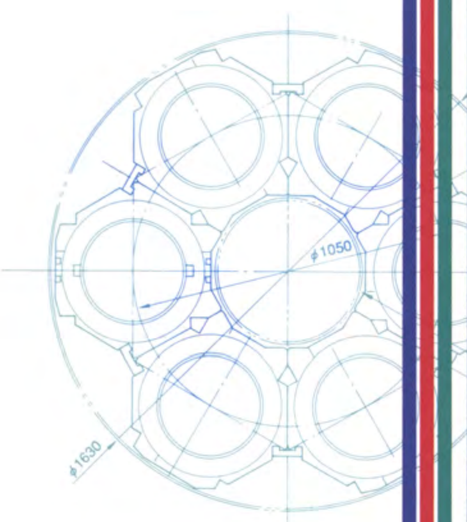
YAMATO-1

World's First Superconducting Magnetohydrodynamic Propulsion Ship



Directed by

Yohei Sasakawa

Chairman of Research and Development Committee
on Superconducting Magnetohydrodynamic Propulsion Ship

YAMATO–1

The World's First Superconducting MHD Propulsion Ship

Under the Editorial Supervision of Yohei Sasakawa,

Chairman of the Research and Development Committee on Superconducting Magnetohydrodynamic Propulsion Ship

The Ship & Ocean Foundation

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FOREWORD

In 1985, well being of the Japanese shipbuilding industry deteriorated substantially due to the maritime recession, and new research and development activity also decelerated. While Japan has been called the "shipbuilding kingdom" with a world market share of over 50 percent, high-value-added ships such as container ships, LNG ships, hovercrafts and jetfoils were developed in other countries. Moreover, Japan had to rely on engines—the heart of those ships—imported from overseas or produced under foreign license.

In order to stimulate the Japanese shipbuilding industry and give the vision of technological development to young engineers and students, I planned the development of the world's first superconducting magnetohydrodynamic (MHD) propulsion ship Yamato-1.

Of course, there were inevitably numerous difficult problems to tackle, since we were starting from scratch. However, these problems were solved one after another in no small part through the enthusiasm of our many scientists and engineers. The greatest difficulty was how to reduce the weight of the superconducting magnet. According to our initial calculation, superconducting magnets weighing more than 100 tons were required for a 50-ton ship. The sea trials of the experimental ship Yamato-1, the world's first of its kind, were conducted successfully in June 1992, after we had overcome the weight reduction problem by reducing the superconducting magnets to 30 tons, thanks to the relentless and enthusiastic effort by researchers and engineers.

There were two different reactions to the success of the Yamato-1. In Japan, there were stolid reactions from experts such as "efficiency is low" and "putting it into practical use is impossible". The reactions from Europe and the United States, on the contrary was high praise for such a high-risk, challenging development project with the originality of the Yamato-1. Many foreign journalists gathered to observe the sea trials, and articles in newspapers and in scientific magazines hailed it as a major event. We received many requests for lectures from throughout the world after the experiments. International acclaim brought with it such awards as the Silver Medal Award from the Institute of Marine Engineers and the Compass

International Award from the U.S. Marine Technology Society.

One has to remember that other primary inventions, for example, the steam locomotive developed by George Stephenson, have not been efficient at the beginning, but improvements made over many years after the development stage have raised their efficiency. I believe that the technology with the greatest expectations in the 21st century is superconductivity. The realization of dramatic progress in superconductor technology, which is central to the superconducting coil, leads us to expect the birth of the age of superconductivity. When the time is right, I expect that the experience obtained from the Yamato-1 will make a significant contribution.

The many lessons gained from the development process of this Yamato-1 are also valuable. I think it is extremely important to pass them on to the next generation, not only in terms of research on the superconducting MHD propulsion ship, but also in the overall application of superconducting technology. We have thus compiled the know-how gained in the process of development and construction of the Yamato-1 for publication.

I hope this book will be a guide for researchers and high-school and college students who hope to become engineers in developing the superconducting MHD propulsion ship in the future. I will be more grateful if the book can serve that purpose.

I also would like to express my sincere gratitude to the author of this book, Dr. Kensaku Imaichi, professor emeritus at Osaka University, and to each of the many others involved in the project, including Dr. Seizo Motora, professor at the University of Tokyo, as well as the Nippon Foundation, which provided us with consistent support.

October 1996

Yohei Sasakawa,
Chairman,
Research and Development Committee
on Superconducting Magnetohydrodynamic Propulsion Ship Yamato-1

YAMATO–1

The World's First Superconducting MHD Propulsion Ship

CHAPTER 1

INTRODUCTION

"Yamato-1" is the name of the experimental ship, which successfully went through the sea trials for the first time, using the superconducting magnetohydrodynamic (MHD) propulsion system.

The ship propulsion system widely in use today is the screw propeller*1), put into practical use in the mid-19th century and rapidly disseminated. But other propulsion systems are also in use today. Paddle steamers*2) that appear in Western are still in active operation on the Mississippi River. Personal watercraft recently seen along seacoasts and high-speed ferries use the water jet for propulsion. The ordinary water-jet system propels the ship forward with the reaction force generated by discharging water at high speed from the stern. Water is sucked in at the hull bottom or close to the bow, funneled into a duct. A high-speed rotating propeller called an "impeller" accelerates the velocity of this intake water. This propulsion system is, in principle, the same as that of jet aircraft, which are thrust forward by a reaction force, generated by sucking in air and discharging it in the form of a high-speed jet. The water-jet also uses the reaction force generated by sucking and discharging water. The ordinary water-jet system produces a high-speed waterjet by energizing water through an impeller, a kind of propeller. The impeller energizes the water mechanically. In that sense, it works similar to the familiar screw propeller.

In the meantime, the Yamato-1 is propelled by the electromagnetic (or magnetohydrodynamic) propulsion system using superconductivity. Superconductivity was used to produce the powerful magnetic field*3) in the propulsion system employed for the Yamato-1. A ship can be propelled as long as a powerful magnetic field is generated, at least theoretically, and such a theory has been known for a long time.

W. A. Rice of the United States proposed a method to propel a ship by using the reaction force of an electromagnetic pump which transferred liquid metal, and in 1961 he obtained a patent on that propulsion system. This encouraged many researchers in the United States to study the MHD propulsion system. Especially worth attention were two research projects (Ref. 1, 2) conducted by Lt. R. A. Doragh, who was studying high-speed ships at the Massachusetts Institute of Technology (MIT), and by S. Way, who was an engineer for Westinghouse Electric Corporation.

Lieutenant Doragh noted that the propulsion system of aircraft

*1) Screw propeller.
There must be very few who have not seen screw propellers. Recent screw propellers resemble the wing of a fan that thrusts air forward. As can be seen, each thrust forward of either air or water are based on the same principle. Of course, aircraft propellers are similar. The propellers and fans differ only in details, from a screw propellers as the former two deal with an easily compressible gas called air, whereas the latter acts on a practically incompressible fluid called water. Until some time ago, screw propellers were generally considered as screws with their structure closer to a screw shape. Today, the theory used for the aircraft wing is applied to the design the screw propeller with vanes of screw propellers having airfoil sections similar to aircraft wings. They were also structurally closer to a screw shape. The name screw propeller is probably reminiscent of a screw.

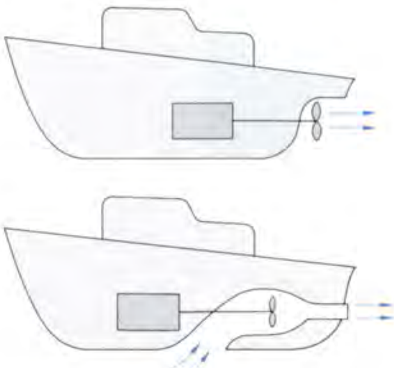


Figure : Screw propeller and water jet

*2) Paddle steamer.
A ship can be equipped with a large water-wheel-like paddlewheels or with a paddlewheel on either side or at the stern. The boards, which function as paddles, are installed at intervals on the circumference of the wheel. A ship that travels by turning

had changed from propeller to jet-engine propulsion in line with resulting higher speeds for jet aircraft, and sought ways to change seagoing ship propulsion systems from propeller to jet. As a result, he reached the conclusion that a higher-speed ship could be realized by magnetohydrodynamic propulsion. Had he stopped there, he would not have drawn as much attention as he eventually did. The extraordinary thing about Lt. Doragh's idea was his conclusion that the only way to induce a magnetic field powerful enough to propel a ship was to use a superconducting coil. At that time, MIT had just succeeded in producing a prototype of the superconducting coil. Lt. Doragh immediately interested himself in applying the superconducting coil to MHD propulsion.

S. Way tried to conduct the world's first sea trial for the MHD-propelled model submarine "EMS-1" as shown in Fig.1.1 off the coast of California in 1966. His attempt was unsuccessful, because his model ship was not equipped with a superconducting coil but rather a ordinary coil with normal conductivity to induce the magnetic field for the electromagnetic propulsion system. The magnetic field was far too weak to generate sufficient power to propel the model.

It may have been due to the failure of Way's experiment or the absence of a technological base to propel the pilotship that virtually no research efforts were made over the next 10 years.

such wheels with an engine is called a paddle steamer. A tourist ship, "Michigan," running on Lake Biwa, has a paddlewheel installed on the stern. Although this ship has a wheel of relatively simple structure, the paddlewheel ships before the time screw-propeller ships came into practical use had very complex and highly efficient paddlewheels.

*3) Magnetic field.
Magnetic field is a technical term used in physics. The term indicates a place where magnetic force is acting or the action of magnetic force itself. For details, refer to notes *1) and *3) in Chapter 3.

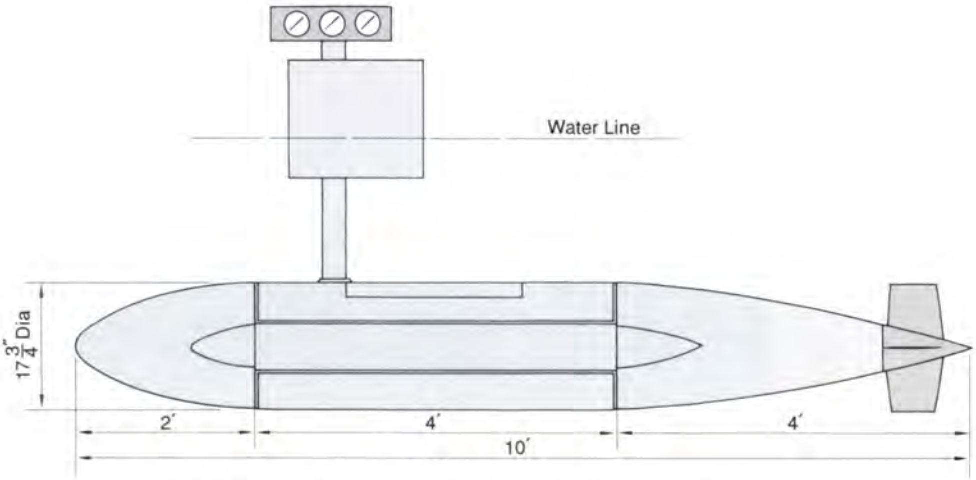


Fig. 1.1 Schematic drawing of the electromagnetic propulsion submarine "EMS-1" used by S. Way (1966)

In the 1970s, having inherited the research work of Way and other predecessors, Prof. Yoshiro Saji and a group led by him at Kobe Mercantile Marine University launched a research program on MHD propulsion using a superconducting coil. Professor Saji is an expert on technology originally used to handle low-temperature (cryogenic) liquid such as liquid helium and superconducting technology. Noting that a superconducting coil can generate a far stronger magnetic field compared to a normal conducting coil, he decided to set out on research and development of an MHD propulsion ship using a superconducting coil.

The first experiment Prof. Saji's group conducted was a propulsion test using a superconducting MHD-propulsion model ship called "SEMD-1" (Ref. 3). This model ship was constructed in such a way as to suspend the propulsion system from the lower part of the hull, as shown in Photo 1.1. The propulsion method was an external magnetic field type as explained later.

The SEMD-1 was a model ship with an overall length of approximately one meter and had a 25-centimeter-long

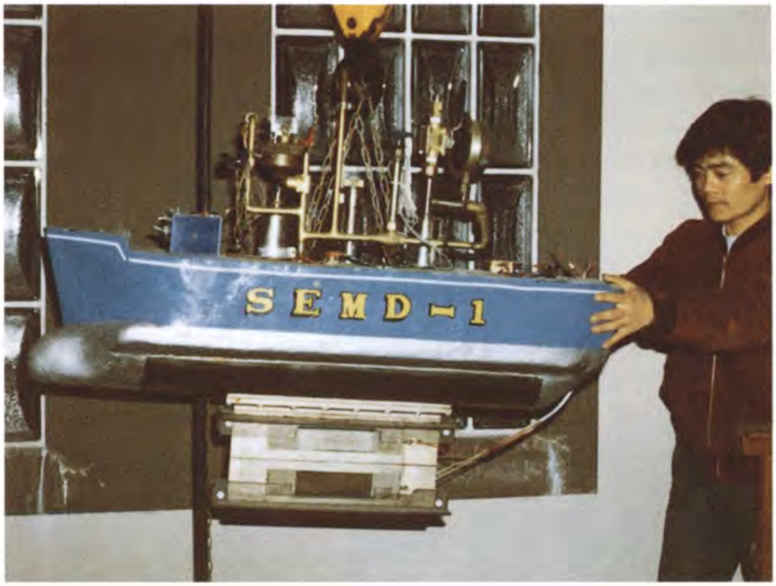


Photo 1.1 Superconducting MHD propulsion model ship "SEMD-1" developed by a Kobe Mercantile Marine University group (1976)
(By courtesy of Professor Emeritus Yoshiro Saji at Kobe Mercantile Marine University)

superconducting coil attached to the keel section (the protruding section of a yacht's bottom). The Saji Group's artificial seawater tank test of the SEMD-1 was a success. Despite it being a model ship the experiment attracted great attention from researchers worldwide as the first example of a ship propelled by a superconducting coil. Some readers may have seen this model exhibited at the Science Exposition held in Tsukuba in 1985.

Encouraged by the result of this experiment, the Saji Group built a larger superconducting MHD-propulsion model ship, the "ST-500," with a 3.6-meter hull weighing 700-kilogram. An experiment in propelling this ship was also conducted successfully in 1979 (Ref. 3). The ST-500 employed the propulsion system of an external magnetic field type. Photo 1.2 shows the ST-500 coursing a pool.

The research conducted by the Saji Group was extremely significant because it proved for the first time that a superconducting MHD thruster could propel a ship without a screw propeller.

Based on the research concerning superconducting MHD

Photo 1.2 Superconducting MHD propulsion model ship "ST-500" running in the water tank at Kobe Mercantile Marine University (By courtesy of Professor Emeritus Yoshiro Saji at Kobe Mercantile Marine University)

propulsion ship and the achievements made in vigorous research on superconducting technology at that time (for example, the magnetic-levitation train; in other words, the "Linear Motor Car" of the Japanese National Railways), the Ship & Ocean Foundation established the Research and Development Committee on Superconducting Magnetohydrodynamic Propulsion Ship. (The chairman is Yohei Sasakawa, currently the President of the Nippon Foundation) and launched research and development on a superconducting MHD propulsion ship in 1985.

The first objective of this research was to build a superconducting MHD propulsion ship (not a model but a full-sized ship equipped with its own energy source) to conduct experiments at sea. By conducting experiments at sea, the committee tried to take superconducting MHD propulsion out of laboratories to a practical application.

Among outstanding scholars from various fields, including mechanical and electrical engineering, were Prof. Saji, the foremost authority on superconducting MHD propulsion ship,and Mr. Yoshihiro Kyotani of the Japanese National Railways, the foremost authority on the magnetic levitation trains. In other words, the two top scientists in superconducting engineering at the time as well as other outstanding scholars and researchers in specialized fields were invited to join the Research and Development Committee.

As subdivisions of the Research and Development Committee, the MHD Ship Design Subcommittee (Chairman Seizo Motora, professor emeritus of the University of Tokyo) and the MHD Thruster Subcommittee (Chairman Kensaku Imaichi, professor emeritus of Osaka University) were established. The former undertook the development of the optimum hull form for ship, and the latter of a superconducting MHD propulsion system. These proceeded both theoretically and experimentally.

Other members, such as the late Prof. Tetsuo Takori of the University of Tokyo, Prof. Michio Nakato of Hiroshima University and Dr. Hiraku Tanaka of the Ship Research Institute of the Ministry of Transport, were on the MHD Ship Design Subcommittee, the Chief Researcher Mr. Hiroshi Nakashima at the Railway Technical Research Institute and Dr. Masayoshi Wake of the National Laboratory for High Energy Physics were on the MHD Thruster Subcommittee. All of the research staff on these subcommittees was so enthusiastic that numerous arguments broke out during project-related meetings as opinions collided. Occasionally someone even blurted out "I'm quitting" because the debates were so heated.

It was in such excitement that research and development progress began in 1989 for the construction of an experimental ship. In July 1990 the hull of the experimental ship with an overall length of approx. 30 meters, width of approx. 10 meters and displacement of 185 tons was completed at the Kobe Shipyard of Mitsubishi Heavy Industries (MHI). The experimental ship was christened "Yamato-1." The Committee Chairman Yohei Sasakawa came up with this name recalling the Japanese people's great aspiration for ships from ancient days, as symbolized by the great "Battleship Yamato" and the "Space Battleship Yamato" (in the popular comic strips). The name "Yamato" also implies an ancient word for "Japan."*4)

*4) "Yamato" was referred to in Japan's ancient (7th Century) history of mythology by a legendary figure Takeru no mikoto Yamato.

Thereafter, a pair of superconducting MHD thrusters were mounted aboard the Yamato-1. With comprehensive adjustments of all equipment, sea trials were finally successfully conducted on June 16, 1992.

This book summarizes the research and development achievements during the eight-year study on Yamato-1 as the world's first superconducting MHD propulsion ship.

The technological achievements during the development process, designs of the MHD thruster and hull and result of the sea trial are explained in details in the chapters to follow.

(1) Lieut. R.A. Doragh: Magnetohydrodynamic Ship Propulsion Using Superconducting Magnets, Transactions of the Society of Naval Architects and Marine Engineers, Vol. 71, 1963, pp. 370-386

(2) S. Way: Electromagnetic Propulsion for Cargo Submarine, Journal of Hydrodynamics, Vol. 71, 1968, pp. 49-57

(3) Akira Iwata, Yoshiro Saji: Chodendo niyoru Denjisuishin no Kagaku (Science of Electromagnetic Propulsion through Superconductivity), Asakura Shoten, 1991

CHAPTER 2

THE EXPERIMENTAL SHIP YAMATO-1

The Yamato-1 was designed as the world's first self-contained, sea-going superconducting magnetohydrodynamic (MHD) propulsion ship. Therefore, all the equipment required for navigation, such as the superconducting MHD propulsion system, the generator system, the steering system and auxiliary machinery*1), were onboard. The Yamato-1 is shown in Photo 2.1.

*1) Auxiliary Machinery
The machinery for feeding energy to propel a ship directly — i.e, such as a mechanism which turns screw propeller — is called the main engine. In addition to propulsion, a ship needs energy power supply for lighting, operating navigational equipment and lifting an anchor. The machinery for these purposes is auxiliary. Typical of these is the engine to run the generator.

This photo was shot during the Yamato-1's maiden cruise in Kobe harbor on June 16, 1992. Many journalists and naval personnel from overseas joined the Japanese mass media and shipbuilding industry came to witness the sea trials. Reuters and other media worldwide distributed news on the success of the Yamato-1's first sea trials. The article which appeared in The Washington Post is shown in Photo 2.2.

A ship equipped with a superconducting MHD propulsion system traveling on sea was such an epochal event.

Photo 2.1 (a) The Yamato-1 turning in the Kobe Harbor (1992)

Photo 2.1 (b) The Yamato-1 sailing in the Kobe Harbor (1992)

The Washington Post

WEDNESDAY, JUNE 17, 1992

Ship Sails on High-Tech, 'Silent' Drive

Japan Tests New Propulsion System Reminiscent of 'Red October'

By T. R. Reid
Washington Post Foreign Service

AGENCE FRANCE-PRESSE

Yamato 1 cruises in Kobe harbor, using a revolutionary no-propeller system.

KOBE, Japan, June 16—A mysterious silent propulsion system reminiscent of author Tom Clancy's fictional submarine "Red October" went to sea in real life today—not at a Russian naval base, but in Japan's most advanced high-tech shipyard.

While workmen at Mitsubishi Heavy Industries' Kobe yard beamed with pride, the 185-ton experimental ship Yamato 1 plowed through the choppy harbor here powered by a revolutionary no-propeller water-propulsion system based on recent advances in superconducting technology.

American, European, and Soviet researchers have tried since the 1960s to develop the so-called "magnetohydrodynamic" propulsion system—MHD, for short—but today's sea trial marked the world's first actual MHD voyage.

Accordingly, executives of the Japanese research consortium that has poured more than $40 million into the project compared today's trial run to the maiden voyage of the first steamship in 1807 and to the 1955 sea trial of the U.S. submarine Nautilus, the world's first nuclear-powered ship.

Coupled with a nuclear- or solar-powered engine, the propeller-free

See JAPAN, A32, Col. 1

Photo 2.2 The success of the Yamato-1 sea trial reported in the Washington Post (1992)

Specifications and Principal Particulars of the Yamato-1

We explain the specifications*2) and principal paticulars of the Yamato-1.The principal particulars are shown in Table 2.1.

*2) Specifications
To produce equipment and other items using machines or tools, a statement of particulars is needed, such as figures and ratings specifying its size, shape, performance and so forth. This is extremely important in manufacturing.

*3) See Chapter 8 on page 100 for the terms listed in the table.

Table 2.1 Principal Particulars*3) of the Yamato-1

YAMATO-1	
Length overall	30.0 m
Length between perpendiculars	26.4 m
Breadth molded	10.39 m
Depth molded	2.50 m
Design draft	1.50 m
Nominal displacement	185 tons
Max. design speed	8 knots
Hull material	Aluminum Alloy
Complement	10persons (Crew:3; Passengers:7)

"Displacement"*4) is the weight of a ship. A 185-ton displacement in the case of a passenger ship generally means a size large enough to carry 500 passengers comfortably. However, in the case of the Yamato-1, due to its extremely heavy propulsion system and overall related systems, the complement was only 10 people in spite of her 185-ton displacement.

"Hull" means the ship body without all of the equipment.

Aluminum alloy was used for the hull after taking its light weight corrosion-resistance*5) and non-magnetic properties into account.

A non-magnetic property is one which is not affected by a magnet, and since aluminum and stainless steel*6) are neither affected by magnets nor do they react to them, they are called non-

*4) Displacement
According to Archimedes' principle, when a ship is afloat, the weight of it is equal to that of the water equivalent to the volume of the ship below the water's surface.

*5) Corrosion resistant
The hull of a ship wears out by seawater in rust (chemical corrosion), since seawater is chemically active. The property or characteristic which is less inclined to corrosion is called corrosion resistance. If a different metal is used in parts of the hull, a circuit similar to battery is formed with other metals. The metal which becomes the anode begins to melt and is diminished. This process is called galvanic corrosion. Measures have to be considered against this process, too.

magnetic materials. On the contrary, material that are affected by and react to a magnet are called magnetic materials, and the typical material is mild steel.

Mild steel is frequently used for the hull of ordinary ships due to their low cost and easy welding characteristics. However, the Yamato-1 had to carry magnets onboard for thrust, and we thus decided to use a non magnetic aluminum alloy*7) for the hull in order to prevent the hull from any magnetic effect and, conversely, protecting the magnet from any effect from the hull.

These are the specifications and principal particulars of the Yamato-1, but there was a history of struggles and hardships for the research staffs of the Research and Development Committee before the completion.

One example was the displacement, or the weight of the ship. The Committee initially planned the ship to have a displacement of approximately 50 tons. But as the weights and sizes of the equipment and devices comprising the propulsion system became clear, the displacement at 50 tons become clearly unfeasible.

This 50-ton ship was planned to cruise at 8 knots by installing one unit of the superconducting MHD thruster on each side of the ship, port and starboard*8). However, when it came to designing precisely the propulsion system following the magnet format used on land, the weight of even a single thruster unit alone was found to weigh nearly 50 tons. In addition to the propulsion systems, the generators and prime movers for supplying electric power to the propulsion system had to be placed onboard. Therefore, the displacement had to be altered drastically.

The Committee then had to make the equipment and devices as smaller and lighter as possible by consolidating all their intelligence and know-how while expanding the ship's size. After they converged the best of the existing technology, the weight per thruster was successfully contained below 20 tons. The Committee finally managed to keep the displacement down to 185 tons.

How the weight reduction was achieved will be discussed later. It is no exaggeration to say that the success won in the weight reduction of the magnets led to the success of the world's first superconducting MHD-propelled ship.

It is because several countries at that time must have had the capability to build a superconducting MHD thruster on their own.

*6) Not all of the stainless steel is non-magnetic. Austenitic stainless steel does not show a magnetic property. In the case of Yamato-1, for example, the helium vessel with coils uses the austenitic materials. Austenite refers to the crystal composition of iron which makes up the steel.

*7) Aluminum alloy
Many ships are built of with aluminum alloy today, and most of the relatively small ferry boats and large pleasure boats are aluminum-made. The aluminum material employed for the Yamato-1 is JIS A5083, a magnesium-inclusive aluminum alloy.

