, based on a toroidal magnet built in the 1970s.

A paper entitled *The Superconducting Cable for SCMII of Yamato 1* gave results of the production and data on the cable used for one of the thrusters of the experimental ship, and was by staff from Nikko R&D Laboratory and Toshiba Corp, Japan. The cable was made by the standard method of drawing and heat treating billets of C/Nb and NbTi inserted into a copper tube, followed by twisting, annealing and taping. Production of long lengths with a nominal current density of 1700 A/mm^2 over a two year mass production development period had been successful. For future application of MHD propulsion, improvements in current density and reduction in weight were needed, and could be achieved by altering the Cu/NbTi ratio.

Development of Superconducting Cable for the Dipole Magnet of Yamato 1 by Sumitomo Electric Industries and Mitsubishi Heavy Industries, Japan, for use in the second thruster assembly in *Yamato 1*, was also presented. Over 2000 kg of uniform cables were produced and wound into the dipole coils.

A paper entitled *Assessment of Critical Cryogenic Systems for Magnetohydrodynamically Driven Naval Surface Ships* from DTRC Annapolis, USA, was presented by J. D. Walters. A figure of at least 75 MW was quoted for an MHD thruster with a 7·25 Tesla magnetic field in a flow channel 1·1 m diameter and 23 m long. The only type that at present meets the overall requirements was the annular design proposed by AVCO for submarines (see TABLE I). A schematic diagram of a 9·4 m outside diameter and 8·3 m inside diameter MHD thruster capable of storing 30 GJ of energy, was shown, as being useful in estimating magnet size, weight and cryogenic requirements. The cryostat was discussed schematically, and the cryogenic refrigeration system in some detail. Conclusions were that, if built today, a ship system would span 300°K to 1·8°K and use turbine-expansion engines to liquefy helium at 4·2°K, and an atmospheric pressure helium system to cool the MHD magnets to 1·8°K.

Castable Light-Weight Polymer Concrete Magnetic Shielding was presented by M. Gunasekaran of Sekar Enterprises, USA. Polymer concrete, a composite of graded inorganic aggregates and fillers bound together by a low viscosity organic resin, was proposed for superconducting MHD propulsion applications. A magnetic polymer concrete proposed for magnetic shielding would include a graded magnetic filler, and be castable, lightweight (about 170 lb/ft^3), mechanically strong and impervious.

Kobe Steel, Japan presented a paper on *Design Concept and Test Result of Micro-Turbine for Compact Helium Refrigeration System.* This turbine was developed for the compact helium refrigeration system (10 W at 4·4°K) in *Yamato 1.* It contains herring-bone grooved gas journal bearings and spiral grooved gas thrust bearings. Design speeds are 10 600 Hz for the high pressure turbine and 8000 Hz for the low pressure turbine. Satisfactory stable operation was obtained during vibration tests simulating operating conditions onboard the experimental ship.

A Fundamental Study on Thermal and Magnetic Shielding of FRP-Metal Alloy Layers for the Cryostat was presented by the Ship Research Institute, Japan. Cryostats are usually manufactured from metals and a steel wall acts as a magnetic shield. To reduce the weight of the shield in *Yamato 1* a cryostat composed of FRP layers and a film of amorphous Ni-Fe-based alloy was successfully made and satisfactorily tested.

The Railway Technical Research Institute of Japan presented *Magnetic Flux Shielding Effect and Repulsion of Laminated Superconducting Leads,* which dealt with the experimental verification of numerical calculations on the magnetic shielding of superconducting material (Meissner effect) and on the repulsive forces experienced between layers of current carrying material.

A paper on *Anode for Superconducting MHDS—Materials and Efficiency* was presented by M. Muroya of Osaka Electro-Communication University, Japan and described investigations and screening test to find a suitable material for use in *Yamato 1.* It was concluded that materials designated DSE and DSE$_{O2}$ (Dimensionally Stable Electrodes—Registered Trademarks of DST, SA), Pt/Ti and Pt had long lifetimes and could be used satisfactorily as anode substrates. The evolution of chlorine by electrolysis of the seawater was reduced by the addition of porous materials (Porous Silica Glass) to the substrate and was less with a magnetic field of 5 Tesla, i.e. with the sea water moving under the magnetohydrodynamic force.

Sea water Conductivity Enhancement by Acid Seeding and the Associated Two-Phase Flow Phenomena was presented by T. F. Lin of the Applied Research Laboratory and Nuclear Engineering Department of The Pennsylvania State University, USA. A test bed containing 1 in × 12 in rectangular electrodes separated by 1 in or 2 in, in both static and flowing synthetic seawater conditions, was used. In practice, seeding could be achieved by injecting an acid upstream of the MHD duct. In the experiments, seeding was by volumetric mixing, steady state injection, or pulse injection, and the corresponding increases in conductance were determined. The effects on MHD thruster performance of seeding with 0·5% and 1·0% sulphuric acid could be predicted for different vehicle geometries by using the experimentally determined conductances. Seeding could not only improve MHDS performance but was considered to be necessary in areas of low conductivity, such as fresh-water rivers and ports. The results agreed with predictions using an analytical model, and also supported the assumption that most of the elctrolytically produced hydrogen does not dissolve before leaving the test section whilst a significant portion of the chlorine does dissolve. In military applications it could also be used for periods of high speed duration for escape and evasion.

T. Nakamura of Physical Sciences Inc, USA, presented *Technical Issues in Seawater MHD Thruster Development*, in which electrical efficiency, MHD thrust, current density and key thruster phenomena (current discharge and boundary layer effects) were discussed. A review and comparison of MHD experiments in USA (Argonne National Laboratory) and Japan (Experimental MHDS Yamato-1) were also presented (see TABLE I).

A paper on *Large Scale Superconducting MHD Magnets Design and Construction in Italy* represented research work from the University of Bologna and Ansaldo Co Genoa, with the main objectives of designing and constructing a prototype (2 m active length) magnet with 62 MJ of stored energy and the reference design of a demonstrator (8 m active length) magnet, both for MHD applications. Design parameters for both magnets are a flux density of 5 Tesla on axis, a 5% field uniformity over the cross section, a tapering off less than 0·15 T/m. The work is included in a five year National budget of about $25 M, started in 1989. A new superconducting cable technology is to be adopted but no details of this were given.