*8) Port and starboard sides
The left-hand side of a ship (looking forward toward the bow when an observer is onboard) is called the "port" side and the right-hand side the "starboard" side.

However, building and fitting onboard superconducting MHD thruster powerful enough to run the ship proved to be extremely difficult, in both engineering and industrial technology because of its very large size and heavy weights. This was why these countries, despite their capability to build a superconducting MHD thruster, had not been capable of constructing an actual ship then.

The significance of the Yamato-1 lies in overcoming these difficult challenges.

General Arrangement of Yamato-1

The general arrangement is shown in Fig. 2.1.

The hull of the Yamato-1 is separated by 2 bulkheads*9) into 3 sections. From fore to aft are the wheel house, electrodes power supply panel room, and engine room.

As seen in the figure, the Yamato-1 is equipped with two units of the superconducting MHD thruster. They are housed in each bulge of the port and starboard sides of the hull.

This superconducting MHD thruster corresponds to the screw propeller of a conventional ship. Even a superconducting MHD thruster cannot obtain the propulsive power*10) to move the ship unless energy is supplied. As the power supply for the superconducting MHD thrusters, two diesel generator systems were mounted in the engine room of the Yamato-1. Each of the thrusters was set on the port and starboard sides in parallel*11), but the diesel generator systems were placed on a straight line (in tandem) on the upper deck in the engine room. Each of the two diesel-generator systems supplies energy to each of the port and starboard superconducting MHD thrusters independently.

In the propeller-driven system, a ship travels by the reaction force generated by the turning propeller, which protrudes into the water, in order to thrust water aft forcefully as it comes into the rotation plane of the propeller. Similarly, in the MHD propulsion system, the thruster must suck in water underwater and must discharge it aft in order to propel the ship. The ship is propelled forward by the reaction force generated by discharging the sucked-in water aft.

The propulsion system of the Yamato-1 was designed to suck in water underwater and thrust it aft underwater in a manner similar to the water jet system mentioned above, except that it discharges

*9) Bulkhead
Transversal separation walls are installed in several stations of the interior of a ship. These walls are called bulkheads. While strengthening the structural integrity of the hull, the bulkheads can keep the ship safe from sinking if they are watertight and the passageway is closed for confining water in a damaged section of the hull even if part of the hull is damaged and takes on water.

*10) Propulsive power
When a ship travels in water at a certain speed, the water always exerts a strong force on its hull opposite to the direction in which the ship travels. This is resistance. The ship travels at a certain speed despite the reverse force. As learned in mechanics, the energy, (magnitude of resistance) × (speed) when considered in terms of unit time, is required for travel against resistance. The ship obtains this propulsive power from the propulsion system. The propulsion system has to be supplied continuously with energy outputting propulsive power from the power supply.

*11) Parallel
Positioning such items as machines side-by-side on the left and right is called a parallel arrangement. In the case of ship machinery, each unit is placed on each side of the hull, port and starboard. Contrary to this arrangement, positioning fore and aft in a straight line is called a series or a tandem. In general, seats of a car are positioned in parallel and those of a light aircraft are positioned in tandem. In addition, there is another form of arrangement called a macadam which positions three items on vertices of a triangle.

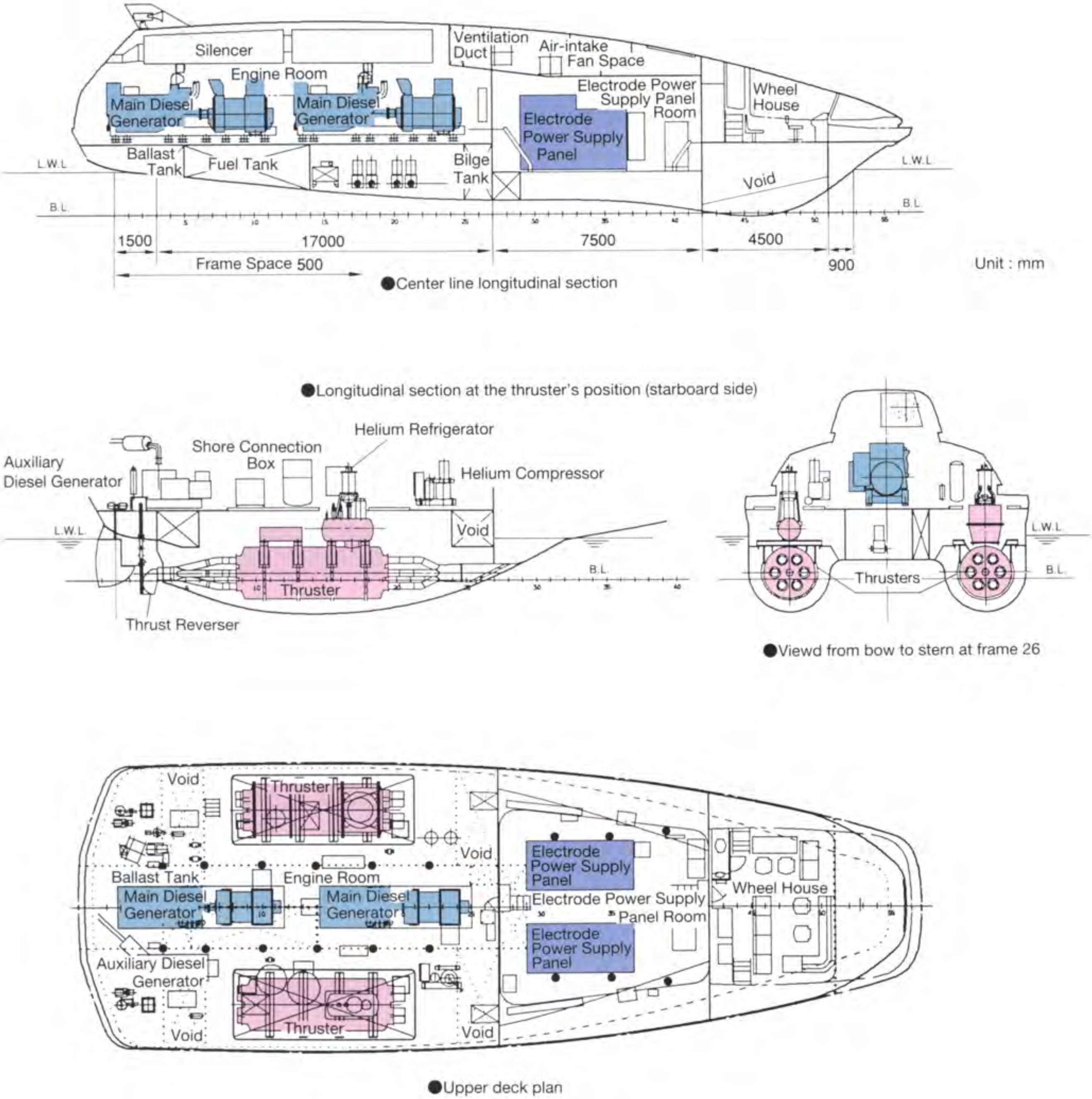


Fig. 2.1 General arrangement of the superconducting MHD propulsion ship Yamato-1

water forcibly after transferring energy to the water in an electromagnetic kinematical manner.

It is not necessary to discharge the sucked-in water underwater; it can be discharged into the air. The principle is the same. For example, the Jetfoils*12) in service, such as between Niigata and Sado or Osaka and Takamatsu, have a mechanism which sucks in water underwater and discharges it into the air, although it is propelled by a water-jet.

*12) Jetfoil
Boeing's high-speed ship, when in motion, is lifted above waterline by the hydrofoil. It travels at a high speed of 40 knots by sucking water from underwater and accelerates it to discharge water at the stern slightly above the water surface.

By taking into account the layout of the equipment, weight distribution, the ship's stability and speed in the case of the Yamato-1, it was decided to have her suck in water underwater and discharge it underwater.

The two superconducting MHD thrusters were built by different manufacturers. The starboard thruster was produced by Toshiba Corporation and the port thruster was made by Mitsubishi Heavy Industries.

There was a reason for not commissioning a single manufacturer to produce the two thrusters. Since construction of the Yamato-1 was undertaken as R&D of the superconducting propulsion system, one of the initial objectives was to widely share the knowledge gained with the shipbuilding and heavy industries. That was why the Committee specifically commissioned two different makers to build each of the two superconducting MHD thrusters.

Even though the orders were placed with two different manufacturers, the thrusters could not be used as a pair to move the ship if each of the port and starboard thrusters had different specifications and performance. Therefore, as shown in Table. 2.2, the basic specifications such as weight and size, and the final performance figures such as the magnitude of the magnetic field of the thrusters, were designed exactly the same. In addition to maintaining the basic specifications and performance, we had the two manufacturers compete with their technologies, utilizing their know-how*13) in detailed areas such as the diameter and number

*13) Know-how
Intangible values such as knowledge, experience and knack in manufacturing and handling machines and other processed products that can hardly be patented.

Table 2.2 Finalized principal specifications of the superconducting magnet

YAMATO-1	
Type	Superconducting magnets of internal magnetic field type containing 6 coils arranged on a circle
Coil	
Quantity	6 pairs
Magnetic field at bore center	4.0 teslas
Effective magnetic field length	3,000 mm
Cooling method	Cooling by immersion in liquid helium
Cryostat*14)	
Diameter	1,850 mm
Overall length	5,400 mm
Bore diameter at normal temperature*15)	260 mm
Weight	15 tons or less
Heat invasion	7 watts or less

*These were the performance figures provided to the manufacturers by the committee for the superconducting magnet design.

*14) Cryostat
A cryostat is a component of a superconducting magnet and is an insulation container for containing the superconducting coil and maintaining super-low temperature (-269℃). See Chapter 5 on page 59 for details.

*15) Bore
Six hollow portions, from one end to the other end, of a cylindrically shaped cryostat. A seawater duct in which seawater accelerated by receiving a Lorentz force flow is inserted to each bore. See Chapter 5 on page 62.

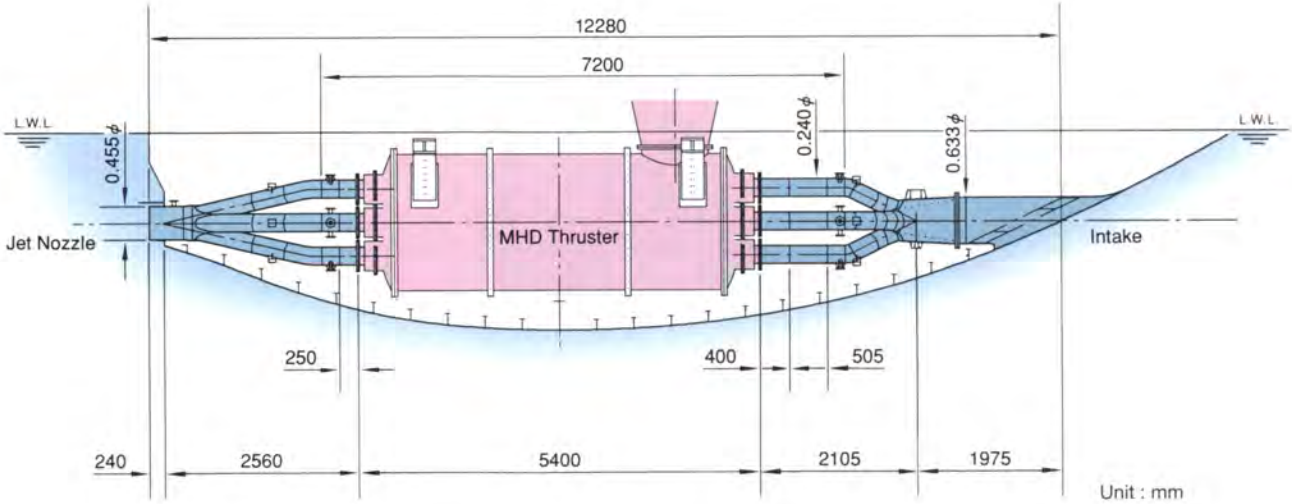


Fig. 2.2 Overall view of the superconducting MHD thruster and duct system housed in a bulge section

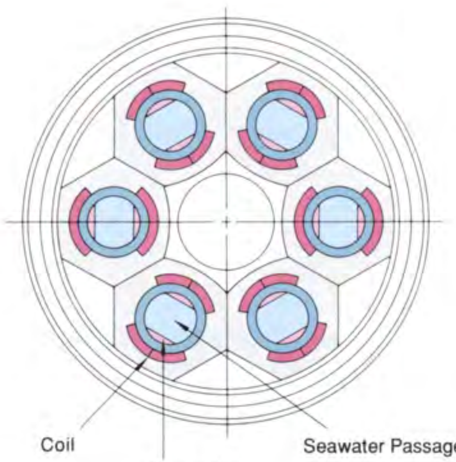


Fig. 2.3 Cross section of the superconducting MHD thruster

of turns of superconducting wire for the magnets.

The competition, in a positive sense, helps to advance the technology. The engineers involved worked very diligently to try to make the best product as a matter of pride. That aim was contained in placing orders for competitive manufacturing.

Interior of the Bulge Portion Containing the Superconducting MHD Thruster

Fig. 2.2 shows the elevation of the thruster in the bulge. The right-hand side of the figure is forward and the left-hand side aft of the ship. An opening to the sea is located on each of the forward and aft sections of the bulge, each functioning as a seawater intake and nozzle. Photo 2.3 shows the seawater intake and nozzle.

The equipment located at the center of Fig. 2.2 is the superconducting MHD thruster, and the interior of the thruster has an "annular arrangement of a six-unit thruster structure," with six unit thrusters positioned at equal intervals on a circle, as shown in Fig. 2.3.

The reasons for adopting this structure are discussed in detail in another chapter. But simply summarized, it was structurally impossible for a large-diameter single duct thruster to provide the performance desired, due to the limitation of the strength*16) of the superconducting coil in use. Six units of smaller-diameter unit thrusters were thus combined to form a single propulsion system.

This is comparable to an automobile or jet plane engine that has 4 or 6 cylinders instead of a single piston cylinder.

Six branching and six joining*17) ducts *18)are connected to the forward and aft ends of the thruster, and these ducts are also

Photo 2.3 Seawater intake and nozzle of the Yamato-1

*16) Strength
As explained later in this book, the electric wire of the coil is subjected to strong electromagnetic force created by mutual action of the magnetic field induced by the coil wire itself and the current flowing through it. Strength means the wire's capacity to withstand the electromagnetic force in order to prevent it from being deformed or snapped off.

*17) Branching and joining
The connection of a single pipe or duct to its multiple counterparts, so that the flow in the single pipe branches out into plural flows, is called branching. On the contrary, the connection of multiple pipes to a single pipe to join flows into one is called joining. Compare these with a tributary or a branch of a river.

*18) Duct
Refers to the passage of pipes where air or water flows. In engineering, it is normally used in relatively large cross-sectional pipes.

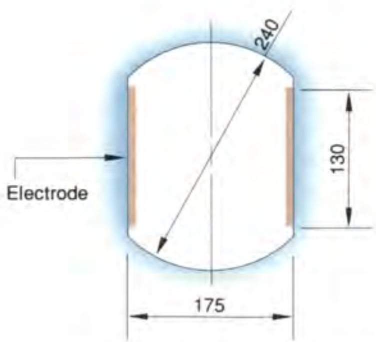


Fig. 2.4 Cross section of a seawater duct in the superconducting MHD thruster

connected forward and aft of the bulge.

The flow of seawater sucked in from the intake of the bulge passes through the thruster and is discharged from the nozzle on the aft end of the bulge.

The seawater coming in via the intake duct is immediately split into six streams to flow through smaller-diameter ducts. These six ducts are connected to each of the six unit thruster seawater ducts.

Fig. 2.4 shows a cross-sectional view of the seawater duct where force is exerted on the seawater in the unit thruster. In other words, the anode (positive electrode) and cathode (negative electrode) are positioned on either side of the seawater duct, parallel to the duct axis, and direct current flows across from the anode to the cathode, at right angles with the magnetic flux. As a result, energy is generated in the direction of the seawater flow in a manner known as "Fleming's Left-Hand Rule" to be explained later. The seawater receives high energy here. The odd point is that the force is exerted on the water by the space between the electrodes, and there is no need for an impeller or screw propeller. This is incredible to people who see the MHD thruster for the first time.

The seawater charged with high energy flows out of the six unit thrusters and then flows into a single duct to reemerge as a single flow. This single duct is the jet nozzle for yielding thrust. In other words, the seawater sucked in at the intake is accelerated by the MHD thruster and is then discharged out of this nozzle as a high-speed jet. Therefore, as explained earlier, the propulsion system we produced was a kind of water jet.

The reason for merging the six ducts into one nozzle was that it is more efficient to discharge high-energy seawater out of a single nozzle than out of the six separately, in an unmerged flow. A similar technique is also applied to jet engines.

Since the Yamato-1 has a thruster on both port and starboard side, it travels forward in reaction to the jets discharged from the two nozzles at high speed. This makes it equivalent to a twin-engine aircraft. Even some conventional screw-propeller ships have 2 or 3 screws.

Incidentally, the Yamato-1 was constructed as an experimental ship, but since from the outset of the project its purpose was to travel on the sea, its design, construction and operation are regulated by current maritime related laws just like any other ships navigating on the water.

Having satisfied all the requirements set by the relevant laws and ordinances, the Yamato-1 received a Certificate of Ship's Nationality and a Ship Inspection Certificate issued by the Ministry of Transport. These are shown in Photo 2.4.

船舶国籍証書

第25058号

番号	133000	総トン数	166 トン
信号符字	JG5168	容積	閉囲場所の合計容積 — 1019・306立方メートル
種類	汽船		上甲板下の容積 — 547・842立方メートル
船名	ヤマト 1		上甲板上の容積 — 471・464立方メートル
			船首楼の容積 — / 立方メートル
			船橋楼の容積 — / 立方メートル
船籍港	東京都		船尾楼の容積 — / 立方メートル
			甲板室の容積 — 471・464立方メートル
船質	軽合金		その他の場所の容積 — / 立方メートル
帆船の帆装			除外場所の合計容積 — / 立方メートル
機関の種類及び数	発電機 2箇		船首楼の容積 — / 立方メートル
推進器の種類及び数	電磁推進器 2箇		船橋楼の容積 — / 立方メートル
造船地	兵庫県 神戸市		船尾楼の容積 — / 立方メートル
造船者	三菱重工業株式会社		甲板室の容積 — / 立方メートル
進水の年月	平成 3年 4月		その他の場所の容積 — / 立方メートル

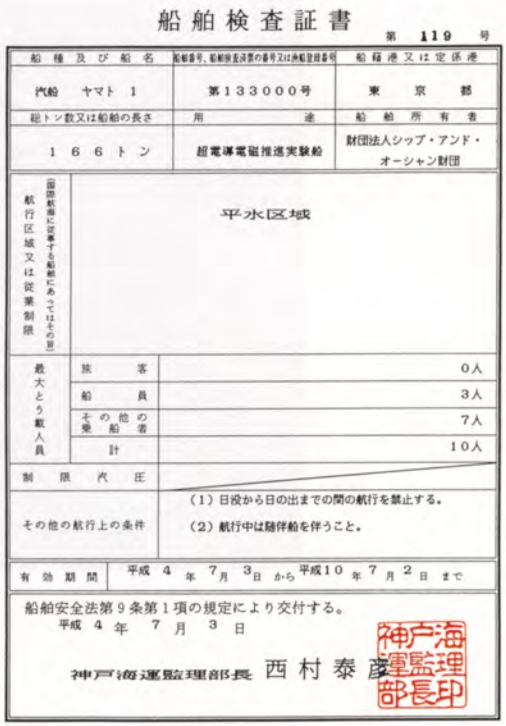
尺度
上甲板の下面において船首材の前面より船尾材の後面に至る長さ — 28・50メートル
船体最広部においてフレームの外面より外面に至る幅 — 10・42メートル
長さの中央においてキールの上面より舷側における上甲板の下面に至る深さ — 2・97メートル

所有者　東京都港区虎ノ門一丁目15番16号
財団法人
シップ・アンド・オーシャン財団

上記の事項はいずれも正確であり本船は日本国の国籍を有することを証明する。
平成 4年 6月 30日

日本国
関東運輸局東京海運支局

Photo 2.4 (a) Certificate of Ship's Nationality



船舶検査証書

第 119 号

船種及び船名	船舶番号、船舶検査済票の番号又は漁船登録番号	船籍港又は定係港
汽船 ヤマト 1	第133000号	東京都
総トン数又は船舶の長さ	用途	船舶所有者
166トン	超電導電磁推進実験船	財団法人シップ・アンド・オーシャン財団

航行区域又は従業制限（国際航海に従事する船舶にあってはその旨）	平水区域	
最大とう載人員	旅客	0人
	船員	3人
	その他の乗船者	7人
	計	10人
制限汽圧		
その他の航行上の条件	(1) 日没から日の出までの間の航行を禁止する。 (2) 航行中は随伴船を伴うこと。	
有効期間	平成4年7月3日から平成10年7月2日まで	

船舶安全法第9条第1項の規定により交付する。
平成 4 年 7 月 3 日

神戸海運監理部長 西村泰彦

Photo 2.4 (b) Ship Inspection Certificate

CHAPTER 3

THE BASICS OF MHD PROPULSION

Principles

One of the basic principles of electromagnetism is "Fleming's Left-Hand Rule." Open your left hand with your thumb, index and middle fingers perpendicular to each other. Direct the magnetic field *1) in the direction of your index finger and let the electric current flow in the direction of your middle finger. According to the Fleming's Left-Hand Rule, electromagnetic force, also known as Lorentz*2) force, will be induced in the direction of the thumb.

The propulsion principle of superconducting MHD propulsion ship is an application of the Fleming's Left-Hand Rule, and is illustrated in Fig. 3.1. As shown in the figure, a bar magnet is set in place onboard the ship. The lines of magnetic force*3) coming out of this magnet form a magnetic field. To let the lines of the magnetic force flow, the hull is made of non-magnetic materials such as aluminum and stainless steel. Therefore, a magnetic field arising from the bar magnet is formed in the seawater surrounding the hull.

The anode and cathode are installed symmetrically on either side of the wall of the bottom of the hull on a plane in the longitudinal direction to or in a near perpendicular angle to the magnetic field.

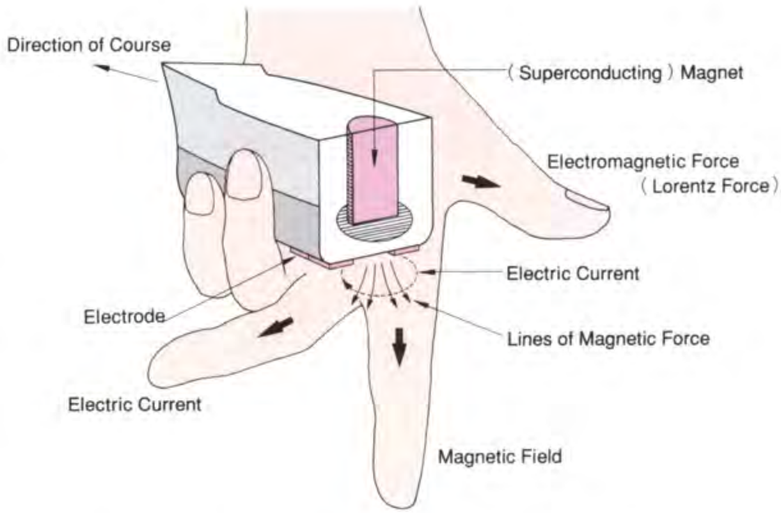


Fig. 3.1 The external magnetic field-type MHD propulsion principle and Fleming's Left-Hand Rule

*1) Magnetic field.
Generally speaking, there are forces of one object acting on another throughout space, and they produce an effect with no physical contact between the objects involved, such as gravitational force and repulsive force generated by two positive electric poles, unlike the force generated by the collision of two moving substances.
When we think of these forces, we use the concept of a field. For example, I live on the earth. Therefore, gravitational force is always acting on me to pull me downward. In such a case, it is considered that I am positioned in a space where the earth's gravitational force exists, or where the gravitational field is located. Naturally, there exists an attraction field created by myself as well. But if we think of the relation between the earth and myself, and my motion with respect to the earth, it is best to think that I am in the earth's gravitational field.
There are objects causing such forces. In the case of forces acting through a space, there is an electric field which is the zone of space around the electric charge where electrostatic force is acting, a magnetic field as a space in which magnetic force is acting, and a gravitational field created by gravitational force. These are the fields we normally experience.

*2) Lorentz force.
The force acting on electrons in motion in the magnetic field is called Lorentz force. In this book, it is expressed in terms of relations between a magnetic field and electric current. However, since the electric current is the current of electrons (the electrons move from negative to positive poles in the opposite direction of the electric current flow), their substance is the same.

*3) Lines of magnetic force.
There is a well-known experiment in which

iron filings are sprinkled over a sheet of white paper uniformly and a horseshoe magnet is placed beneath the paper, and then the paper is shaken lightly. The iron filings coalesce into a beautiful pattern of visible lines connecting both ends of the magnet. These lines are the lines of magnetic force. When a small compass is placed on these lines, it points to the tangential direction of these lines. In other words, the N pole of the compass points toward the S pole of the horseshoe magnet in alignment with lines. We note that the lines of magnetic force point in the direction of the N pole of this small compass, or in the direction of N to S of a horseshoe magnet (by convention). The distribution of these lines is dense in the vicinity of both poles. This clearly indicates that the areas where the distribution of the lines of magnetic force is most dense is where the magnetic force is strongest. In practice we should deal only with the area where the density of the lines of magnetic force is greater than a certain degree.

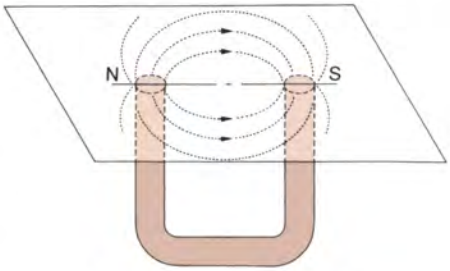


Figure Lines of magnetic force

Based on Fleming's Left-Hand Rule, the electromagnetic force, or the Lorentz force, acts on the seawater carrying the electric current.

This Lorentz force act to thrust the seawater aft. A reaction force is then exerted on the ship's magnet. Since the magnet is fixed to the hull, the ship is propelled forward.

This is the basic principle of electromagnetic, or magnetohydrodynamic (MHD), propulsion.

Types of MHD Propulsion

MHD propulsion is classified into two types by the difference in the kind of magnetic field and in the action zone respectively. There are two kinds of magnetic fields, the alternating current (AC) magnetic field and the direct current (DC) magnetic field.

The AC magnetic field induces electromagnetic force by the interaction of the magnetic field and the current induced in seawater. This method does not require electricity to be conducted directly into seawater. Therefore, as an MHD propulsion type, it is preferable to the DC magnetic type. Unfortunately, however, a practical application of an AC superconducting magnet was not available. For the MHD propulsion system of the Yamato-1, we therefore had no choice but to use the DC magnetic field.

The MHD propulsion type are classified by electromagnetic action zones into two types: 1) the external magnetic type, which propels a vessel by using electromagnetic force generated in seawater around the hull (Fig.3.1); and, 2) the internal magnetic field type, which propels a ship by electromagnetic force generated in seawater in the duct which runs through the hull longitudinally as a type of water-jet (Fig.3.2).

The characteristic of each type indicates that the advantage of the external magnetic field type, in comparison to the internal type, is its simple system configuration. Therefore, this external magnetic field type is frequently used in propelling model ships. This type was the one used in the experiments conducted by S. Way and Prof. Saji's group at Kobe Mercantile Marine University (Chapter 1). The propulsion system of Prof. Saji's SEMD-1 (Fig. 3.3) is suspended from the bottom of the hull.

However, the external magnetic field type has one negative effect: it exerts a very great effect on the external environment, by creating a powerful magnetic field in the seawater around the hull

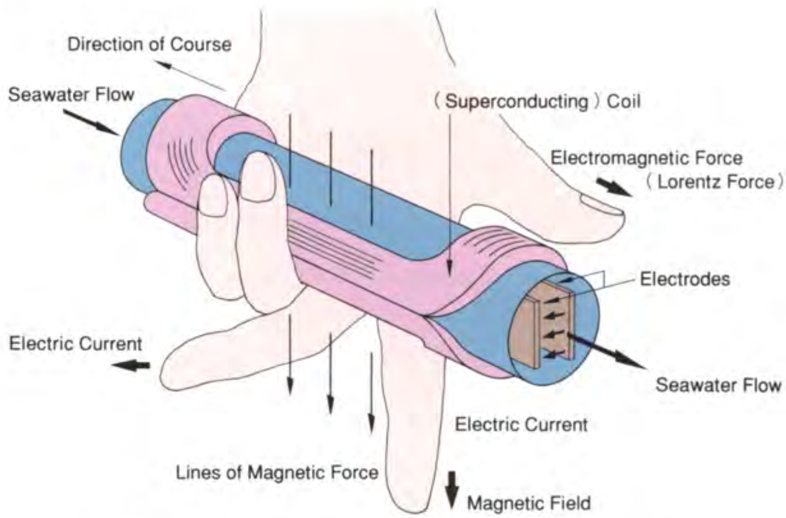


Fig. 3.2 The internal magnetic field-type MHD propulsion principle and Fleming's Left-Hand Rule

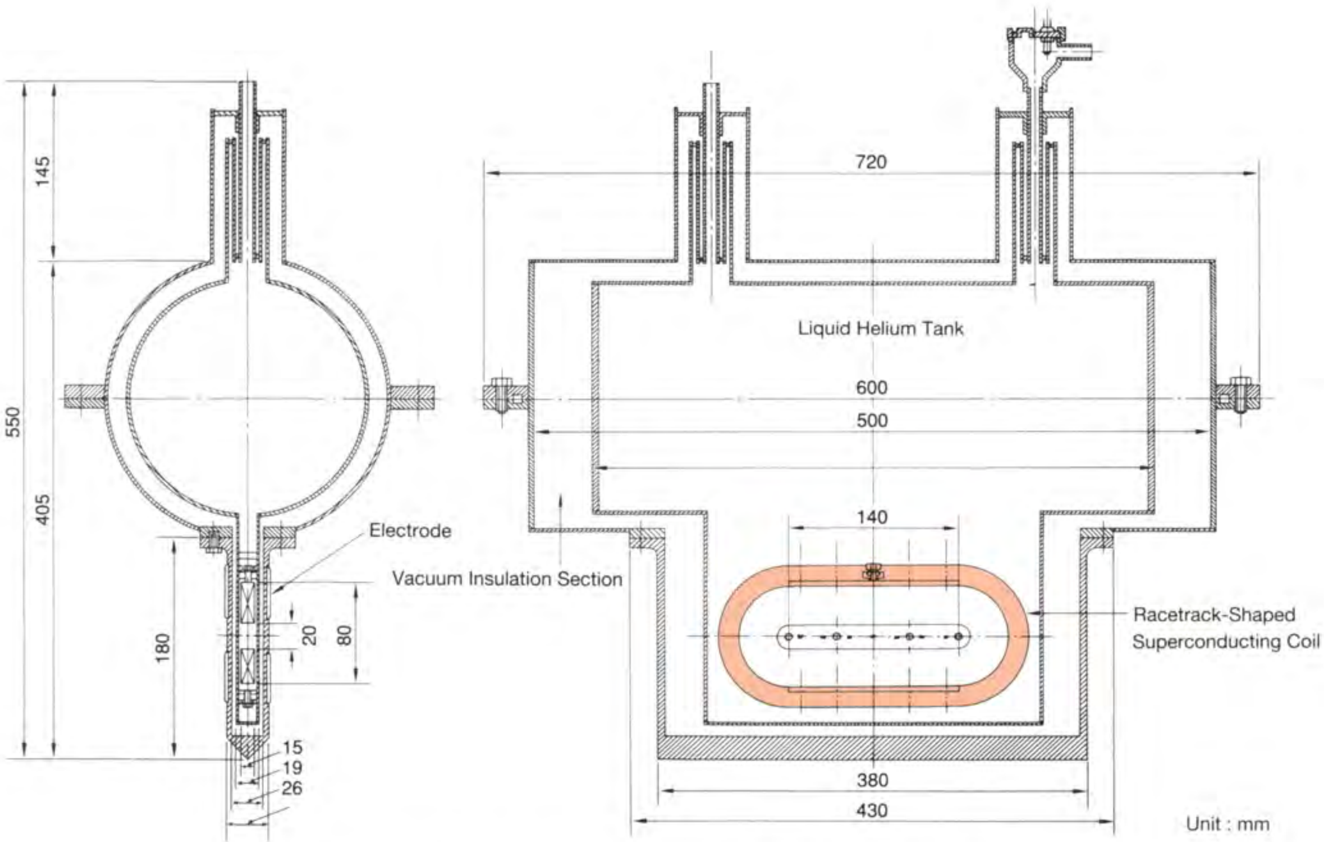


Fig. 3.3 Superconducting MHD thruster used for the model ship "SMED-1"
(Chodendo niyoru Denjisuishinn no Kagaku (Science of Electromagnetic Propulsion through Superconductivity) by Akira Iwata and Yoshiro Saji, Asakura Shoten, 1991)

and producing a strong electric current through the water.

For example, if there is an iron object in the sea, it will be drawn to and stick to the hull bottom in response to the strong magnetic field. If there is an electrical instrument nearby, the effect of the strong magnetic field causes electromagnetic disruption.

Furthermore, there is an ecological problem. Birds are known to shy away from strong magnetic fields. Even though it has been said that strong magnetic fields have no effect on humans, there is no clear experimental data to prove that contention. And we know, at least, that there must be some effect on people who have pacemakers or hearing aids. For all these reasons, it is not appropriate to employ the external magnetic field type for actual

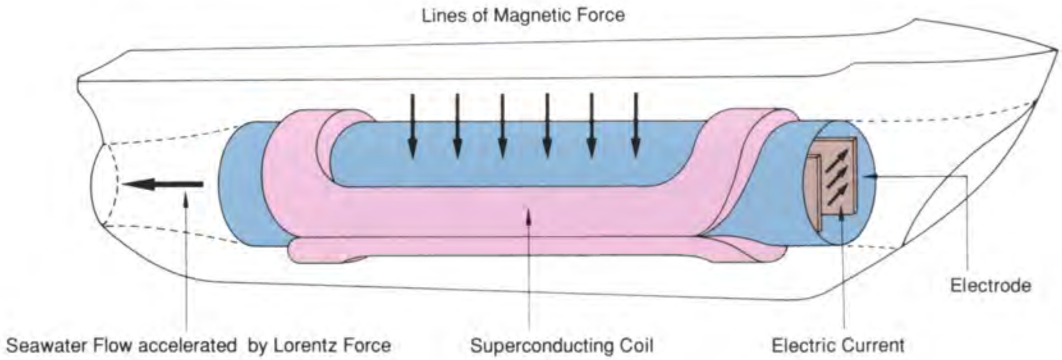


Fig. 3.4 Conceptual illustration of internal magnetic field-type MHD propulsion ship
Propelled by the reaction force of seawater discharged from the stern opening after it comes through the bow opening and is accelerated by the superconducting MHD thruster located at midships

ship apart from model ships.

The internal magnetic field type on the other hand has the disadvantage of less efficiency in ship propulsion because fluid friction is created in the duct due as the seawater flows through it. But it has the advantage that the action zones of the magnetic and electric fields can be confined easily within a part of the duct. In addition, preventive measures can be taken against possible magnetic leakage.

For these reasons, it was decided to adopt one for the Yamato-1 the internal magnetic field type rather than the external type taking into account these effects on the external environment.
The internal-magnetic field type of the MHD propulsion system employed for the Yamato-1 is explained below in more details.

Model of the Internal Magnetic Field Type MHD Thruster

Fig.3.4 shows a conceptual drawing of the internal magnetic field type MHD thruster adopted for the Yamato-1. The duct runs through the hull longitudinally, connected to the sea via openings at the bow and stern. Water enters the duct through the bow opening and exits from the stern opening.

The duct is made of non-magnetic material, so it does not affect the magnetic field. Two saddle-shaped coils facing each other are mounted on its exterior. These two coils induce a powerful magnetic field in the space within the duct perpendicular to the axis of the duct.

There is also a racetrack-shaped coil for inducing a magnetic field inside the duct. But the magnetic field induced by a racetrack-shaped coil cannot be used effectively. On the contrary, the saddle-shaped coil induces another and intensive uniform magnetic field inside the duct which can be used effectively. Thus the saddle-shaped coil was used for the Yamato-1.

An anode was installed on one side of the inner wall and a cathode on the opposite side of the duct where the magnetic field is induced (Fig. 3.4). Polarity is so defined that one of the two is positive and the other is negative. The polarity here is set so that the current flows through the seawater in a direction perpendicular to the magnetic field and the Lorentz force acts on the seawater in the direction of the stern, according to Fleming's Left-Hand Rule.

Inside the duct, where the seawater is energized by the Lorentz force, is the action zone of the magnetic and electric fields*4). In this action zone, the electricity-conducted seawater receives the Lorentz force in the form of volumetric force, acting proportional to the volume of seawater just as the gravitational force acts. And the direction of the force coincides with the direction of the axis of

*4) Electric field.
Electric force acts in the zone of space around the electric charge. This zone of space is called the electric field caused by the electric charge.

the duct — that is toward the stern. Therefore, the seawater flowing through the duct very much resembles the water flowing down the duct perpendicular to the gravitational field. In other words, the pressure of the seawater increases as it flows toward the stern.

According to Bernoulli's equation, seawater in this zone receives energy in the form of pressure. Then the highly pressurized seawater in the duct is thrust aft. A nozzle with a narrow outlet equipped at the stern to discharge seawater in a jet converts the pressure energy into kinetic energy. The reaction force of this jet-blast propels the ship forward.

Features of MHD Propulsion

MHD propulsion has the following outstanding features differing from conventional screw-propeller propulsion:

(1) Conventional propeller propulsion has power transmission mechanisms such as the propeller and the shaft that transmits torque to the propeller, and they are configured to transmit powerful force to the hull. With MHD propulsion, there is no such mechanical power transmission system, so there is no vibration or noise due to such a mechanism.

(2) Since there is no rotating shaft running through the hull, no stern tube*5) is needed. Therefore, no seawater leaks into the hull and no bilge *6) leaks into the sea.

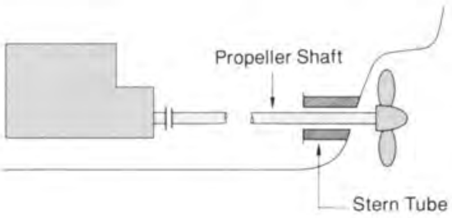
(3) Since there is no propeller, it is possible to design the stern shape much more freely than that of a conventional ship. *7)

(4) Because the thrust is proportional to the electric current flowing through the seawater when the magnetic field of the superconducting magnet is constant, both forward and astern speed control *8) is a simple matter of changing the direction and/or strength of the current. Simply put, the speed of a ship can be controlled by merely controlling the electrical current.

(5) If a screw propeller turns at high speed, cavitation *9) is created and the bubbles lower the thrust and efficiency as well as generating noise and vibration. Since MHD propulsion is less likely to cause cavitation, high-speed propulsion is possible.

Putting an MHD propulsion ship into practical use has great

*5) Stern tube.
A shaft from the engine or a gear box connected to the engine onboard is connected with the screw-propeller shaft to turn the propeller. Therefore, the propeller shaft must be led through the shell of the hull inboard from outside. The stern tube is a device that functions to support the propeller shaft in the shell area while preventing water from entering. The inside of the tube is made of a special material in order to grip the propeller shaft while permitting it to turn smoothly and yet prevent water penetration. A wood called Lignumvitae produced in Latin America was used for this purpose in the past, but a hard rubber-like organic compound is used today. Because of such a structure, a bit of seawater comes in from outside and bilge water leaks out. Even more complex and sophisticated devices are used in this section of large modern ships.



Figure

*6) Bilge.
Dirty water trapped in the very bottom of the hull.

*7) Stern shape.
Since important components such as a screw propeller to generate thrust and a rúdder to guide a ship are installed at the stern, design and construction must take into account such factors as the flow of water, strength and vibration of water into account.

*8) Astern.
In ship propulsion the emphasis, obviously, is placed on moving the ship. It is less likely to have a device installed specifically for going astern. The screw propeller is commonly turned in reverse for moving backward. Therefore, a reverse turning

significance because of these outstanding characteristics. When MHD propulsion ships become operational, it is likely that they will be used widely as super-high-speed ships because they could be much faster than any screw propeller-driven ship. MHD propulsion ships can be envisioned as passenger ships with extremely low noise and vibration, and even as research and observation ships with outstanding performance utilizing their ease of speed control.

mechanism using gears similar to those for an automobile are used for small craft. In large craft if the propeller and the engine output shaft are directly connected, the engine turn is reversed.

*9) Cavitation.
The reason why a screw propeller functions as a propeller is that water pressure exerted on the propeller's surface facing the direction of its rotation is higher than the pressure on the surface facing the opposite direction of the rotation. The pressure distribution on both surfaces of the propeller is not even; there are low and high pressure areas. If the pressure of the lowest pressure area on the surface facing the opposite direction of the rotation drops lower than the water vapor pressure corresponding to the water temperature, then water vaporizes locally to create a cavity. This is the cavitation phenomenon. If this continues, then a high-frequency underwater sound is generated when the cavitation is carried downstream and collapses. If the phenomenon is severe, holes like bug bites appear on the propeller surface.

CHAPTER 4

PRACTICAL APPLICATIONS PROBLEMS

The Research and Development Committee decided to adopt the internal magnetic field type as the propulsion system for the Yamato-1. However, there were several difficult problems that had to be solved before gaining sufficient power from the MHD thruster to be able to install it on the Yamato-1. These problems were solved eventually in one way or the other, but it took time and painstaking work to produce the solutions.

The first problem was how to confine the powerful magnetic field so that it would not leak into the external environment. External and internal magnetic field type are not different in generating Lorentz force from a powerful magnetic field.

But the external magnetic field type does constantly expose its powerful field type does constantly, while the internal magnetic field type makes it easier to confine the magnetic field inside the duct. And even though the Research and Development Committee adopted the internal magnetic field type, our scientists found they could not completely prevent magnetic field leakage from the duct. Therefore, we somehow had to come up with a way to prevent in so far as it was possible magnetic field leakage.

Theoretically all this takes is to wrap a magnetic shielding material around the system. However, this was easier said than done, and it developed that it was not a realistic way to solve the problem. It would have required that as much time, labor and equipment to produce a shield to minimize leakage as it would cost to produce a strong magnetic field.

We held thorough discussions on a configuration in which the magnetic flux would only be inside the propulsion system. As a result we decided to employ an "annular arrangement of a six-unit thruster configuration" (to be discussed in detail in the next chapter) to minimize magnetic field leakage. We were able to proceed with the internal magnetic field type since particular configuration prevented leakage while maintaining the power of the magnetic field. It is no exaggeration to say that the solution to this magnetic field leakage problem was the essence of the development of the thruster itself.

The second problem we encountered was that the concept of an internal magnetic field type had existed for many years, but how efficiently it would function as a propulsion system was not known. This is also true of the propeller propulsion in general use today.

Not all the energy generated for moving the ship is used to propel it. Part of the energy is released in the form of heat or used up by mutual friction of machines. The energy used for propulsion is actually only 20-30% of the total energy output. Of course, the higher the ratio of the total energy output used for propulsion the better is the propulsion efficiency.*1)

From the outset of the project the Yamato-1 was thought of as a vehicle that could travel on the sea even though it would be an experimental ship. This efficiency issue had to be tackled before the internal magnetic field type was applied practically. Specifically, the issue was: how strong would the magnetic field have to be to provide an efficiency equivalent to that of propeller propulsion? Unfortunately, because no MHD propulsion ship had ever existed, little research had been done previously on the subject.

Of course, the SEMD-1 of Prof. Saji and ST-500 had done some research on this problem and there were materials on them. But these used the external magnetic field type. Thus we built a model ship with the internal magnetic field type and let it run experimentally on a pool in the Tsukuba Institute. At the same time, we built a superconducting MHD propulsion system, which became a prototype for the Yamato-1's unit thruster. We tested it in the Tsukuba Institute to obtain detailed data.

We also decided to conduct our own theoretical research on the magnitude of the magnetic field and propulsive efficiency. The achievements of this research are discussed in detail in "The superconducting magnetohydrodynamic propulsion system of the Yamato-1 design, structure and performance" written jointly by Kensaku Imaichi, Professor Emeritus at Osaka University, and Hiroshi Tamama of the Ship & Ocean Foundation. Both are members of the Research and Development Committee, and submitted this paper to the Institute of Marine Engineers). (Incidentally, this paper received three awards, including the Silver Medal from the Institute of Marine Engineers.)

We will deal only with the outcome here. As a result of this research, we found that a field of at least 20 to 30-tesla*2) magnetic strength was needed for the MHD propulsion system. One tesla stands for 10,000 gauss. It meant that if we could use a strong magnetic field of 200,000 to 300,000 gauss, an efficiency

*1) Efficiency
An ordinary ship is equipped with a diesel engine as the prime mover. The fuel of diesel engine is either heavy or light oil. These fuels have approximately 10,000 kcal/kg = 41,850 kJ/kg (lower order) calorific power. Approximately 35% to 40% of this energy is transmitted to the piston through the burning of the fuel. This ratio is the thermal efficiency of that operation. The remaining 65% to 60% of thermal energy is expelled from the engine along with cooling water or exhaust gas. Around 98% of the energy the piston receives goes out of the crankshaft as mechanical output. This 98% is the engine's mechanical efficiency. The remainder is lost as friction related to piston and crankshaft movement in the engine which is necessary to raise the lubricant's temperature. The output from the engine is transmitted to the propeller shaft, and most of it is then transmitted to the screw propeller with 2% to 5% lost from the shaft and stern tube in the form of friction. Therefore, the ratio of the engine output, converted into the power required, meaning the transmission efficiency, is 95% to 98%. Part of the power supplied to the screw propeller is used for propulsion and the remainder used as the kinetic energy of the water that is pushed aft. The ratio of energy used effectively for thrust to energy transmitted to a screw propeller is called propulsive efficiency.It range from 50-70%.Therefore, only a small fraction of the calorific power supplied through burning of fuel, as indicated earlier, is converted to propulsion power.
According to the theory of thermodynamics, heat engines whether diesel, gasoline, jet or steam, cannot convert all the calories generated by burning fuel into mechanical work. While the diesel engine referred to here has one of the highest efficiencies, the locomotive steam engine equipped has the highest efficiency of only about10%.

*2) Tesla.
The SI unit (International System of units of measurement) of the magnetic field is the tesla (T). A capital T is used to denote the unit. A unit used frequently in electromagnetics is gauss (G), and

1 T = 10,000 G.

The tesla is named after Nikola Tesla (1857-1943), an electrical engineer, who was born in Croatia and emigrated to the United States at the age of 27 and naturalized. He established the basis of the present-day alternate current transmission system.
The gauss is the unit, named after the great German scholar Karl F. Gauss (1777 - 1855), used for measuring magnetic flux density, decided upon at the International Electrotechnical Commission in 1930.
The strength of the earth's magnetic field in Japan is approximately 0.46 G, or 4.6×10^{-5} T. This indicates that 1 T is a considerably strong magnetic field.
Tesla and gauss are fully spelled out in this book most of the tiem to avoid unnecessary confusion with other symbols and abbreviations.

equivalent to that of propeller propulsion could be achieved.

However, it was utterly impossible at the time the Research and Development Committee was established to create such a strong magnetic field for the Yamato-1 propulsion system. Even today, it is considered extremely difficult to generate such a powerful magnetic field for a ship's propulsion system.

Insofar as the magnitude of the magnetic field was concerned, a 20-to-30 tesla magnetic field had been achieved even then. And today, the achievement of far stronger magnetic fields of, say, 50 and 80 teslas, are reported in the sphere of experimental physics. However, the magnetic field in each of these cases is small, with a volumetric size and span of only a few cubic centimeters, and is achieved only momentarily. Therefore, it was impossible to achieve a 20-to-30 tesla strength magnetic field uniformly and continuously

throughout a sufficiently larger space.

The Research and Development Committee then considered setting a target value of 4 teslas, based on the technological level at that time, and after evaluating the magnetic field attainable with a sufficient magnitude and the span of space to serve our purpose.

With a 4-tesla magnetic field magnitude, the propulsive efficiency attainable with an MHD thruster would be only 2% or less. Increasing the propulsive efficiency, needless to say, would require a stronger magnetic field. The reason why we could only set 4 teslas as the target value was that it was not easy to produce a magnetic field magnitude of even 4 teslas within a sufficient space and with sufficient duration.

Frankly, it was considered doubtful whether even a 4-tesla magnetic field could really be achieved. But the aim was that by setting the target and making an effort to achieve it could contribute to technological progress. This view prevailed, so the design for the magnetic field magnitude was set at 4 teslas.

There was another reason why we could not set the target value at more than 4 teslas. Even if we would have succeeded with a stronger magnetic field exceeding 4 teslas, it was extremely difficult to structurally make the coil which was light enough in weight to be mounted onboard and capable of bearing the magnitude of the magnetic field.

What this means in other words is that a strong force is exerted on the cross section of the coil wire or the cross section of the structure supporting the coil, due to the effect of the strong magnetic field generated by the coil itself and the current flowing through the coil. This is called "hoop stress" *4), and if the coil is not strong enough to withstand hoop stress, it will break off.

*4) Hoop stress
Hoops are made of steel wires or braided bamboo to tighten kegs and barrels to set staves in place. Tightening staves means the reaction force is also acting on the hoop as tension. This tension acts on the cross section of the hoop is called "hoop stress."

Suppose you make an electric magnet by winding a copper wire around a nail and conduct a strong current through the wire. The copper wire is cut off by the hoop stress caused by the strong magnetic field induced by the wire itself, if it does not have enough strength to withstand the magnitude of the magnetic field.

What is worse, in the case of a superconducting coil, the conducting wire material itself is often much finer and weaker than normal conducting wire material. Unless some adequate countermeasure is taken, the superconducting wire is easily snapped off by hoop stress.

One possible solution is a coil holder, which fortifies the coil with a sturdy material such as steel and concrete. But this method could not be used for an MHD thruster on a ship. If the coil is fortified with steel or concrete, the weight of the MHD thruster would be much too heavy for onboard installation.

Furthermore, there was the difficulty of a coolant to cool the superconducting coil. To create a superconducting state (the state in which the electric resistance becomes zero), the coil had to be cooled down to a very low temperature. To achieve that low temperature, liquid helium at -269℃ had to be used as a coolant in order to cool a Niobium-Titanium (Nb-Ti) *5) alloy as a superconducting material. Therefore, the thermal capacity of the conducting wire and the structure around it had to be kept as uniform as possible.

*5) Nb-Ti
Nb-Ti denotes a niobium-titanium alloy. See *9) and *10) of this chapter for alloy and intermetallic compound.

For these reasons, the Research and Development Committee set the final target magnitude of the magnetic field at 4 teslas in order to proceed with the development of MHD thrusters that could actually move the ship.

Superconductivity (Ref.1, 2)

The superconducting phenomena must be explained before proceeding with a discussion of the superconducting MHD propulsion system of the Yamato-1 itself. As mentioned earlier, a powerful electromagnetic coil is required to generate the magnetic field necessary for magnetohydrodynamic propulsion. Ordinary and familiar material such as a wire made of copper, silver or aluminum, at normal temperatures cannot be used as this coil cable. The reason, as mentioned already, is that all of these wires have electrical resistance. It is not easy to remove the large volume of the heat generated*6) due to electrical resistance in association with the strong current and long conducting wire needed to create a strong magnetic field. Therefore, the coil for the MHD thruster for a ship with limited weight restrictions cannot be produced unless a wire made of a superconducting material with no electrical resistance is used.

The electrical resistance of a wire made of a normal material under normal temperatures is proportional to its length and inversely proportional to its cross-sectional area. In brief, the thicker and shorter the wire, the lower the electrical resistance, even though the wire is made of the same material. To express the electrical resistance of the material, the resistance per 1 m length and 1 m^2 cross-sectional area, or resistivity ρ (Ωm) is used. In the case of a pure metal, this resitivity is lowered as the temperature drops*7).

This was already well known to the experimental physicists early in the 20th century. The major issue was what would occur to the electrical resistance of metal when the absolute temperature was zero, 0 K*8). Three possibilities were assumed: when the temperature is lowered toward absolute zero, (1) the electrical resistance decreases continuously and reaches zero as the temperature becomes 0 K; (2) not so, because once the temperature reaches a certain point, the resistance becomes constant below that temperature; and (3) the resistance value decreases to a certain

*6) Heat generation
The quantity of heat generated by electric current flowing through an object is proportional to resistance of the object times the square of the current. This is called Joule's law and the heat generated by it is called Joule heat.
Assuming resistance is R (ohm: Ω) and current I (ampere: A), the quantity of heat generated H (Joule:J) during time t seconds is expressed as the following equation:

$$H = I^2Rt$$

The quantity of heat generated Q watts (W) per unit time is:

$$Q = H/t = I^2R.$$

*7) Resistivity
The resistivity of copper at 0℃ is:

$$\rho_0(\mathrm{Cu}) = 1.6\times 10^{-8}\,\Omega\,\mathrm{m}$$

Here the temperature is specified, because the resistance varies depending on the temperature. In the case of copper, at the temperature of -195℃, it is:

$$\rho_{-195}(\mathrm{Cu}) = 0.2\times 10^{-8}\,\Omega\,\mathrm{m}.$$

The resistance clearly decreases as the temperature is lowered.

*8) Absolute temperature
0 K is not OK but is read as "zero Kelvin." From the research of thermodynamics, the existence of the lowest physical value of the temperature is known. The K (Kelvin) is a

scale of thermodynamic temperature measured from absolute zero at -273.16℃, and one kelvin equals one degree Celsius. The triple point of water, which we use as one of the reference points of the temperature, is 273.16 K on the absolute temperature scale, or +0.01℃ on the Celsius scale. Therefore, at absolute temperature "a K" is "(a - 273.15)℃" on the Celsius scale. It is written as "K," not "°K." Kelvin is named after the famous British physicist, William Thomson Kelvin, the 1st Baron Kelvin.

temperature but increases below that temperature. The great Dutch physicist Heike Kamerlingh-Onnes (1853 - 1926) and his group of scientists finally solved this problem.

Dr. Kamerlingh-Onnes, who became a professor of experimental physics at the University of Leiden in 1882, established the world's first cryogenics laboratory in 1894. In 1908, he was the first to succeed in liquefying helium (He). The helium liquefying temperature is 4.2 K. By using liquefied helium, he clarified the physical properties of substances down to about the 1 K low-temperature range.

In 1911, Dr. Kamerlingh-Onnes and his associates, while examining the electrical resistance of mercury (Hg) in this temperature range, discovered that the electrical resistance dropped either to zero abruptly or became too small to be measured (Fig. 4.1), when the temperature was lowered to the neighborhood of 4 K. Furthermore, they proved that a similar phenomenon occurred with lead (Pb) at 7.2 K and tin (Sn) at 3.7 K. In brief, phenomena which did not fit into any of the three predicted possibilities at that time were observed. This discovery was announced at an academic conference in Chicago in 1913, and there the term "superconductive state" was used for the first time.

The fact that resistance is extremely low in the superconductive state was recognized immediately, but verification is not simple to prove that resistance really becomes zero. A researcher at MIT in the United States showed experimentally that current was still flowing continuously by electromagnetic induction in a loop made of lead which had been cooled to the superconductive state even two and half years after it had been set up.

As a result, the conclusion was drawn that it was possible to create a persistent current flowing in a circuit made solely of superconducting material where electric resistance is zero. Naturally, many people, including Dr. Kamerlingh-Onnes' group, thought of making an electromagnetic coil with superconducting material to create a powerful magnet generated by a persistent current. However, it was not that simple.

Soon after the discovery of the superconducting phenomena, Dr. Kamerlingh- Onnes and his team found that when a metal conductor in the state of superconductivity was placed in a magnetic field, the superconductive state would vanish if the magnetic field were increased by a certain magnitude. The magnetic field in such a case is called critical magnetic field (Bc). The value of Bc varies, depending on the temperature, Bc = 0 at the transition temperature (critical temperature) Tc. In other words, if a magnetic field is introduced at this temperature, the superconductive state collapses immediately. Of course, if the temperature falls below Tc, the Bc value would not be zero. However, it would not be a significantly large value. It was also verified that the critical value Ic existed for the amperage of a current that can be carried by a single conductor while maintaining the superconductive state.

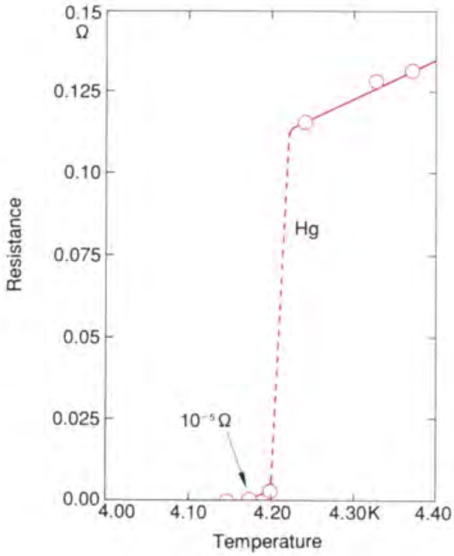


Fig. 4.1 Result of an experiment conducted by Kamerlingh-Onnes and his associates in 1911 on the relationship between electrical resistance and abslute temperature of mercury (Hg) (Recreated by referring to the figure included in "Superconductivity-Fundamentals and Applications" by Werner Buckel, VCH (1990))

The pure metals in which Dr. Kamerlingh-Onnes and his associates initially discovered the superconductivity generally had relatively small Bc and Ic values, and therefore could hardly be used as conductive materials to create a magnetic field. The pure metals showing these superconductive properties are called Type I superconductors. Various experimental and theoretical experiments have been conducted on the superconductive properties shown by Type I superconductors, and it has become clear that superconductive phenomena are extremely important in research in properties.

However, apart from that, materials with a large Bc and Ic, which we desired, could not easily be discovered. But as the 1930s arrived, scientists began to understand that an alloy made of Bismuth (Bi) and Lead (Pb) has the desirable property as a superconductive material. Research on alloys bloomed after World War II, and it was found that metals such as niobium (Nb) and vanadium (V) themselves, as well as their alloys and compounds with other metals, have values of Bc and Ic several times higher than those of pure-metal materials. It was revealed that Niobium 3 tin (Nb_3Sn) a compound of niobium (Nb) and tin (Sn), showed superconductivity exceeding $10^4 A/cm^2$ current density in a 15-tesla magnetic field. It also became clear that many alloys*9) such as niobium-titanium (Nb-Ti) and niobium-zirconium (Nb-Zr) have similarly high Bc and Ic values. The relationship between the superconductive critical values of Tc, Bc and the critical current density Jc of Nb-Ti alloy, intermetalic compound*10) Nb_3Sm and niobium 3 germanium (Nb_3Ge) is shown in Fig. 4.2. These relationships are expressed as curved surfaces, using the three axes

*9) Alloy
Alloy is a general term for a mixture of two or more kinds of metals and something else having substance metallic properties. The duralumin which is widely used for aircraft is an alloy using aluminum as a base metal, to which about 4% copper and a minute amount of magnesium, manganese and so on are added. Steel is an alloy of iron with a

minute amount of carbon.
Alloys are called by their main components, or base metals, such as aluminum alloy and ferro-alloy much of the time. But there are many alloys that are made of equal amounts of many different components, and it is hard to determine which one of them is the base metal. Thus, they are often called by totally new names.

*10) Intermetallic compound
As we discussed about alloys, duralumin and carbon steel are classified in a group called solid solution. An alloy can be formed even if the composition ratio of the consisting elements vary, and their characteristics change continuously as the elements' ratios change.

On the contrary, there is a group of alloys that have a very definite alloy element ratio, and if their ratio changes, alloys cannot be formed. This is when the alloy-consisting elements are firm-bonded chemically to form a single compound, or new substance. They are called intermetallic compounds.

of T Kelvin (K) for the respective absolute temperature, magnetic field strength B tesla (T) and current density J ampere per square centimeter (A/cm^2). The conditions of these materials for actual use must have a point, which is determined by the values of T, B and J in the working state, located inside the curved surface (on the side of origin) of each relevant material.

We had already decided on a magnetic field magnitude of 4 teslas, based on such factors as the coil strength. This value, 4 teslas, was the magnetic field magnitude for an area where seawater would flow, and an even stronger magnetic field would be generated within the coil. But let us assume B = 4 teslas for convenience. Since the coil would be cooled by liquid helium under atmospheric pressure, the temperature is T = 4. 2 K. If the relationship of Bc and Jc at T = 4.2 K is extracted from the curved surface groups (Fig. 4.2), it is expressed as shown in Fig. 4.3. As mentioned later, we decided to use Nb-Ti alloy as the coil material from the standpoint of its workability. The critical value of Ni-Ti corresponding to B = 4 teslas in this figure is a large value on the order of $Jc \fallingdotseq 3 \times 10^5 A/cm^2$.

Returning to where we were, it is believed that the

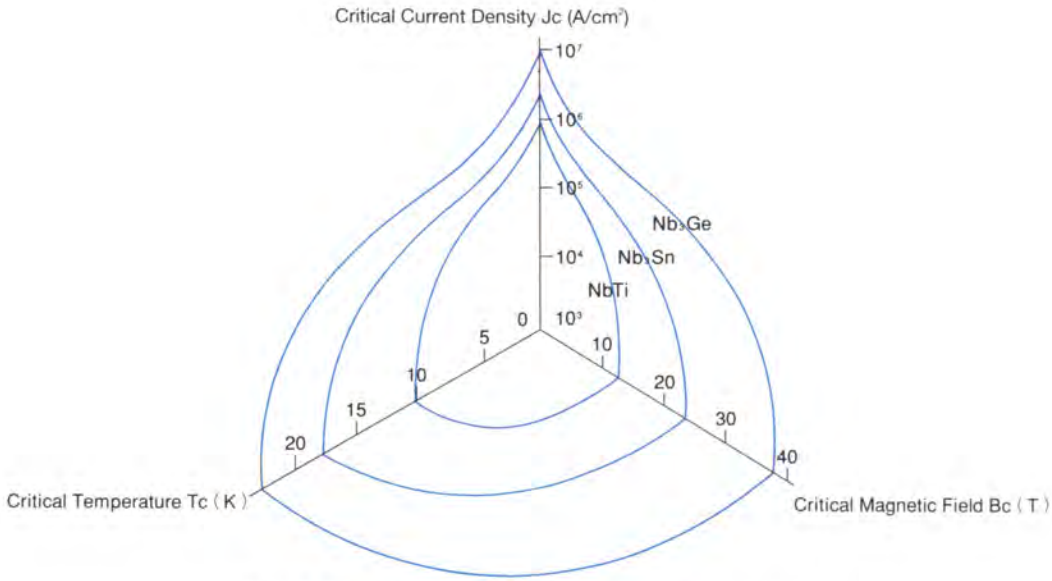


Fig. 4.2 Critical characteristics of superconductivity of easier-to-use Type II superconductors

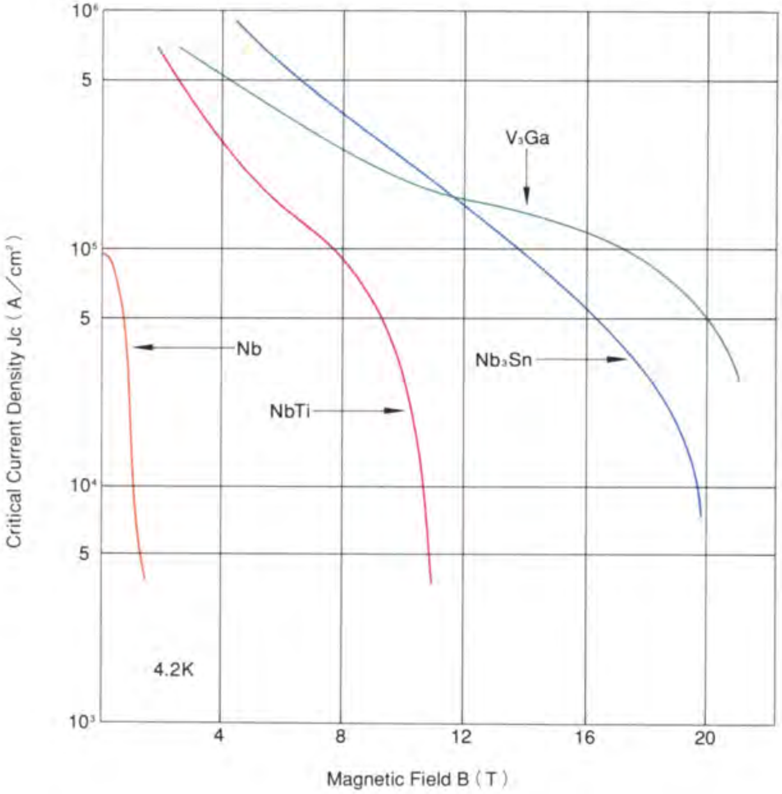


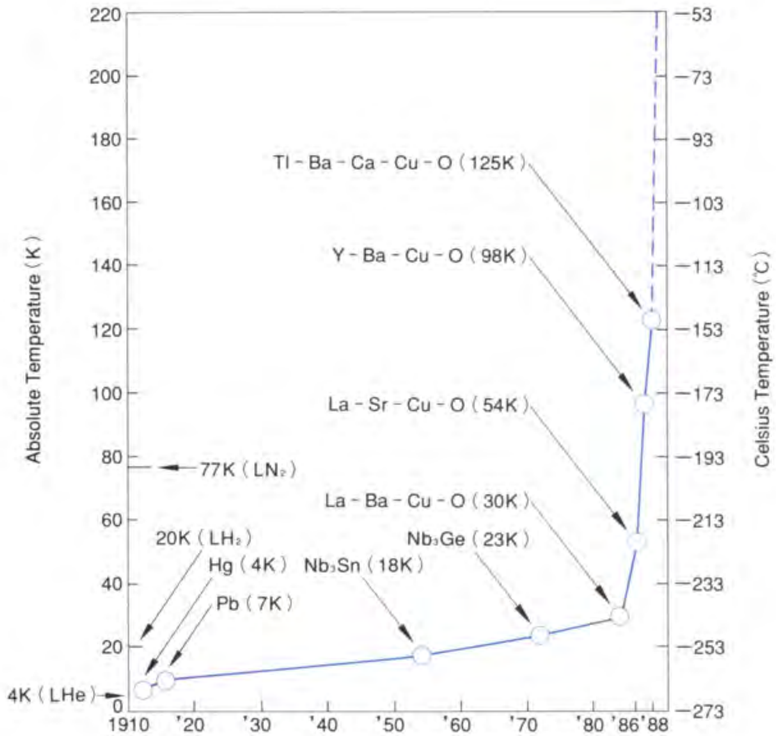
Fig. 4.3 Critical current density Jc vs. magnetic field magnitude B at T = 4.2 K

superconductivity shown by such materials as Nb-Ti and Nb_3Sn is based on a different principle from that of the previously mentioned pure metal materials of Type I. Therefore, these materials are called Type II Superconductors. Apart from the cause of the phenomena as such, obtaining materials with the capability of maintaining superconductivity up to a high current density in a high-magnitude magnetic field delighted the engineers.

However, like the old saying, "There's many a slip between cup and lip," whereas the materials in Type I are soft and rich in ductility*11), the materials in Type II, particularly intermetalic compounds, are generally brittle. Therefore, it is difficult to work them into wires. It is even more difficult to make wires out of such materials as Nb_3Sn and wind them into coils. If we had adopted Nb_3Sn as the superconducting coil wire material for the Yamato-1

*11) Ductility
Many of the pure metals, such as pure gold and lead, stretch easily when tapped or pounded at around room temperature. These metals are called ductile materials, and this property is called ductility. On the contrary,

such materials as cast iron, which are hard but crack or break when pounded, are called brittle materials. This property of cast iron is due to the carbon content in the iron, but it also becomes a ductile material when it is near pure iron with decreased carbon content. Such iron is called mild steel.



The high critical temperatures of the superconductors followingthe discovery of La-Ba-Cu-O (30 K) in 1986 brought a high-temperature conductor boom for some time.

Fig. 4.4 Superconductor discoveries and their transitiontemperature (based on "Superconductive Engineering" (Revised Edition) Institute of Electrical Engineers ,Japan (1991))

at that time, we could certainly have achieved, on paper at least, a thruster with far superior performance than the one actually produced. But that was only on theoretical. In the end, we would probably have failed, exhausting all our energy in trying to overcome the technological barriers to produce the coils. However, if we were to do it over again today, the Nb_3Sn coil would be our first candidate. The technological advances in the last 10 years have been so splendid that it is possible to achieve it now.

But with the Yamato-1, we decided to use the alloy material Nb-Ti, which offered incentives in working including an established method of making it into wire. It was cheaper, as well. The decision was a result of heated discussions in the Committee. In a sense, the employment of Nb-Ti might have been a decisive factor in the successful completion of theYamato-1.

It must also be mentioned that in the second year in our project, around 1987, the so-called high-temperature superconductor boom was on, and it started to reverberate all around us. It was a rush to discover high-temperature superconductors, which all started with the announcement made in 1986 on research into the electrical resistance properties of copper oxides of the La-Ba-Cu-O at low temperature conducted jointly by J. G. Bednorz (1950-) and K. A. Müller (1920-). Ultimately, the existence of the astonishing substance (Tc = 125 K) in the Tl-Ba-Ca-Cu-O was revealed *12). These materials are now called copper-oxide superconductors.

The history of these superconducting materials is summarized in Fig. 4.4. As clearly shown in the figure, the graph rises sharply after 1986. This shows the origin of the term "high-temperature superconductivity" very well.

We wanted to leap on these high-temperature oxide superconductors, if they could have been used for the Yamato-1. However, to our regret, after evaluation made on the critical current density, critical magnetic field value, mechanical strength, stability and ability to work the materials, we reached the conclusion that there was no way we could use them at that time. That is still true even today. If we could put these materials into actual use, it would be great from every aspect, including the coolant and insulation structure costs, since we would be able to cool them by using liquid nitrogen (77.3 K boiling point). In addition, a material with higher critical temperature theoretically has a higher critical magnetic field. We look forward to the earliest possible realization of these materials in practical use for the superconducting MHD propulsion ships that require a strong magnetic field.

*12) La, Tl, Ba
Although these are not very faliar element symbols, they stand for the elements as follows:

Symbol	Name	Atomic number
La	Lanthanum	57
Tl	Thallium	81
Ba	Barium	56

Cu, Ca and O are copper, calcium and oxygen, respectively.

References:
(1)Toshihiko Tuneo : Chodendo no Kenkyu (Research on Superconductivity), Iwanami Shoten (1995)
(2)Werner Buckel : Superconductivity Fundamentals and Applications,VCH (1990)

CHAPTER 5

SUPERCONDUCTING MHD THRUSTER STRUCTURE

The structure of the superconducting MHD thrusters adopted for the Yamato-1 is discussed in detail in this section.

The perspective cross-sectional drawing of the MHD thruster (made by Toshiba) is shown in Fig. 5.1. The MHD thruster is consisted of six unit thrusters, each positioned at an equal interval in a circle in what has been termed "the annular arrangement of the six-unit thruster configuration structure."

There were two main reasons why this structure was adopted:

(1) Although a very strong magnetic field was required to actually move the ship using the MHD thruster, it was impossible, in terms of the coil strength, to obtain the 4-tesla magnetic field magnitude we wanted by using a single large-diameter thruster shown in Fig. 3.4 in Chapter 3. It was then that the idea of grouping six smaller-diameter unit thrusters to function as one thruster originated among the scientists.

(2) This structure was seen as minimizing magnetic field leakage. If there had been only a single unit thruster, every iron

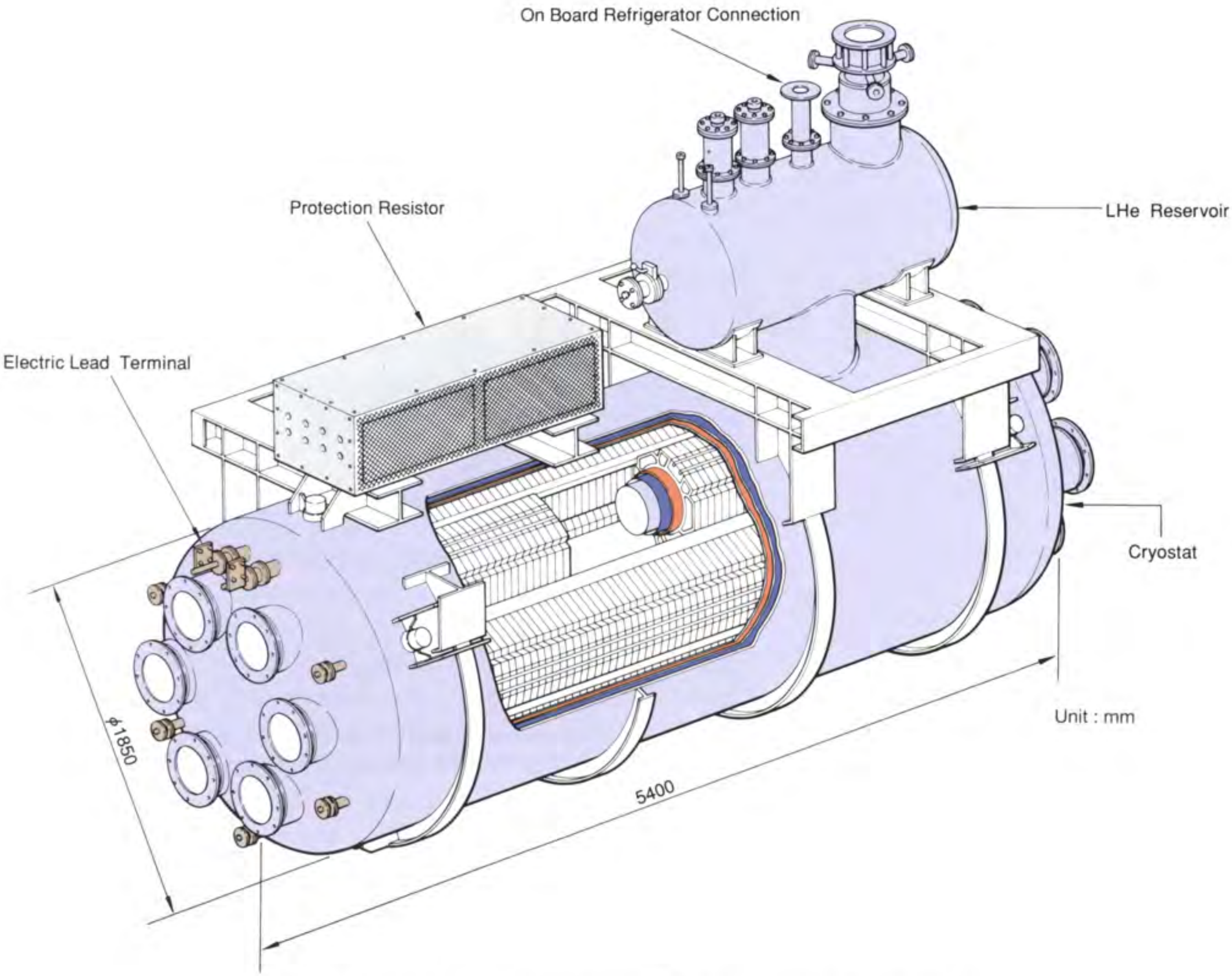


Fig. 5.1 Perspective cross-sectional drawing of the superconducting MHD thruster

object around the unit would be attracted to the thruster module, as the magnetic field is in an open state much like that of an ordinary bar magnet. We actually conducted an experiment using one single unit thruster; it created an awesome magnetic field. It may seem comical, but iron objects from as far as one meter away were so attracted, they were on the verge of flying to the thruster.

If, on the contrary, the six unit thrusters were positioned on a

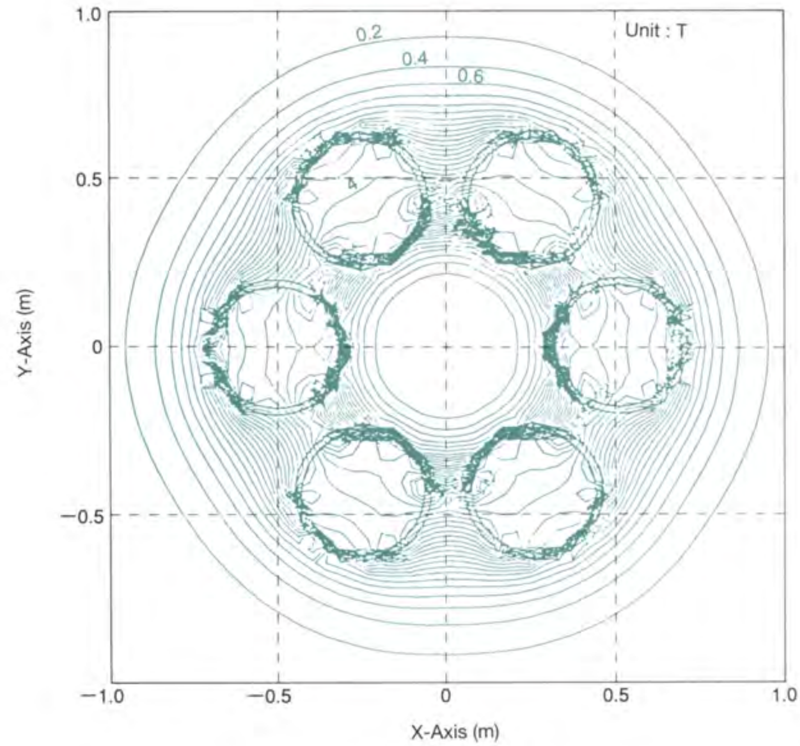


Fig. 5.2 Line drawing indicating the magnetic field magnitude distribution of the superconducting magnet in cross section

circle at equal intervals in an annular arrangement, the direction of the magnetic field created by each thruster module acts in the tangential direction of the circle to form a single ring-shaped magnetic field. In other words, by putting them in an annular structure, all of the magnetic fields created by the six unit thrusters are linked to form a single ring-shaped magnetic field.

We call this a closed form of the magnetic field. By closing the magnetic field, the leakage from the thruster would be extremely weak (Fig. 5. 2) .

This figure, indicating computer-produced contour lines*1) of the magnetic field of the thruster in cross section, shows that the magnetic field inside each unit thruster is almost uniformly 4 teslas.

But what about the magnetic field leakage from the thruster? As shown clearly in the figure, the magnetic field which has leaked in very close proximity to the thruster circumference is extremely

*1) Contour line
A line on a map connecting all points of the same elevation from standard sea level in a particular area. Similarly, the contour line here means a line connecting all points of the same magnitude in the magnetic field.

weak at 0.2 tesla (2000 gauss). This magnetic field has the characteristic of decreasing its magnitude in proportion to its distance to the sixth power of distance, so the field magnitude decreases rapidly to 600 gauss and 300 gauss, if the distance from the thruster increases to 10 and 20 centimeters. It becomes less than 10 gauss if the distance is one meter. A readily available magnetic device for curing a stiff neck has a magnetic field magnitude of about 1,000 gauss at its strongest point. Anyone can thus appreciate how scant was the magnetic leakage from the thruster.

Furthermore, since all of the MHD thrusters were actually housed in bulges below the deck(Fig. 2.1), there was little external magnetic field leakage. People could walk around on-deck with perfect safety.

When we actually measured the magnitude of leakage on the deck during the sea trials, it turned out to be less than 1 gauss, and more or less equivalent to the geomagnetic field (approx. 0.5 gauss). Therefore, it would pose no problem at all even for a person with a pacemaker.

Making the structure an annular arrangement of six unit thrusters solved our major problem: in effect, any danger to people, especially physiologically, was completely eliminated.

The cryostat housing the six unit thrusters (Fig. 5.1, again) is a large thermos, so to speak, and its wall has a triple layer structure. We can call the wall layers, A, B and C, from inner to outer for convenience. The two gaps between the three wall layers are a vacuum which is why the entire cryostat function as a large thermos.

The reason we adopted a thermos like structure is that the cryostat was filled with liquid helium at -269℃ as a coil coolant to maintain the stability of the superconductivity. Assuming a room temperature of 20℃ the temperature difference would be almost 300℃. If there were that large a difference in temperature, the liquid helium would readily evaporate owing to invasive heat from room-temperature air, and could not function as a coolant. To avoid that, the gaps between walls A and B as well as between B and C were kept as a vacuum to prevent as much as possible heat invasion by outside air.

The innermost wall A was made of 5 mm thick stainless steel and served as a container vessel of liquid-helium poured in cryostat. So it is called the helium vessel. Non-magnetic stainless steel was selected as the material for helium vessel A, for its outstanding strength and toughness*2) at an extremely low temperature and with no effect on the magnetic field.

The outermost wall C which is in contact with the room temperature was made of aluminum plating of 10 mm thickness. Although the gap between A and C were kept in a vacuum to prevent heat invasion as much as possible, this was not enough to maintain the extremely low temperature of -269℃. This arises from the fact that there are three forms of heat transfers: conduction*3) which transfers heat directly through a substance to a substance, convection*3) which transfers heat by a gas, and radiation*3). Maintaining the vacuum can shut off heat transfer by convection, but cannot prevent heat invasion by conduction through the supporting structure or by radiation.

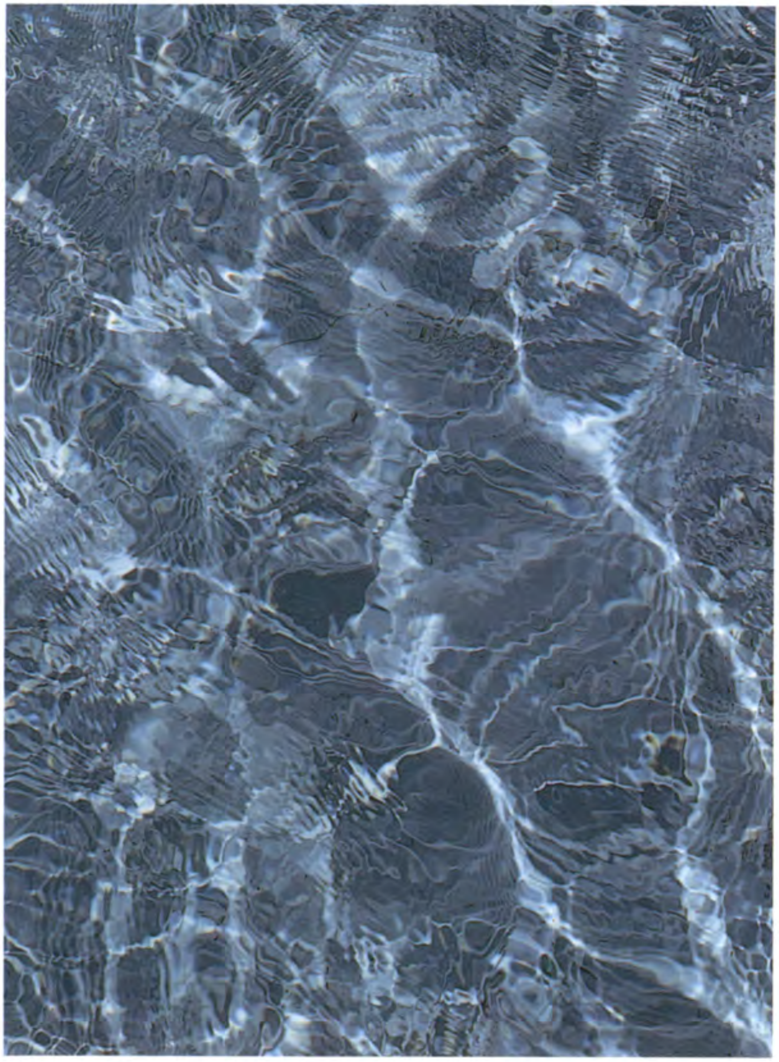
We thus had to take two additional measures:

(1) The insertion of a stainless steel plate B, called the heat shield plate, as the middle plate in a vacuum gap between the walls. Many small diameter pipes run on the surface of the B heat shield plate. We decided to circulate liquid nitrogen at -196℃ supplied from an external tank to remove heat invading from outside. The temperature difference between A and B was 73℃. Since heat invasion by radiation between the two walls is proportional to the difference between the 4th power of the temperature in kelvin on the high-temperature side and the 4th power of the temperature in kelvin on the low-temperature side, the heat radiation between A and B would become significantly lower compared to that between B and C.

(2) In a second device, we laminated and inserted approximately 30 layers of superinsulation made of a combination of aluminum-coated mylar and polyester net between the gaps of walls A and B as well as B and C. The aluminum-coated mylar sheet is an extremely thin teflon polymer material with an aluminum film coating on one side with a very strong metallic gloss. When the material has a metallic gloss, it reflects heat rays and prevents heat invasion. (A film with metallic gloss is sometimes glued to car windows to shield the inside of the car from heat by solar radiation in summertime. The principle was the same.)

*2) Toughness
The property in substances used as structural materials which can withstand powerful external force or shocks with their own elastic or plastic transformation.

*3) Conduction, convection and radiation
Conduction: If one holds one end of a steel rod and places the other end in a fire, the end he/she is holding becomes hot after a while. Such a form of heat transfer is called conduction.
Convection: A form of heat transfer associated with the motion of a substance such as water in a kettle in which the water at bottom is heated to replace the lower-temperature water at the top repeatedly to raise the entire water temperature.
Radiation (of heat): A phenomenon of a substance emitting the quantity of heat corresponding to its temperature in the form of heat rays (infrared). One can feel warmth as such a phenomenon when one's hands are held over a stove.



If there is only a little difference between the inside and outside of the cryostat, not much consideration need be given to radiation. But if the temperature difference is as great as 300℃, the heat effect by radiation is intense. In that case even a slight loss of metallic gloss caused by a little dust could reduce the reflection of radiation heat and allow the heat to pass through. Taking that into account, we made a lamination comprised of numerous layers of aluminum-coated mylar sheets, and inserted them in the gaps

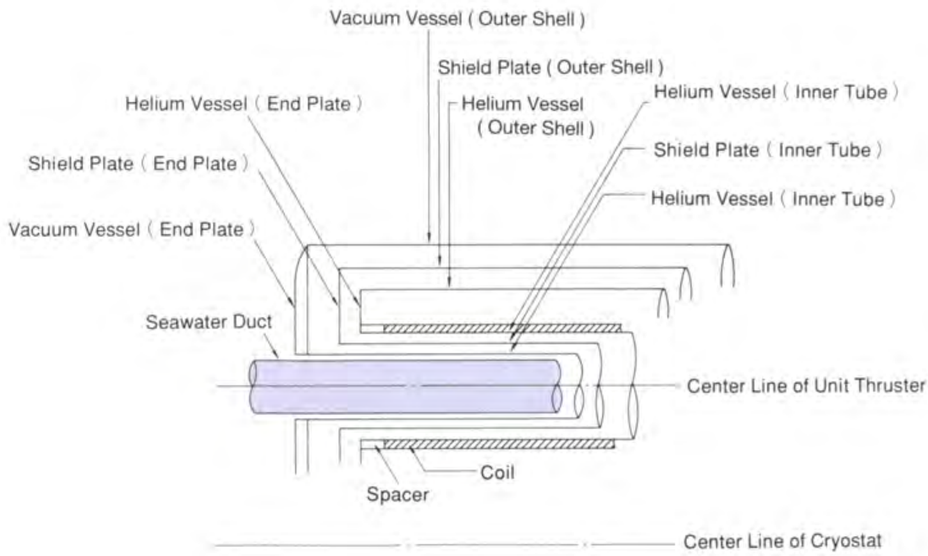


Fig. 5.3 Schematic illustration of the cryostat end structure

between the three walls.

The six unit thrusters were housed in the wall structure of the cryostat. We shall next see how the cryostat and six unit thrusters were connected: the ducts going through the insides of the six unit thrusters — in other words, the holes to be connected to the inner tube — are opened on the end surface, or the end plate, of the helium vessel that is the innermost wall of the cryostat. The cryostat and unit thrusters are connected at these holes.

Moreover, the three walls of the cryostat are structured through the unit thrusters like sleeves pulled inside out to the trunk of a jacket when it is taken off (Fig. 5.3). We call these areas "bore areas." Since the three walls of the cryostat are reversed in the bore areas, the outermost wall C of the cryostat becomes the innermost wall of the bore area and the innermost wall A of the cryostat becomes the outermost wall. In between these walls is wall B, the middle wall.

The innermost wall A of the cryostat, the liquid helium vessel, is made of stainless steel. This stainless steel wall A becomes the outermost wall in the bore area and goes through the duct as a single stainless pipe. This pipe is actually an important structural member of the unit thrusters as a perspective cross section drawing of a unit thruster (Fig. 5.4). The one shown as the helium vessel (inner tube) in this figure is the stainless pipe just described. We will call it "inner tube" hereafter.

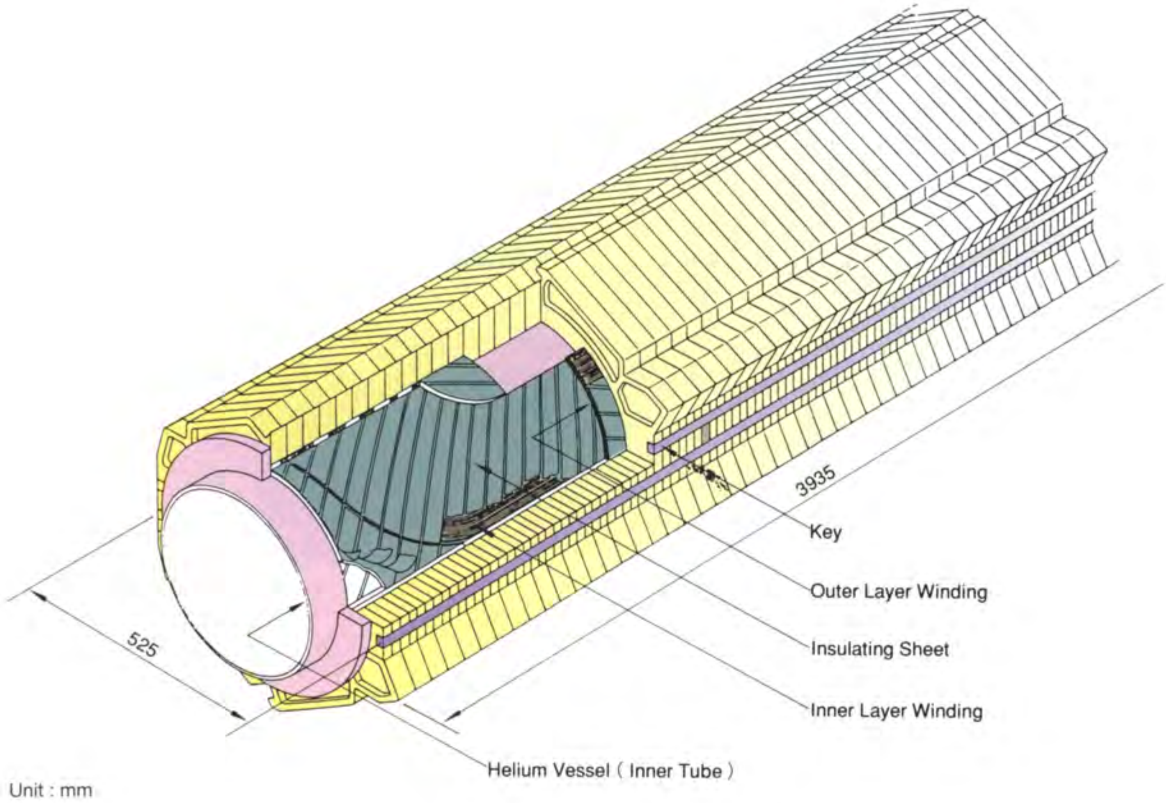


Fig. 5.4 Perspective cross-sectional drawing of a unit thruster

CHAPTER 6

UNIT THRUSTER STRUCTURE

The perspective cross-sectional drawing (Fig. 5.4) of a unit thruster is given another look again. The unit thruster consists of three components: the inner tube, the superconducting coil, and the collar to hold the coil in place. Each component is explained below:

Inner Tube

As described in the preceding chapter, the inner tube is a stainless tube welded to the helium vessel, which is the innermost wall of the cryostat, at the end plate. Therefore, this pipe itself is also part of the helium vessel.

The larger the internal diameter of this inner tube, the larger the usable magnetic field space and the additional convenience from the user's point of view. However, if the internal diameter increases the stress*1) exerted by electromagnetic force, the hoop stress increases. If the stress exceeds the strength of the coil itself or the coil-holding collars, the electromagnetic structure might be damaged. When taking into account the degree of strength needed to withstand this stress, we came to the conclusion that approximately 350 mm would be the maximum value for the inner-tube diameter to safely attain a 4-tesla magnetic field. A diameter value close to this was adopted for the unit thruster on the Yamato-1.

*1) Stress
If you press an eraser between your hands, the pressure exerted on the eraser by your right hand is in balance with the force exerted by your left hand (the reaction force to that of the right hand) via the eraser. In such a case, the eraser squeezed by the hands is deformed slightly. This corresponds to the state of the force exerted by the right hand being transferred to the left hand. In such a case, adjoining sections of the eraser interior transfer the force from the right hand to the left in the form of pressure. That pressure is what causes the eraser to deform slightly. The force caused in a substance as opposed to the external force acting on the substance, such as pressure within the eraser, is commonly called stress, and is expressed in the form of force per unit area exactly the same as for pressure. Hoop stress is created in reaction to the electromagnetic force acting on a coil, which is tension as opposed to pressure.

Superconducting Coil

The next component is the coil. A coil for an internal magnetic field type of superconducting MHD thruster is required to induce a magnetic field that is perpendicular to the seawater duct as well as strong and uniform along a wide range of the duct. We discussed a coil shape that would satisfy these requirements, and for reasons such as a uniform magnetic field and coil compactness, we decided to adopt a saddle-shaped coil.

A pair of saddle-shaped coils (Fig. 6.1) are installed systematically at top and bottom along the external surface of the inner tube, with the axis of the tube as the center.

Each of the pair of coils is identical. One of the pairs (Fig. 6. 2) shows that the coil is made of the two layers, inner and outer. The number of turns (windings) of one layer of the coil is about 120, and since each of the four layers is connected so that the direction of the magnetic field induced by each layer is the same, the total

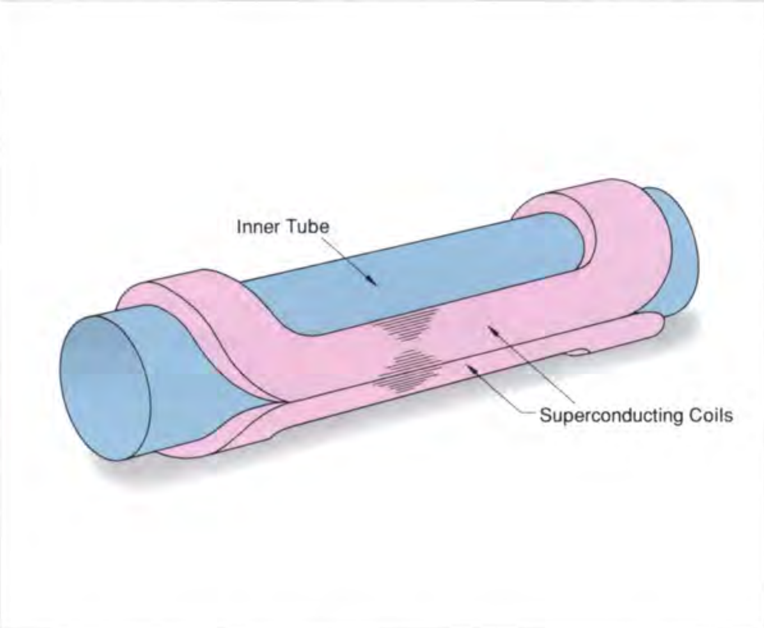


Fig. 6.1 Inner tube with a pair of saddle-shaped coils facing each other

turns of all layers combined is about 500.

The number of turns and the electric current determine the magnitude of the magnetic field. In other words, the greater the ampere-turn value becomes, the stronger the magnetic field. We calculated the required number of turns and amperage to induce the 4-tesla magnetic field magnitude we sought. After considering various conditions, we then decided on an approximate total of 500 coil turns for one pair of coils.

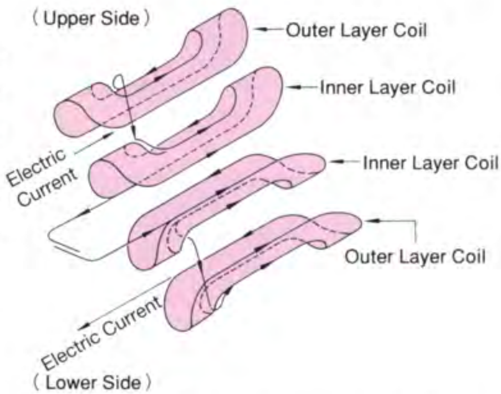


Fig. 6.2 Saddle-shaped coil pair construction

Coil Holder

The coil holder, called a collar, is installed to hold the saddle-shaped coil firmly in place by pressing it against the outer wall of the inner tube. At the same time it prevents the coil from deformation and destruction when the magnetic field is induced by the flow of electric current through the coil.

As described previously, when the magnetic field is induced by an electric current flow, the coil itself is subjected to a strong electromagnetic force. As a result, sometimes the coil slips out of

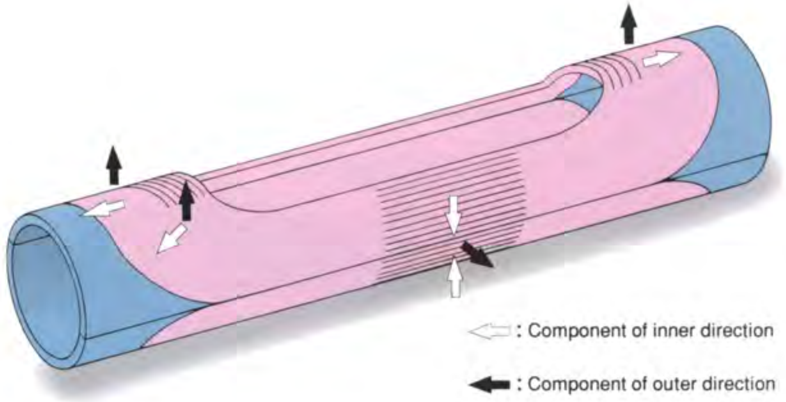


Fig. 6.3 Conceptual drawing of the electromagnetic forces acting on a saddle-shaped coil pair

place, or even worse, deforms or snaps off. In the case of a saddle-shaped coil subjected to strong electromagnetic force by the induced magnetic field, it tends to flatten to form a shape. The specific saddle shape will eventually come to be a flattened circular coil. Fig.6.3 illustrates the forces exerted on the coil in concept. To prevent the coil from misalignment or deformation, the collar is used to hold the coil in place. Fig. 6.4 shows the collars in detail.

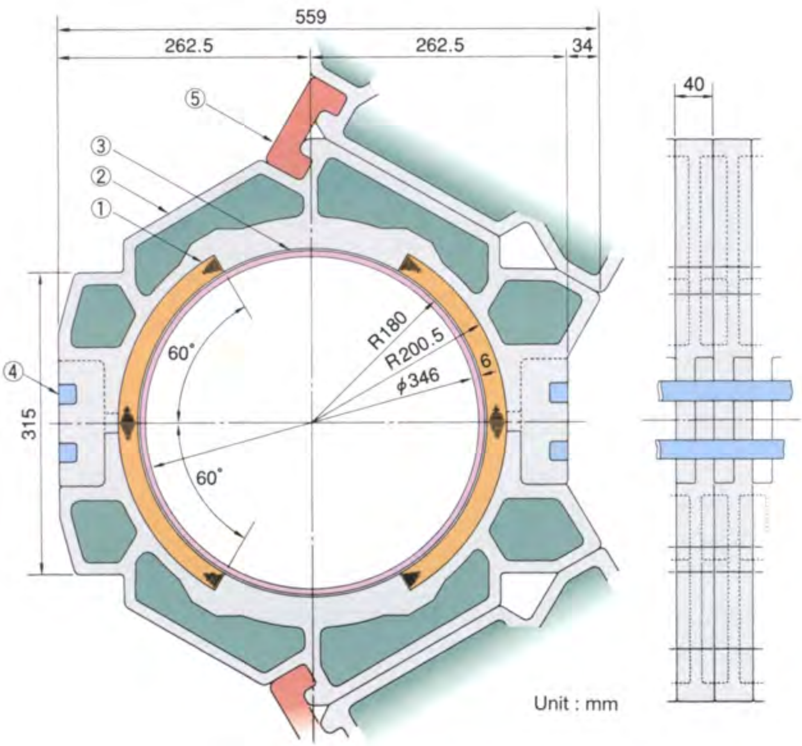
The material is a nonmagnetic high-grade aluminum alloy. Reactions to the magnetic material cuts off the magnetic flux if a magnetic material such as iron is used. Therefore, the nonmagnetic aluminum alloy was adopted to let the magnetic flux flow freely through the collar. In general, aluminum connotes something weak, but aluminum alloys with added specific amounts of magnesium (Mg), copper (Cu), zinc (Zn) and so forth, are very tough.

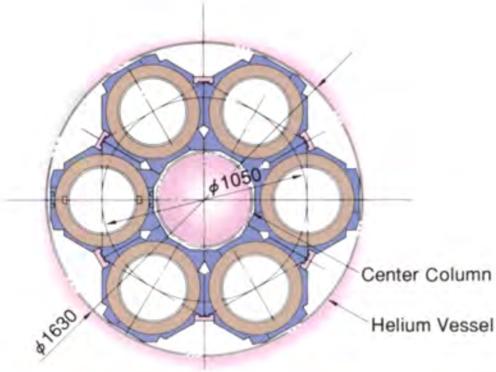
The shape of the collar shown in the figure is an assemblage of hexagonal blocks split into halves, and the necessary number of half-hexagon blocks is placed on top of the coil parallel to the axis of the inner tube over the coil's entire length. The other halves of the hexagonal blocks are arranged over its entire length around the bottom part of the coil. The mesh areas of these half-hexagons are finished as half of the collar (Fig. 6.4). The top and bottom parts of the half-hexagon blocks are identical to each other, and one full hexagonal block has two half-hexagonal blocks placed as one on the top and the other on the bottom upside down. Keeping the number of parts as minimal as possible is important economically.

The green areas shown in the plan indicate portion the hollowed out to reduce weight. Naturally, since the component is subjected to powerful force, a portion is shaved off while maintaining sufficient strength to withstand that force. The inside surfaces of these half-hexagonal collar blocks are formed as semicircles so that they can fit around the inner tube. They are combined as one unit by binding them together with long keys*2) running through the collar blocks.

It means that the inner tube and collar blocks sandwich the coil to hold it firmly in place. To do that, the two rows of half-hexagons

*2) Key
Suppose a certain size of hole is bored in the center of a circular plate, and a suitable shaft (hub) is inserted into the hole. A piece of steel inserted between the circular plate and the shaft acts as a wedge and prevents relative rotation. Such a small piece is called a key in mechanical engineering





No.	Part	Material
①	Dipole Coil	NbTi/Cu
②	Collar	Al Alloy A6061-T6
③	He Vessel (Inner Tube)	Stainless Steel SUS316L
④	Key	Al Alloy A6061-T6
⑤	Cotter	Al Alloy A6061-T6

Fig.6.4 Coil holder (collar) details

are pressed against one another from both sides with a force as massive as 1,000 tons (approx. 10,000 kN). The reason why we had to hold the coil so firmly in place is that if the coil shifts position or is deformed by an electromagnetic force due to inadequate binding, the superconducting state created is abruptly disrupted. We have covered this in such detail because it is an important aspect of the superconducting MHD thruster.

When the coil is cooled and goes into the superconducting state (the state in which electrical resistance is zero), tremendous electric current density on the order of 700 A/mm^2 *3) per cross-sectional area of superconducting strand, flows through the coil. This density is unimaginable in a normal conductive state, and a powerful electromagnetic force also unimaginable in the normal conductive state is induced. This powerful electromagnetic force will first act on the coil itself, and if the coil is not held in place, part of the coil may shift out of place or may be deformed.

*3) Electric current density
In the case of a home-use copper wire, normally, an electric current density of approximately 6 - 10A/mm^2 is considered to be the safe limit.

Assuming that a part of that area is point A, frictional heat is generated at point A due to the movement associated with shifting and deformation. If the frictional heat exceeds a certain limit, the temperatures at point A rises above the critical level and disrupts the superconducting state returning it to a normal conductive state. Since the high current is conducted through the entire coil, point A in a state of normal conductivity generates a considerable amount of Joule heat*4) locally due to the current encountering resistance there. As a result, the temperature of adjoining areas also rises above the critical temperature and they change to a normal conductive state. This phenomenon propagates rapidly abruptly destroying the superconducting state of the entire coil .

*4) See *6) in Chapter 4 on page 47.

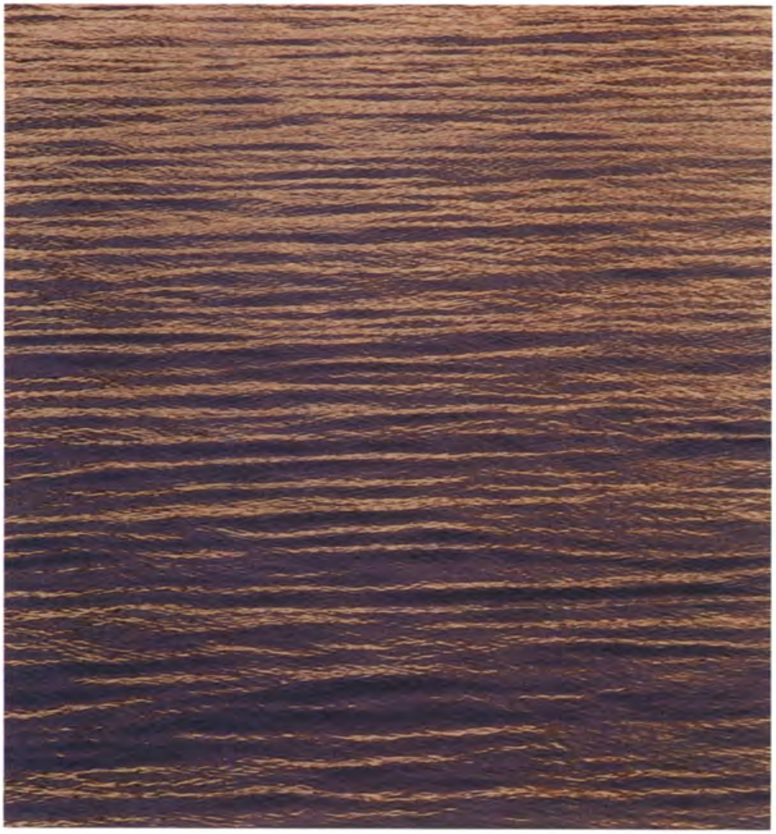
Such a phenomenon, in which a stable state of superconductivity is disrupted throughout the entire coil, is called "a quench" *5) and dreaded by researchers and engineers in the field of superconducting engineering. If a quench occurs, the coil cannot perform its function as a magnet and also burns out unless the energy in the coil is released externally at once.

*5) Quench
Quench is more frequently used in association with hardening in general. However, in the field of superconducting engineering, it connotes an abrupt disruption of superconductivity.

To prevent a quench, the coil must be fixed to the inner tube firmly with a collar. That is the primary function of the collar. The collar has one other important role: it binds the six unit thrusters as one group to produce a collective magnetic field which has a near-perfect ring shape.

As described previously, the collar has a hexagonal shape. The reason why the round inner tube is covered by a hexagonal collar is that the hexagonal shape can be clustered very tightly and it is as spatially stable — as in a honeycomb.

The magnetic field acts parallel to the tangential direction of the circle inside each thruster module of the collective structure or the annular arrangement of the structure that has the six unit thrusters positioned on the circle. On the whole, a perfect ring-shaped magnetic field is formed. As this ring-shaped magnetic field also acts as a centripetal force that connects each thruster module tightly, the unit thrusters as a whole, in conjunction with the hexagonal outline of the collar, hold themselves very firmly in place.



Coil Cable

A cable (Photo 6.1) is made of 25 or 26 strands. The reason for the difference in numbers of strands is due to different manufacturers. Although we will examine the case of a 25-strand cable (used by MHI), a 26-strand cable is essentially the same. The cross section of the cable is trapezoidal (Fig.6.5). The angles of the two slopes are called "keystone angles." The reason for making it trapezoidal was that it was difficult to wind the cable in a saddle shape if the cross section were round, because it would wriggle around and be unstable. Therefore, we angled the cross section of the cable as a trapezoid so that the cross section of the straight linear area, which was the principal part of the coil, would become a cylindrical cross section. Doing this made it possible to pile one trapezoid on another along the circumference of the inner tube. That made it possible to wind the coil in a saddle shape.

The external diameter of a single strand is 0.8 mm (Photo 6.5, Fig. 6.5). The white areas in the photo are copper (Cu) and each one of the small dots is an extremely fine filament made of niobium-titanium (NbTi), which is an alloy of Nb and Ti. The filament shown is composed of a 47: 53 weight ratio of niobium and titanium. The diameter of a single filament is only 20 microns (1micron = $1\mu m = 10^{-6}m$) and a single strand contains approximately 1,000 filaments. A filament made by another manufacturer is slightly larger in diameter, with about 300 filaments contained in one strand.

A single strand is structured to encase these extremely fine Nb-Ti filaments in copper. By area ratio, the filament is 1 and copper is approximately 1.3 times greater. Incidentally, the outermost thin reddish-brown layer shown in the photo is a tape form of an insulation material called Kapton*6).

Since copper has electric resistance, the electric current does not flow through it, but flows only in the very fine filament portions in the superconducting state. In other words, only the Ni-Ti filaments play the central role in the superconducting coil. An unimaginably high-density current flows in the superconducting state. The rated electric current for a home-use wire in general is 10 or 15 amperes, but in the superconducting state thousands of amperes of current flow through these filaments.

*6) Kapton
A product developed by du Pont of the United States. This is widely used as the name for the polyimide film whose physical and chemical properties are stable throughout the range of -269℃, a cryogenic state, and +400(℃, and is used in space development material.

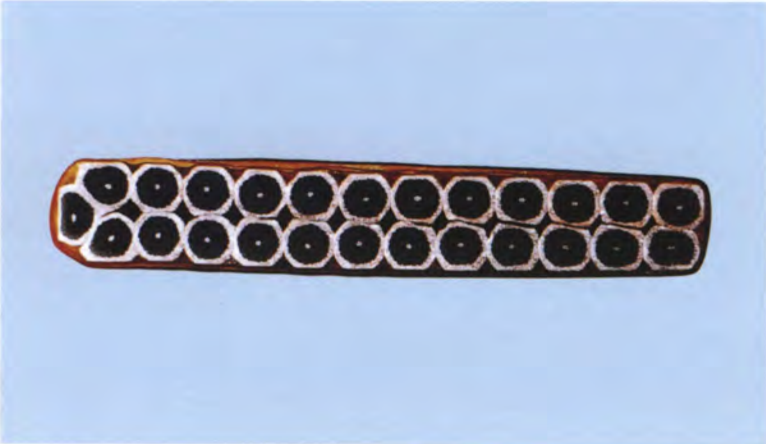


Photo 6.1 Cross section of the cable used as the superconducting coil (made by MHI)

Photo 6.2 Cross section of a strand as a component of the superconducting cable; diameter of the actual strand is 0.85mm

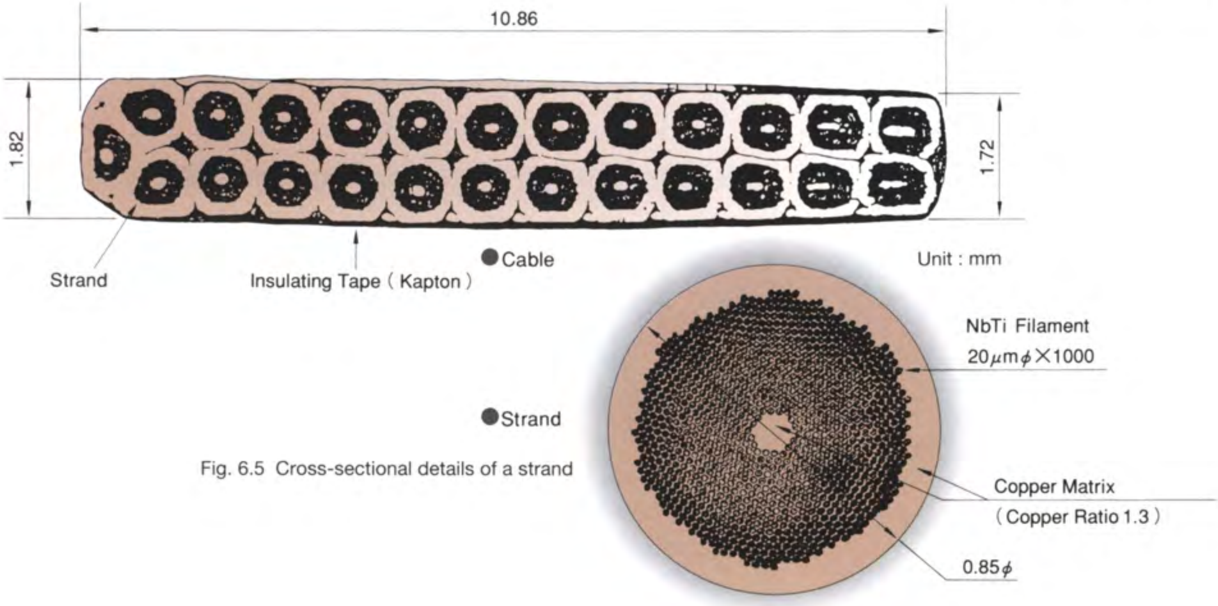


Fig. 6.5 Cross-sectional details of a strand

Furthermore, even in the case of a 10-ampere-rated wire, it blows a fuse or melts the plastic cover around the wire with heat created by resistance and could cause fire if the current surges over the safe rating. However, in the superconducting state, one can say that it is both mysterious and astonishing that an electric current

hundreds of times stronger than a house current flow through a superconducting cable with no loss.

From Coil Winding to Assembly of the Unit Thruster

The cross section of the cable is trapezoidal so the cable turns easily on a saddle-shaped coil, but that is not enough. Since the cross section is trapezoidal, turning the cable on the straight-line part of the coil can be done neatly. But since the turnover part, or the saddle-shape part, is curved, some way has to be devised to turn it on neatly.

We decided to insert a plastic plate between the layers of the cable to compensate for the turn. This plate is called a spacer. Photo 6.3 shows the process of coil winding. A robot, manufactured for this purpose, that can maintain a pre-set tension constantly winds the cable. A completely wound coil using spacers is shown in photo 6.4. The white areas seen in the turnover area are the spacers. Photo6.5 shows the wound coil placed on both sides of the inner tube and held with the collar. After this, a half-collar is pressed

against the other half, then a long key is inserted through the joint of the half-cut collars so the coil does not slide.
This is the procedure for producing a single unit thruster.

Six unit thrusters completed with this procedure are then assembled in an annular arrangement to function as a single thruster (Photo 6.6). The center column is placed in the center of the thruster in order to facilitate the assembly of the six unit thrusters. The one wrapped around the thruster is the outer cylinder of the helium vessel described earlier.

Liquid helium at a ultra-low temperature, 4.2 K at atmospheric pressure to be precise, is poured into this cryostat to cool the coils to ready them for superconductivity. The total volume of liquid helium is approximately 3,000 liters per thruster. That translates to fifteen 200-liter drums. Liquid helium was actually poured from a 1,000-liter Dewar vessel *7) of the suppliers. A very large quantity of liquid helium was required for the Yamato-1 experiment - 6,000 liters of liquid helium had to be used for the two thrusters of the Yamato-1 and in addition, spare liquid helium had to be on hand.

*7) Dewar vessel.
A vessel constructed with vacuumed space between the walls, and the wall surfaces facing the vacuum are devised in such a way that they reflect thermal rays. In short, it is a high-grade thermos, a vacuum bottle. The vacuum insulation with multiple-layered insulation materials is adopted especially for the Dewar vessel for liquid helium. Dewar is the name of the British chemical physicist James Dewar (1842 - 1923), who succeeded in liquifying hydrogen for the first time.

Photo 6.3 Coil winding operation using the winding machine
To keep tension constant on the cable to be wound,
this computer-control coil winding machine was developed.

There was one interesting incident with this liquid helium: liquid helium is very expensive, costing as much as 100 to 200 dollars per liter in Japan. We needed over 6,000 liters of that high-cost helium, representing a significant expenditure.

Several years ago, Dr. Kensaku Imaichi, Professor Emeritus of

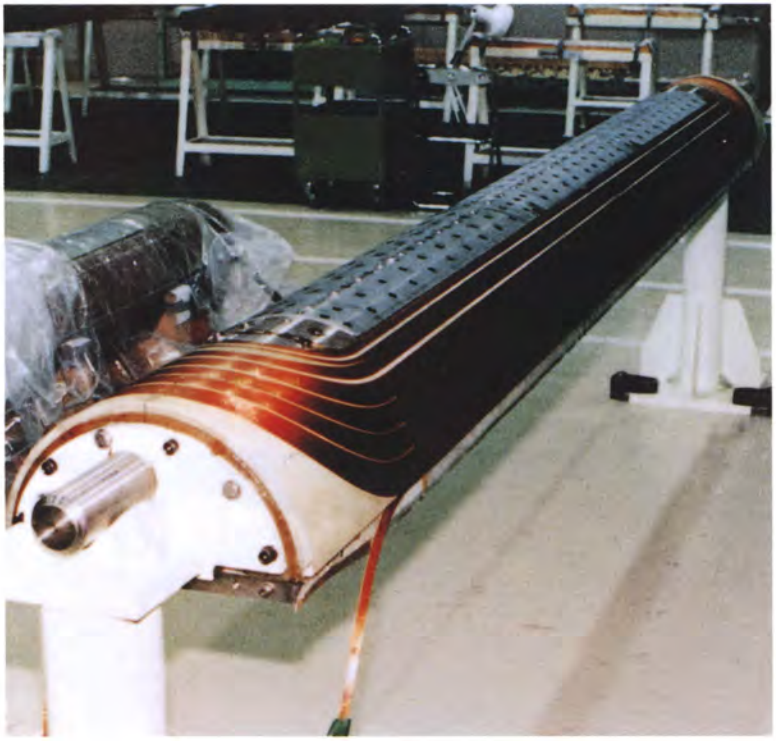


Photo 6.4 Completely wound coil

The reddish-brown, saddle-shaped area is the saddle-shape coil wound by the machine. The cable is being wound on a jig with the same diameter as the inner tube, which is the core of the coil in this photo. The white semicircular part, seen in the area where the coil cable is crossing over the core mold, is called a spacer and is made of FRP (fiber reinforced plastic) needed to form coil winding into a saddle shape. The wound coil in the shape as shown in the photo is heated to approximately 150℃, at the same time pressurizing each of the cables with about 6 kgf/mm^2 (= 60 MPa), to heat cure epoxy applied on the surface of the insulation tape (Kapton), which is wound around the cable. This is done in order to bond-fix the cables to each other so that the wound cable can maintain its saddle shape even after various jigs, such as the core, are removed. This is how to complete a coil.

Osaka University, who worked as the Chairman of the MHD Thruster Subcommittee (and now the Chairman of the Ship & Ocean Foundation), spoke on the research and development of the Yamato-1 to an English shipbuilder group. When he mentioned cost of liquid helium, the English audience unexpectedly reacted in

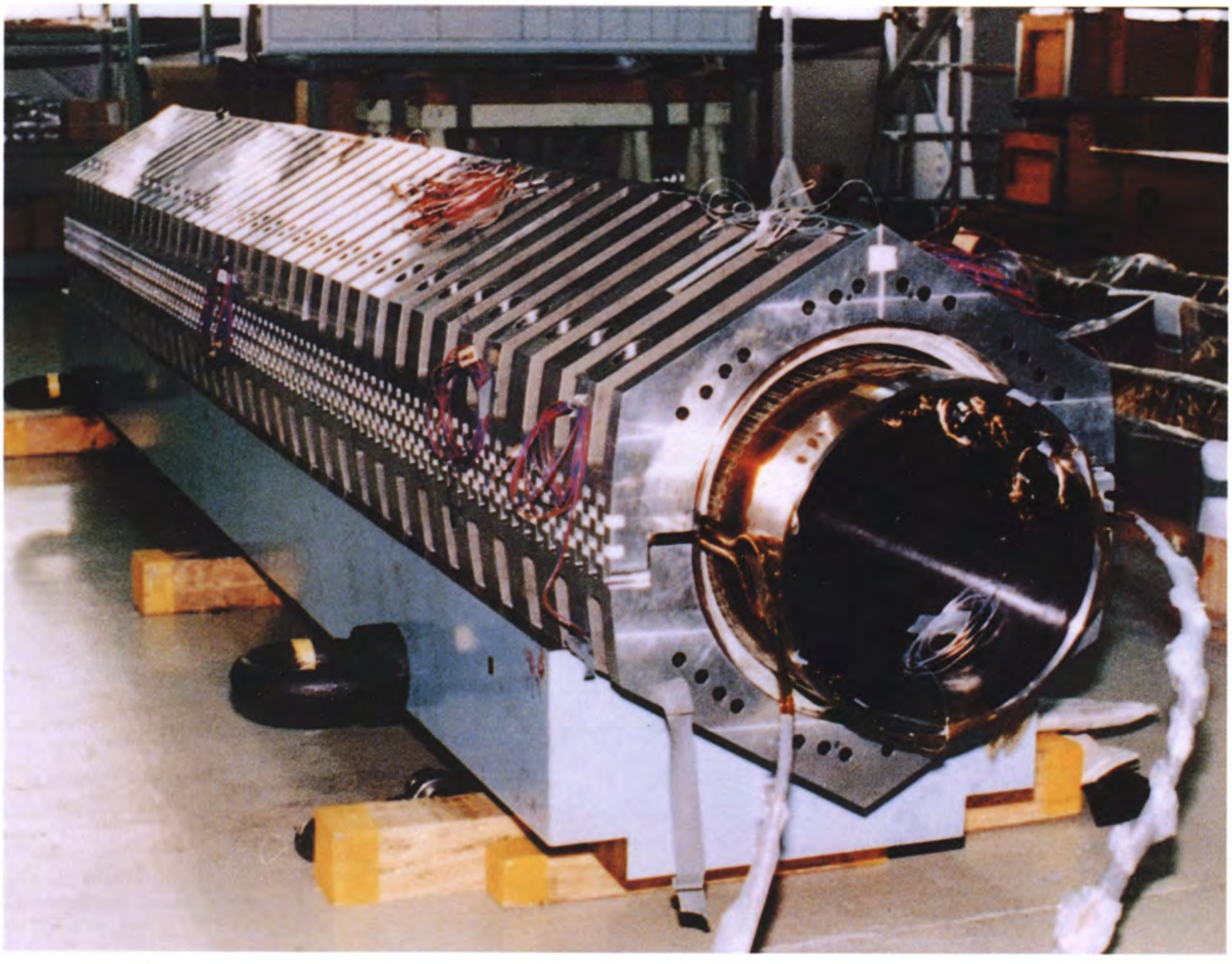
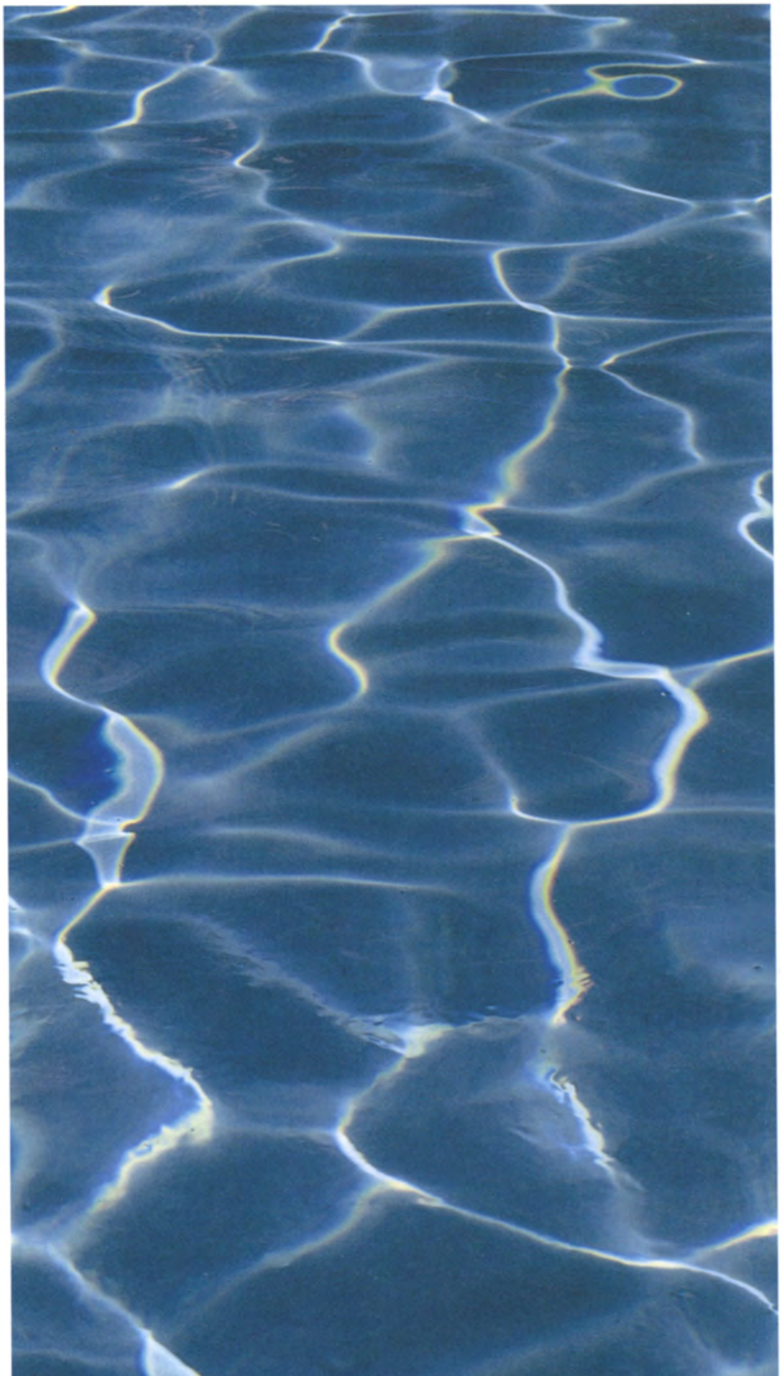


Photo 6.5 Collars set on the wound coil
The wound coil is placed on the inner tube and held down with a pair of half-collars. The collars are later pressed together from both sides and keys to connect them are inserted



a chorus of surprised sighs that implied, "You use such an expensive liquid in so large an amount as 6,000 liters?"

Professor Imaichi jokingly responded by saying, "You shouldn't be so surprised. For Japanese people, scotch whisky costs more than liquid helium." When Professor Imaichi's speech was over, several English people came to him and said, "We can drink scotch whiskey a lot cheaper than that." To the members of the Research and Development Committee, that episode is now nostalgic memory.

Completed Thruster

Photo 6.7 shows the overall view of the completed thruster as described previously. Fig.6.6 also shows that the cross section of the thuster. The cryostat houses the six unit thrusters . The seawater duct with the electrodes is positioned in the bore of each unit thruster, but the seawater duct is not included in Fig. 6.6.

Mounted on top of the cryostat is a reservoir for liquid helium. The reason this reservoir is necessary is that the liquid helium in

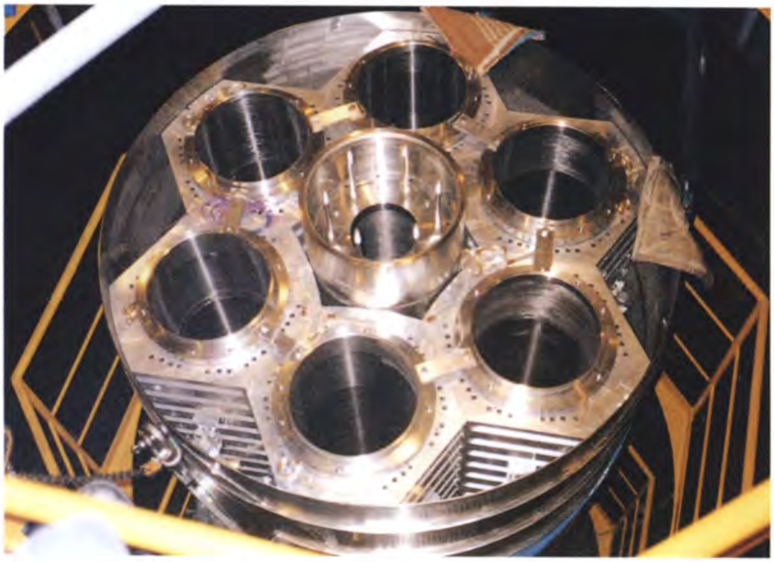


Photo 6.6 End section of the annular arrangement of the six coils.
Each of the six coils is assembled into the annular arrangement by using the hexagonal collars inserted into the outer cylinder of the helium vessel. The end plate of the helium vessel is placed over this as a cap.

the cryostat absorbs invading heat and a small amount of the liquid always evaporates as helium gas. The evaporated amount would decrease the supply of liquid helium. The superconducting coil would not be sufficiently cooled if the liquid helium decreased. So the design compensated for the amount of helium lost in evaporation by storing liquid helium in a reservoir atop the cryostat. Furthermore, the evaporated helium is recovered at the top of the cryostat and fed into the onboard refrigerator. The helium liquefied there is then returned to the reservoir again.

No special pressure is applied to the liquid helium in the cryostat. However, a 3.6-meter degree of pressure, from the liquid helium level of the reservoir to the lower part of the cryostat, due to gravitational force, acts on the liquid helium in the lower part of the cryostat.

In the case of water, a 10-meter depth is equal to 1 atmospheric pressure (1,000 hectopascal), and that translates at 3.6 meters into 0.36 atmospheric pressure. Since the specific gravity of liquid

Photo 6.7 Overall view of the completed superconducting MHD thruster (made by MHI)

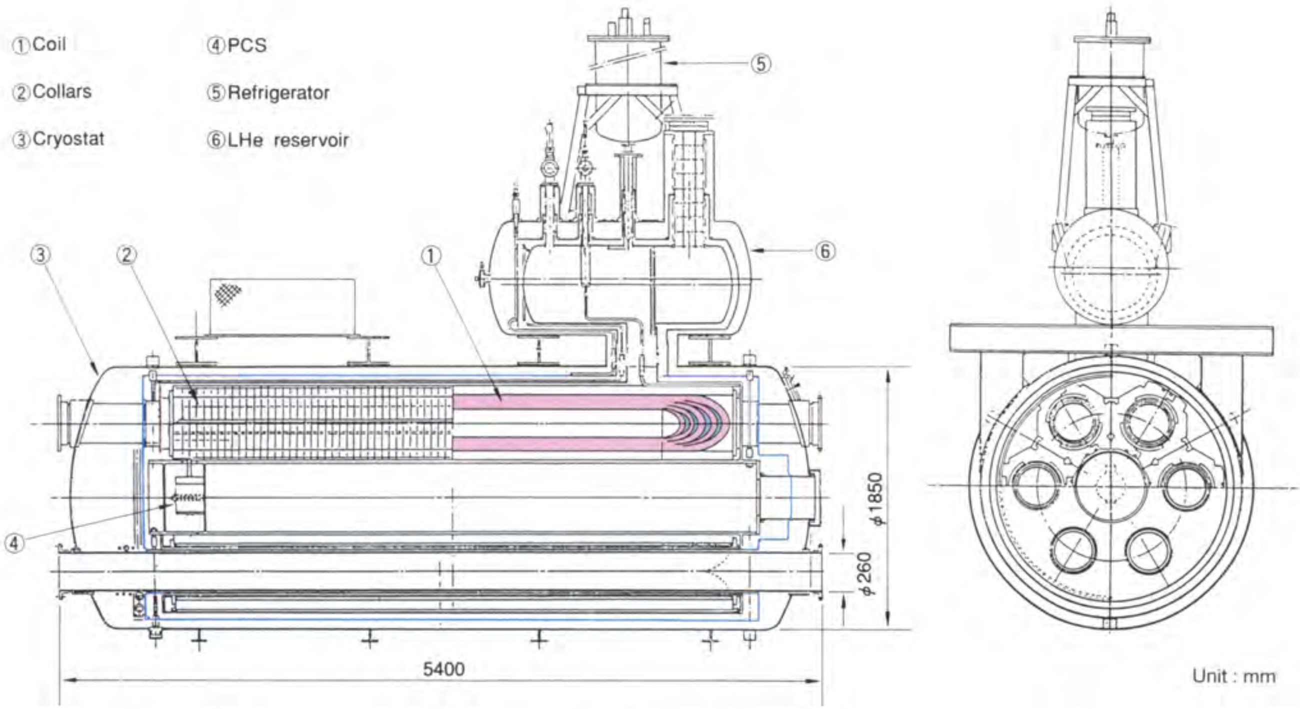


Fig. 6.6 Overall assembly of the superconducting MHD thruster before inserting the seawater ducts (made by Toshiba)

helium is 0.125, or 1/8 of the weight of water, only a minute pressure of about 0.05 atmospheric pressure acts on the liquid helium in the lower part of the cryostat even though the reservoir-height pressure is applied.

How does the liquid helium evaporate to become helium gas, and how does the helium gas return to the liquid state with respect to the heat transfer? As already mentioned, various measurements were devised in order to prevent heat invading the cryostat from outside. However, our current technology is not able completely to shut off such heat invasion, no matter how sophisticated a technique is utilized. Some heat always gets in.

The heat that does get in heats the liquid helium in the cryostat. Since liquid helium is volatile, heating evaporates it, and it absorbs the heat during that process to prevent the temperature of the liquid helium on the whole from rising. Liquid requires energy to

evaporate. Energy in the form of heat is drawn away.

Heat, which does not raise the temperature in spite of incremental heating, is called latent heat. In contrast, incremental heat that raises the temperature is called sensible heat.

Here is a specific example: When water is heated, the temperature rises to 100℃ at 1 atmospheric pressure. This is sensible heat. However, once the water temperature reaches 100℃ at 1 atmospheric pressure, no matter how much heat is added to the water, the water temperature does not rise any higher. The water will simply evaporate. Since water consumes the energy required to transform it from a liquid to steam, no matter how much heat is added, the temperature remains the same.

The calories required to evaporate 1 kg of liquid are called the latent heat of vaporization, and the latent heat of vaporization for

water is 539 kcal/kg. In contrast to the latent heat of vaporization, there is also the latent heat of fusion. When ice is heated, it melts. But as long as the ice is not completely melted, the temperature of the ice water does not rise. It also requires energy to transform the ice into water. That energy is absorbed in the form of heat during a transformation that causes the temperature to stay constant. The calories required to liquefy a solid are called the latent heat of fusion.

To return to the subject of helium, the latent heat of vaporization for liquid helium is 5.0 kcal/kg, which is far less than that of water. This low latent heat means that the liquid evaporates rapidly as heat enters. Since the evaporating helium absorbs and thus removes the invasive heat, the liquid helium temperature does not rise. Inversely, if none of the liquid helium evaporates to draw the heat off rapidly, the temperature of the superconducting coil rises to cause a quench.

The evaporated helium is gathered at the upper part of the cryostat, liquified in the helium refrigerator. and returned to the reservoir. When being liquified, helium gas is cooled off by the heat calories equivalent to the latent heat of fusion. In other words, the heat invading the cryostat is carried into the refrigerator by helium gas and is thrown out. As heat is removed in this process, the inside temperature of the cryostat is kept at 4.2 K or - 269℃.

Since Yamato-1 cryostat has such complicated structures with six bores as mentioned above, great care had been taken to design and produce it. However, to our regret, it was found to have 15-watt (W) *8) heat invasion, in fact, as opposed to the design value of 7 watts. This gap between the design and actual values of heat invasion resulted in more excessive helium evaporation than our expectations. Therefore, we coped with the problem with a full operation of the onboard refrigerator during the superconducting MHD thruster operation, and used liquid helium in the reservoir as a supplement for any liquid helium shortfall.

After the trials were completed, detailed analyses of the problem of the greater-than-expected heat invasion into the cryostat were undertaken. No matter what, unlike the electric current, it is impossible to shut off the invading heat completely. Even to come up with the technique to contain the heat invasion in a permissible range is a difficult task.

*8) Watt(W)
This unit is used to express the transfer of heat per unit time, such as the time rate of doing work, or how much energy is generated per unit of time. In this chapter, the unit expresses the quantity of heat which invades the cryostat from outside. Therefore:

1 watt (W) = 1 joule per second (J/sec.)

which means one joule per second energy is generated (or consumed).Whereas joule (J) is a unit defined as mechanical work, or "force × distance," and expressed as:

1 J = 1 N m(newton-meter)

the mechanical work done is expressed in energy and is equivalent to the heat quantity. Its conversion is:

1 cal = 4.1868 J

The watt is a unit named after the famous Scottish engineer James Watt (1736 - 1819), who built the steam engine. Joule is named after the English physicist James P. Joule (1818-1889), who clarified experimentally the relationship between heat and mechanical work.

CHAPTER 7

ELECTRODES AND SEAWATER DUCTS

Photo 7.1 shows the exterior of the seawater duct to be inserted into the bore of a unit thruster. The seawater duct, much like the hull bottom plate, needs to be sufficiently strong against water pressure, since seawater flows through the duct. Since electric current is conducted to seawater via electrodes, the seawater duct must also have electrical insulation properties between the electrode and the superconducting magnet as well as chemical resistance to chlorine created by seawater electrolysis. Taking these factors into account, it was decided to adopt glass fiber-reinforced plastic (GFRP) for the seawater duct. The part attached to the seawater duct end is called a "flange"*1), which plays the role of connecting the inboard seawater duct after it is inserted into the bore of the unit thruster.

If flanges were first installed on both ends of the seawater duct, it could not be inserted into the bore. So the flange is first attached to only one end, then the seawater duct is inserted into the bore and the another flange is installed on the other end.

A conceptual drawing of the cryostat bore portion after insertion of the seawater duct is shown in Fig.7.1. A cross-section of the seawater duct is also shown in Fig.7.2.

Positive and negative electrodes (anode and cathode) are

*1) Flange
Generally speaking, an overhang part of a main structure is called a flange; for example, the overhang of a train wheel. However, it is referred to as a circular plate-shaped part which is installed as if it were a sword-guard by either being welded or screwed to the side of a pipe for the purpose of connecting pipes. The flange of one pipe and the flange of another pipe are joined by tightening bolts to connect them together to produce the required length of the pipe.

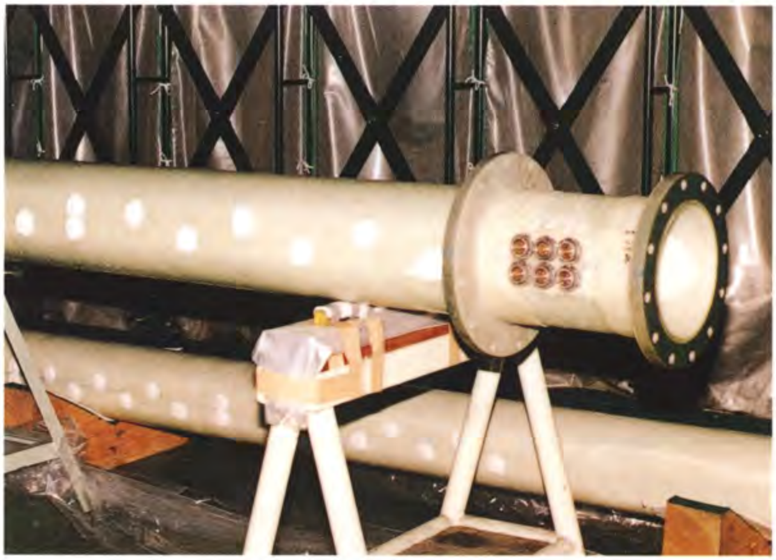
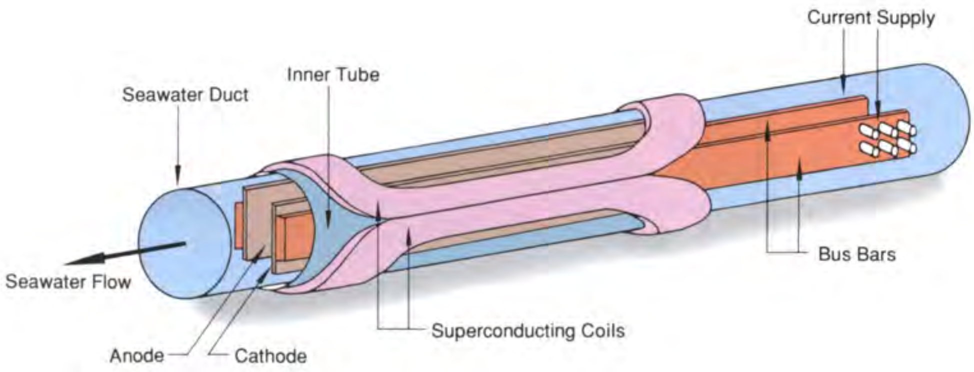


Photo 7.1 Exterior of a seawater duct



In order to insulate invading heat through the seawater duct wall, there is a bore portion connected to the vacuum vessel, or the outer wall of the cryostat, between the inner tube and seawater duct. And a heat-shield plate is inserted toward the lower temperature inner tube in the outer side of the vacuum vessel.

Fig. 7.1 Conceptual drawing of the cryostat bore portion after the insertion of a seawater duct

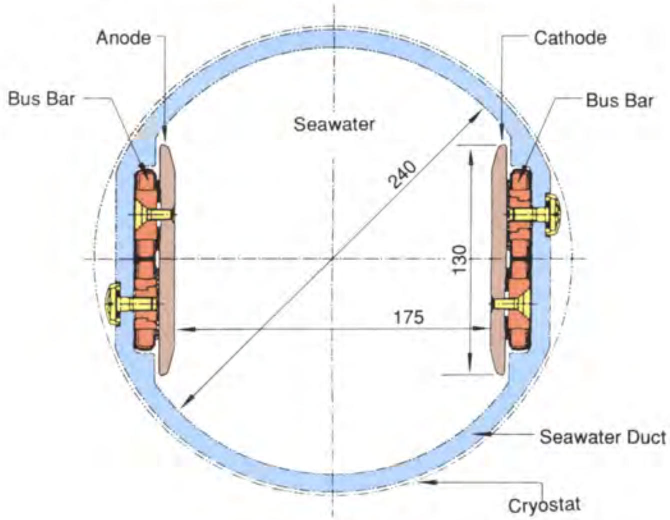


Fig. 7.2 Cross-section of a seawater duct
The bus bars are conductors carrying a high current to the electrodes. The anode and cathode are made of different materials from an electro-chemical standpoint

installed facing each other on the inner wall of the seawater duct. The electrodes induce Lorentz force by conducting electric current to seawater perpendicular to the direction of the magnetic field that was formed in the seawater by the superconducting magnet. The electrodes are comprised not only of the two anode and cathode

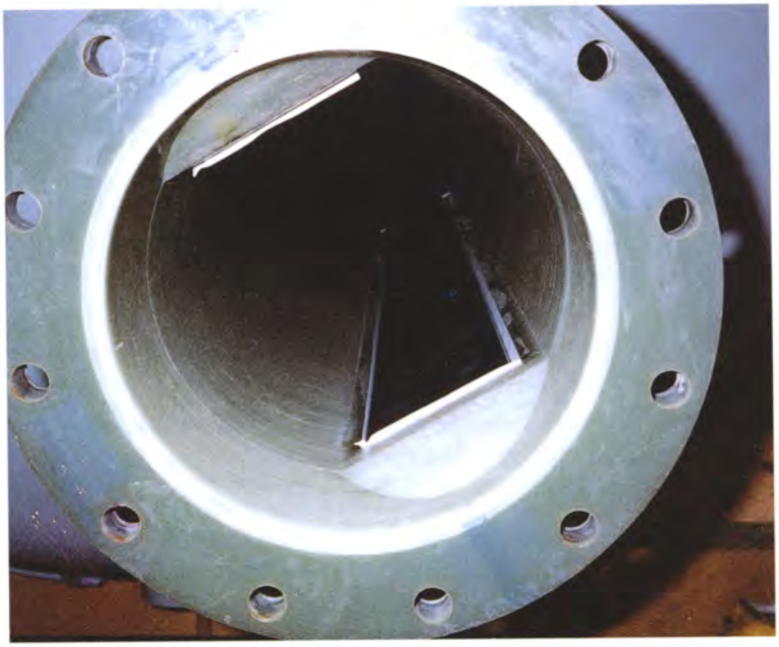


Photo 7.2 Electrodes seen from the end of a seawater duct.

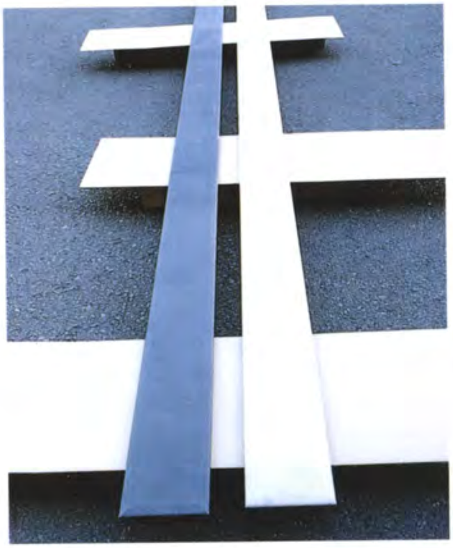


Photo 7.3 Electrodes to be inserted into a seawater duct.
The positive pole (anode) is on the left.

electrodes, but also the conductors called a "bus bar" which sends direct current to each electrode. The electrodes must be installed so that their longitudinal direction is perpendicular to the direction of the magnetic field, or the tangential direction of a plane of the concentric circle, with the center of the bore in an annular arrangement of the six unit thrusters at its center. Naturally, the orientation of the electrodes' polarity must be carefully considered for installation.

The electrodes can be seen clearly in the interior of the seawater duct (Photo 7.2).

A large electric current of up to 2,000 amperes flows to each of the electrodes. Therefore, the electrode materials must be able to provide stable performance for a long period without erosion. When the electric current is conducted in seawater, electrolysis*2) generates chlorine and oxygen gas at the anode and hydrogen gas at the cathode. The amount of electric current and the materials of the electrodes determine the ratio of the chlorine and oxygen gases generated. Therefore, materials that emit as little chlorine gas as possible must be selected.

We evaluated several materials for the anode, and chose DSA, an iridium-oxide based product with high durability to contend with a large current, which had a record of many practical applications in the electrochemistry field. Photo 7.3 shows the electrode plates before installation in a seawater duct. The one on the left is the anode*3).

In this connection, when we measured the amount of chlorine gas generated in the seawater at the outlet of the nozzle of the thruster during the sea trial, it was only 0.1 ppm even at full throttle, much less than we expected. Since the minimum amount of chlorine gas contained in municipal running water in Japan is 0.1 ppm, you can see how minute was the chlorine gas generated by the electrodes.

The material for the bus bar, the conductor flowing the direct current to the electrodes, must also withstand massive current and strong electromagnetic force. More precisely, since the bus bar is to be used in the normal conducting state, a material with the least possible resistance is required. We decided to use a copper plate with a large cross section.

As mentioned in our discussion of the superconducting coil, the electric current of nearly 5,000 amperes is conducted through a

*2) Electrolysis
If an anode and a cathode are placed in saltwater, the following two oxidation reactions take place at the anode:

$$Cl^- \rightarrow \frac{1}{2} Cl_2 + e^-$$

$$H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$$

In other words, oxygen gas and chlorine gas are liberated. The kind of electrode determines which of the two reactions has a higher priority. On the other hand, the following reduction reaction proceeds to release hydrogen gas at the cathode:

$$H_2O + e^- \rightarrow \frac{1}{2} H_2 + OH^-$$

However, a further reaction proceeds between chlorine gas from the anode and water molecule.

$$Cl_2 + H_2O \rightarrow HCl + HClO$$

Part of the white foam seen in the photo of the Yamato-1 under way is hydrogen bubbles released from the cathodes of the thrusters. Most of the oxygen was probably dissolved in the water.

*3) Electrodes
If the magnetic field induced by a magnet is constant in the case of an MHD propulsion ship, thrust forward and astern is obtained by changing the direction of the electric current between the electrodes.
Therefore, material which could be used for either the anode or cathode was desirable, but such a dual-polarity electrode material having excellent reliability and also suppressing the generation of chlorine gas had not been developed. So titanium and iridium oxide based DSA was used for anodes and platinum-plated titanium used for cathodes. However, the development of electrode plates capable of sufficiently withstanding the polarity switch-over is essential, and such development is considered possible in the future. The electrodes' polarity switch-over was conducted only during the "polarity switch-over test" in the case of the sea trial. For normal thrust astern, thrust reversers, which are devices to divert the direction of water-jet thrust out of the nozzles in the reverse direction (in the direction of the bow), were

used. This equipment was stored onboard. Since they create resistance, the reversers were lowered into the water immediately aft of the nozzles for heading astern. (Fig. 2.1).

bundle of fine filaments with only a 20-micron diameter (with a total cross-sectional area of 6 mm^2) in the superconducting state. However, since the current conducted to the electrodes in the seawater duct is done in the normal conducting state, even a mere 2,000-ampere electric current needs a very large conductor (with 1,000 mm^2 cross section). This tells us how great the power of superconductivity can be.

Electric Current Supply Circuit to the Electrode Group

The electric current supply circuit to electrodes is shown in Fig. 7.3. As explained later, it is very complicated, in fact. But theoretically, a pair of rectifiers converts the alternating current (AC) from the generator to direct current (DC). The AC component is not completely removed even after the current has flowed through the rectifiers. Therefore, after removing the rest of the AC component and smoothing out the current by conducting it through the DC reactor — in other words, after minimizing the AC component contained in the DC — as much as possible, the DC is conducted to the electrodes in the unit thrusters.

Notice how each electrode is connected to another in each of the six unit thrusters to comprise the thruster.

The connection of electrodes and power supply are shown in

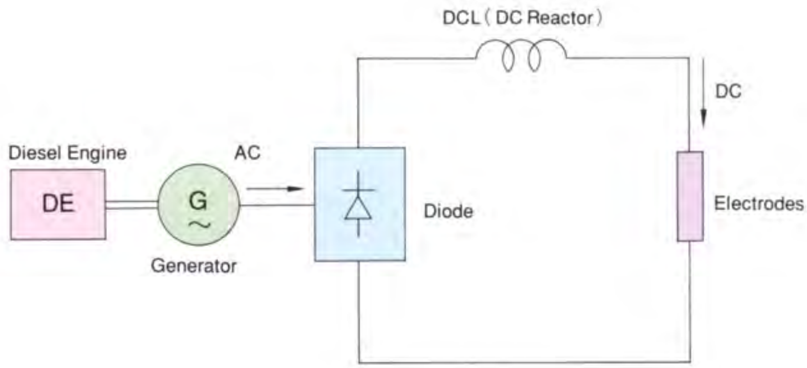


Fig. 7.3 Simplified circuit diagram of the electrode current supply

Fig. 7.4. Also, Fig. 7.5. shows a near-actual circuit diagram delineating the power supply to the six pairs of electrodes. As shown in these figures, the electrode pairs of the six unit thrusters of the Yamato-1 are divided into two systems and interconnected. In other words, the electric current conducted to the electrode pair of unit thruster 1 is led to that of unit thruster 3, skipping unit thruster 2, then is conducted to unit thruster 5 before returning to

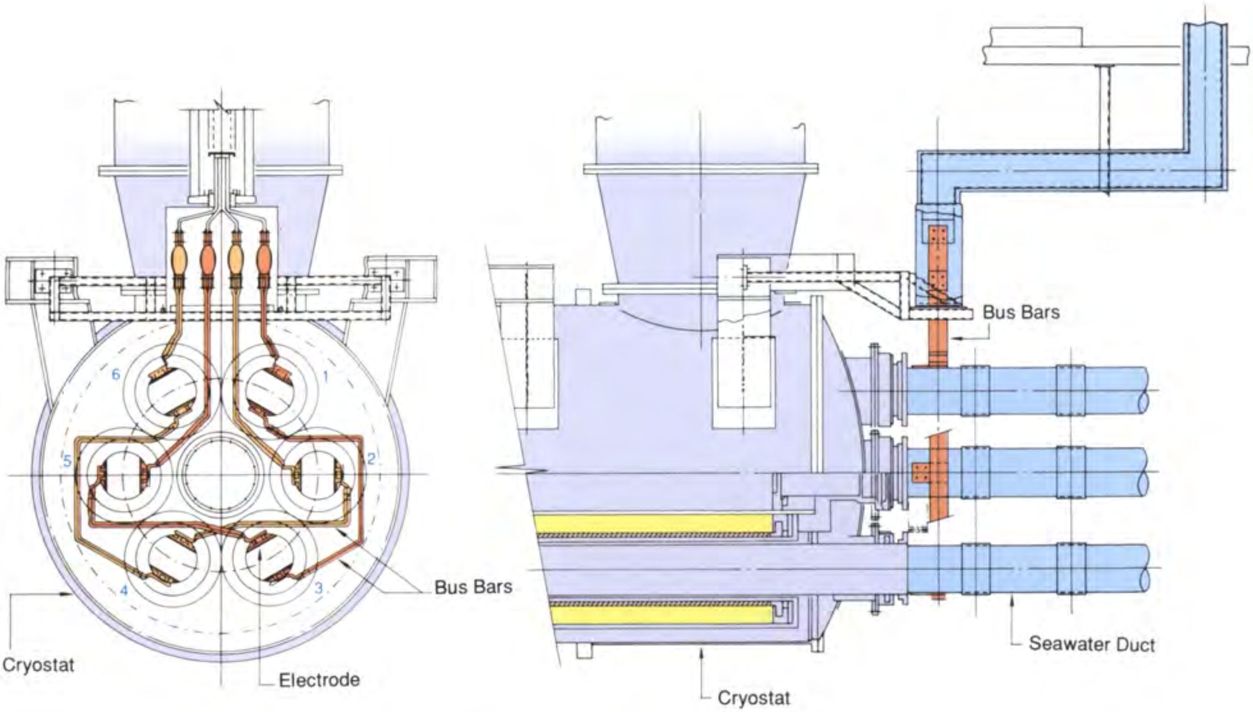


Fig. 7.4 Conceptual drawings of electrode connections

the switchboard. This is one system. In another system, the electric current similarly is led to unit thruster 4 from unit thruster 6, then conducted to unit thruster 2 before returning to the switchboard.

There were several reasons for these connections: There are 6 parallel, 6 serial, 2 serial with 3 parallel, and 3 parallel with 2 serial connections for connecting the electrode pairs of the six unit thrusters. Each connection has its own characteristics. In the cases of 6 parallel and 2 serial with 3 parallel, there is a disadvantage, since the electrode current exceeds the capacity of a conventional generator circuit breaker, so no conventional protective breaker can be used.

In the case of 3 serial with 2 parallel and 6 serial connections, the electrode current does not become that large. Therefore, an existing conventional protective device can be used for either of them. However, the 6 serial connection has the disadvantage of large current leakage. In other words, the reason for conducting the electric current is to generate Lorentz force by acting on the portion where the magnetic flux is present. Therefore, it is meaningless if the electric current does not flow where the magnetic flux is located. The 6 serial connection arrangement increases wasted electric current by flowing even to an area where there is no magnetic flux. Specifically, 15 percent to 30 percent of the

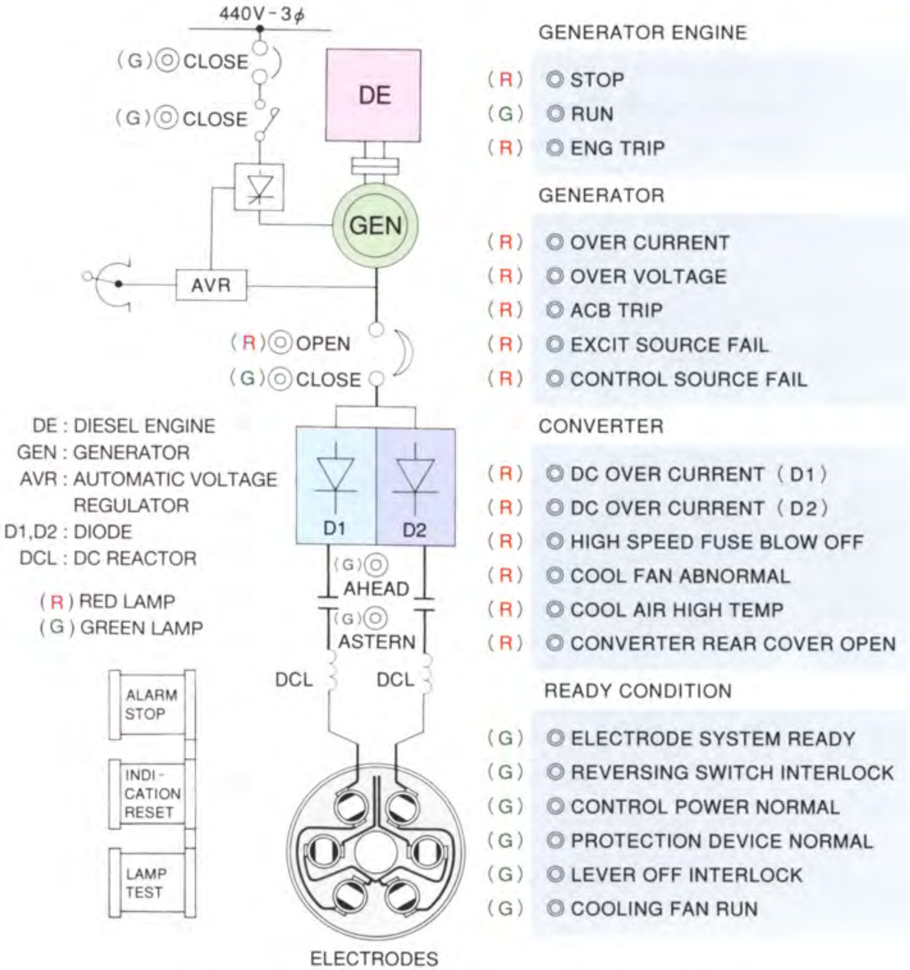


Fig. 7.5 Circuit diagram connecting the electrode power supply and the six sets of electrodes

The vertically arranged lamps on the right-hand side indicate the operational status of various items of equipment. They are actually displayed in English on the distribution panel as shown here. The green lamps (G) are lighted when operation is normal, and if a malfunction occurs, the corresponding red lamp (R) turns on.

conducted electric current is wasted in the case of the 6 serial connection.

For these reasons, the Research and Development Committee adopted a 3 serial with 2 parallel connection as the most efficient and rational connection. Also, in order to secure a balanced thrust by using the remaining thrusters in the event of a breakdown of one of the two systems, we decided to connect the electrode pairs alternately.

The amperage fed to the electrodes is controlled by a voltage regulator, shown as "AVR" (Automatic Voltage Regulator) in the figure, by controlling the voltage between the electrodes. If the electric current is not conducted, the ship does not move. If a large ampere current flows, the power output increases. Regulating the amperage with the voltage regulator controls the ship's propulsion.

CHAPTER 8

HULL AND OUTFIT

The history of ships is a long one: ships with a normal structure were already in use in Egypt 7,000 years ago. Ships also existed in China as old as those in Egypt. It was China from which the Japanese borrowed the ideograms for ships. The English language also has ancient and distinctive terms that specify ships, such as vessel, boat, ferry and craft.

These different words probably means that there were too many types of ships to be covered by just one word. Even when classified only by purpose, there are two categories of ships: merchant ships which primarily carry passengers and cargo for pay, and ships built for other specific reasons, such as warships, research ships and cable ships. I believe the Yamato-1, with its sea trials of a superconducting MHD propulsion system onboard a real ship naturally falls into the latter category.

Although there are numerous varieties of ships, their basic nomenclature and structural principles all have a common basis. First, we have the dimensions of a ship. As mentioned earlier, the length between perpendiculars is used to measure the length of a ship in naval architecture and in legal language. An L_{pp} notation is used. This indicates the horizontal distance between the forward point of the bow at the load waterline, or the forward end of the stem at the load waterline, more accurately speaking, and the center of the rudder stock at the stern. The horizontal distance between the forward end of the bow and aft end of the stern is literally called the length over all (L_{OA}) of a ship.

The horizontal distance from the inside of the side plating to that of the other side at the maximum hull width is called molded breadth (B_{mld}), and the thickness of both side platings added to this is called the extreme breadth. Of course, the cross section of a ship is not a rectangular shape, and there are many complex shapes, but the method of measurement for each ship's breadth is determined specifically for that ship.

The height from inside the center bottom of the ship, or the keel (a thick plate which runs through longitudinally the ships bottom-center), to the waterline at full load is called the molded draft (d_{mld}); the height from the outside of the ship's bottom to the waterline is called the extreme draft (d_{ext}). The height from the waterline to the end of the deck is called the freeboard. A small freeboard figure means that the deck is close to the water's surface, and in that

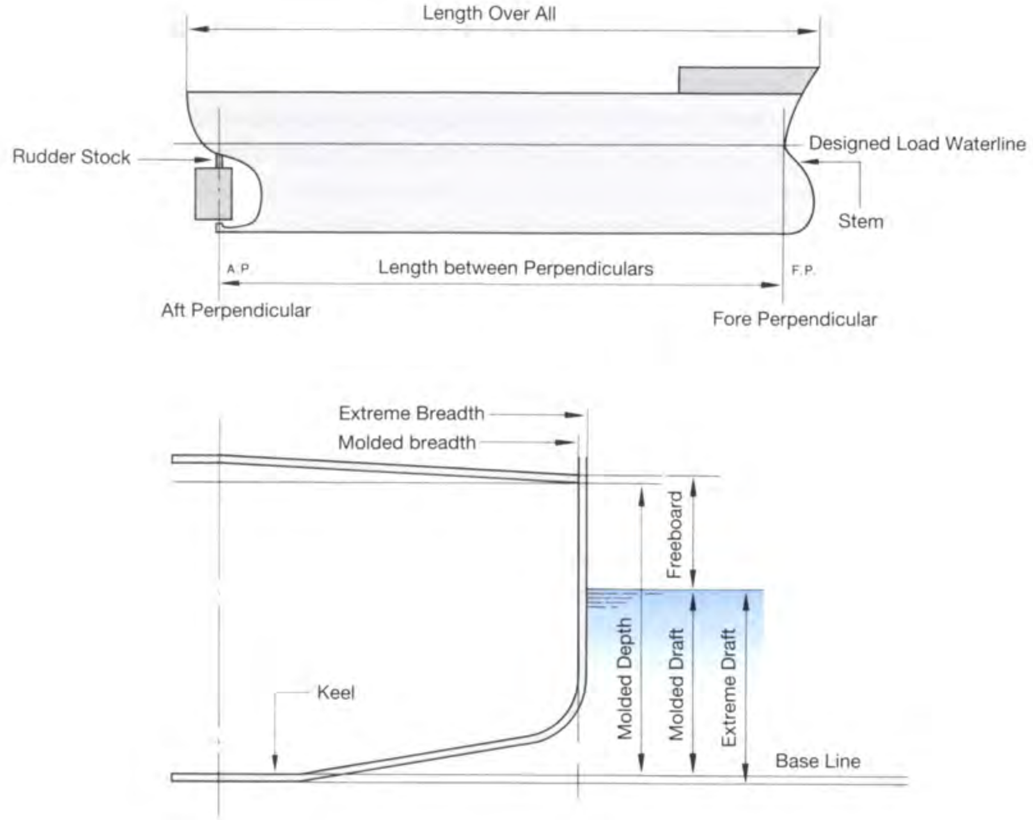


Fig. 8.1 Ship length, breadth, draft, etc.

regard, there is danger of the sea washing aboard.

Ships are the largest man-made mobile objects, and the sizes of very large tankers exceeding 300 meters in length and 50 meters in breadth are not uncommon. The greatest advantage ships have is that they can travel to desired destinations freely without moving on roads or tracks but on water. However, the depth of the sea is different. That is why the draft value is critical. If a ship travels through water where the depth of sea or river is too shallow, it would run aground. Due to its size, it would be very difficult to free the ship once it is grounded.

Everyone is aware that the size of a ship is expressed in tons. This tonnage is a bit complicated. The easiest weight to understand is the loading capacity, the deadweight. It clearly indicates the maximum weight of the cargo that can be carried onboard, and its notation is DW. This weight does not include that of the hull, machinery and equipment, fuel, water and crew on board.

In contrast, the size of a passenger ship is expressed as the sum of usable passenger space onboard by setting 1 ton (volumetric ton) to equal 100 ft^3, or 2.38 m^3. This tonnage is the gross tonnage (GT). Of course, the volume of the engine room and toilets is excluded.

Lastly, the tonnage for ship such as war ships, which do not have payload space, is expressed in the displacement by multiplying the volume of the hull underwater by 1.025, the specific gravity of the seawater. Therefore, this value is the true weight of a ship according to Archimedes' principle. Normally, the weight of the ship is expressed as the full load displacement. The figure of 78,000 tons (weight tonnage) of the battleship "Yamato" was exactly that. The size of our Yamato-1 is also expressed by displacement.

The configuration of a ship with noticeable structures on the bow and stern sections, and with a structure which houses important equipment to control the motion of the ship, called the bridge at midships, used to be a familiar sight. This is a classic configuration called a three-islander. Today, ships are variegated and only a few have such classic configurations. The appearance of the latest passenger ships and ferries are frequently designed by industrial designers as smartly as they design automobiles.

The most different aspect of a ship compared to automobiles and trains structurally is that the immense weight of the ship itself and its cargo is supported by water buoyancy acting on the entire underbody (that part of the hull below the waterline). In this respect, it resembles aircraft with a total wing surface supporting its weight. However, the aircraft uses a dynamic force called lift, and this is different from the static force of the buoyancy that floats a ship when motionless. A car, on the other hand, has its weight supported on four wheels. Therefore, it is structured to hold a heavy weight bearing down on the relatively small size of each wheel.

On the contrary, a ship supports its immense weight over the wide size of the shell plating from bow to stern with water pressure.

When a man is upon his feet, his weight fall on the soles, while his weight is supported uniformly by entire area of his back against the pressure of a mattress when lying on his back. A ship is like this.

Unlike a mattress, the sea has constant swells and waves, and sometimes a ship heads into incredibly high waves. Since the density of water is high, and hardly compressible*1), the power generated by waves is immense. The ship is structured to bear it. Today, almost all large ships are made of steel. Although more and more ships of small to medium size are made of aluminum, the number of steel vessels is still in a clear majority. The low cost of steel is one reason, but it also has extremely superior strength and workability*2).

To build an ordinary merchant ship, a thick belt of steel called a "keel plate" is laid first from bow to stern, running through the center, to constitute part of the ship's bottom. This is where the sturdy timber called a "keel" was laid for a wooden ship in former times. Structural members called "frames" are installed with the keel plate at their center, much as if ribs join the backbone. Naturally, additional strength members are used in the keel plate and frame joinery areas. The shell plating is welded to the exterior part of the frames. Reinforcements such as girders and stiffeners are inserted inside the plating to secure sufficient strength.

The bow and stern sections at both ends of a ship are structured to be uniquely strong. The bow in motion cuts through the water, and that is where high waves crash in a storm. Naturally, a strong structure that serves its purpose is required. A screw propeller is normally installed at the stern, and it is subjected to heavy propulsion force from the propeller transmitted to the hull. A large rudder is also installed. The rudder is subject to a strong force when the course is changed of a ship in motion. This is the only part of the hull subjected to such heavy force. Therefore, the structure of this section must be particularly strong.

When the bottom and sides of the hull have been constructed with shell plating and the bow and stern sections have been joined, a long, narrow container-like structure is completed. The deck is like the lid of this container. The deck has an important role to play in the functioning of a ship, along with the shell plating on the bottom and sides of the hull. The deck is not installed as a simple lid, but has reinforcement components installed on the deck

*1) Compressibility
As stated in the text, water is hardly compressible. Therefore, in the event of a hull being pounded by waves, it is subjected to strong impact. Such impact caused by the low compressibility of water is called "water hammer."

*2) Workability
The hull manufacturing process requires bending, cutting and welding operations. Good workability here indicates total characteristics, including the requirement of gentle force for the bending process, no occurrence of cracking and local damage during working, and the requirement of no complicated process in the welding operation.

backside. Furthermore, by dividing the hull in several sections from bow to stern, bulkheads are built in. If the deck covers the hull completely, like a lid, the ship would not serve its purpose. The deck always has openings for people and cargo to enter and exit. This completes the hull.

Building a hull demands a large-scale building technique. All components were carried by crane until recently in order to lay a long keel plate on the building berth first and then install frames on it and so forth mainly by riveting. But today, the hull is divided into several sections called blocks, and each block is built independently, then joined together by welding. It may sound simple to weld the blocks together. However, it is a very hard work to build a ship equivalent to one built from the ground up in a single location in terms of strength and in other aspects, since welding joins such important components of a ship as the keel.

Japan is known the world over as expert with respect to the modern manufacturing technique. This is one of the basics in engineering that supports the Japanese shipbuilding industry*3).

What determines performance most is the area of the hull displacing water, or the area of water plane, and the ship form below the waterline. It is easy to float a large, empty steel box on water, just like floating a bowl or a washtub. However, it is not easy to keep the bowl and washtub from heeling when heavy items are placed in them. A ship is skinnier than a bowl or a washtub, and in addition is equipped with heavy essential items onboard. Furthermore, cargo must also be loaded onboard. A ship would not serve its purpose unless it can float as designed. If a ship is not properly designed, it might heel to the left or right, or forward or aft, even in still water, and in the worst case could take on water.

A ship floats with the balance of its weight acting as the center

*3) Shipbuilding technology
Currently, thanks to the development of technology which intensively utilizes computers, ranging from design and production control to producing contoured areas of a hull, the large steel ship production industry in Japan is successful in labor-saving and energy-saving ways that were unimaginable until quite recently.

of gravity and the buoyancy of water acting on the hull. It is designed and built in such a way that it floats exactly as expected. To achieve that, the ship form below the waterline and the weight distribution are calculated in detail, and the ship is built in line with the design. It is also natural for a ship to float in specified conditions. Even when it leans due to waves, it tends to right itself immediately. This characteristic is called stability. This stability is determined by the relative locations of the ship's center of gravity and center of buoyancy. It is widely known that the higher the center of gravity, the lower the stability. A poorly built ship will heel too much and eventually turn over (capsize). You may see on TV fishermen working hard to remove ice from a deck on a fishing boat operating in a cold northern sea. This is a very important work. It prevents the center of gravity from rising due to icing on the deck.

A ship is a ship only if it can travel on water. Therefore, we must verify the performance of a ship, such as whether it can achieve the designed speed and whether the rudder functions properly. It is impossible for current naval architecture to fully predict performance theoretically. Therefore, every time before a new hull form ship is built, we always conduct tank tests to confirm performance, and if necessary, we modify the design partially or sometimes do a complete redesign.

The above is about ships in general. Our Yamato-1 was a special ship, but a ship after all, and therefore everything stated above had to be fully evaluated. The starting point was, naturally, the weight and dimensions of the superconducting MHD propulsion system. In 1987 the MHD Thruster Subcommittee was able to make a system presentation. The dry weight of the two MHD thrusters was 30 tons, meaning the weight without seawater in the seawater ducts and without helium for refrigeration in the cryostat. The working-space length of a thruster was three meters and the internal diameter of the seawater duct of a unit thruster was 240 mm. The weight and dimensions of the diesel generator systems (2,000 kW × 2 units) for supplying the power to these thrusters, as well as the weight of various equipment for converting AC into DC, the voltage control system and the switchboard for electrodes were all estimated.

In the case of an ordinary merchant ship, the so-called payload, such as the maximum number of passengers or cargo weight, route and speed and so forth are worked out first, and the ship design progresses as such considerations as the weight of the machinery are estimated one after another based on empirical data. However, in the case of the Yamato-1, the superconducting MHD propulsion system, which was the core of the experiment, had the highest priority. The engineering philosophy, or fundamental design concept, in the design of this ship, was:

(1) The ship is supposed to travel at 8 knots*4) at maximum power output, meaning a combined Lorentz force of 16,000 N (newton) acting on seawater in the thrusters at both port and starboard sides. The displacement target should be set at 150 tons. Therefore, the hull form should have extremely small resistance while underway, with the propulsion system as compact as possible.

(2) It is essential to conduct inspection and maintenance thoroughly. Therefore, the hull structure and machinery arrangement should be made so as to enable removal and installation of the thruster units as easily as possible.

(3) This is to be the world's first full-size superconducting MHD propulsion ship. Therefore, the ship form cannot be based on any traditional concept of how it should look.

Based on these fundamental concepts, design work to plug in the specific figures started around the end of 1987. Of course, even before that, in keeping with the progress in work being carried out by the MHD Thruster Committee, we discussed ship type vigorously. And in 1987 we conducted basic model tests. By using such pioneering development data as a basis, we conducted not only theoretical evaluations of various ship types, including a simple monohull, catamaran and combined ship, but also the necessary model tests, and in 1988 the form of the Yamato-1 was finalized.

The ship has a shallow draft, with a bulge to accommodate the thrusters on the port and starboard sides. The ship also had a concentration of heavy equipments at the stern such as diesel generators. Therefore, the ship's center of gravity was offset to the aft of the hull. The distance between the bulges was also sufficiently large to prevent water flowing around each bulge increasing resistance. Based on these factors, the bulges were also

*4) Knot
The unit which is commonly used even today to express ship speed. One knot is defined as one nautical mile per hour. One nautical mile originally meant the distance of one-minute latitude at 45 degree north. A metric conversion for one nautical mile, commonly used in Japan today, is 1,852 m. Therefore: 1 kt = 1.852 km/h.

laid out at the after-hull, where breadth was maximum. As a result, the center of gravity was shifted more toward the aft to achieve a shallow-draft hull form with a small L/B. In addition, since the forward hull bottom was a near-arc U shape, insufficient cource stability was anticipated. Maneuvering and seakeeping tests using a model were then conducted. Based on these tests, the hull form in the vicinity of the bow was changed to a V-shape from a U-shape. The hull bottom lines were also changed to increase the area of the hull below the waterline when viewed from either side, in order to improve cource stability.This will be described later in this chapter. Furthermore, the ship length was extended, since we decided to increase the equipment for reducing the alternate current components of the direct current to the electrodes*5). As a result, at long last in 1989, the design of the Yamato-1 with L_{pp} = 26.40 m, B = 10.39 m, D = 2.5 m, d = 1.5 m and displacement of 185 tons was finalized.

The design and building of the main hull, which is ship structure under upper deck, was carried out by Mitsubishi Heavy Industries, using aluminum as the structural material. The beautiful superstructure shown in the photos was created at a design office, in Hiroshima*6). Based on the drawings provided by the design office, detail drawings were made and the superstructure was built at a Mitsubishi-affiliated factory in Osaka. The superstructure completed there was transported to MHI's Shimonoseki Shipyard by sea and joined to the main hull, which was equipped already with the main power supply to feed the electric current to the electrodes, the auxiliary power supply, and so forth. Then the ship was towed to Kobe to be equipped with its most important equipment, the superconducting MHD thrusters. At the Kobe Shipyard, loading and installation of important equipment, such as the thrusters, was done onboard. The outfitting of the Yamato-1 is covered in detail later.

Various Equipment Tests before Outfit

Equipment was not installed onboard immediately after completion. It was inspected and tested at various stages. Problem areas were checked and improved to make sure their functions, and performance sufficiently met the designed requirements. Only after that were they ready for onboard installation.

*5) The Equipment for reducing the alternate current components of direct electric current. If AC generated by an AC alternator is rectified as DC as in the case with the Yamato-1, inclusion of an AC component is unavoidable. This inclusion of the AC component is usually called "ripple." However, a flow of this kind causes various inconveniences in circuits that have been designed completely for DC. Therefore, the ratio of the AC component in DC in general is lowered as much as possible and a limit is set. We set this limit to 3% by voltage ratio. The equipment is used for this purpose.

*6) As everyone knows, the appearance of a car affects its sales a great deal. Therefore, styling-dedicated designers, who are usually called "industrial designers," create a body shape that can catch people's eyes and also fits in well with street scenes. It is a common practice for engineers to produce the body designed by industrial designers.

At present, there are still only a few opportunities for styling-dedicated industrial designers to design the entire appearance of a relatively large ship. The example of the Yamato-1 is one of such few cases. It seems that ship appearance based not only on function, which is essential, but also with attractive aesthetics will make Japanese sea scenes more beautiful.

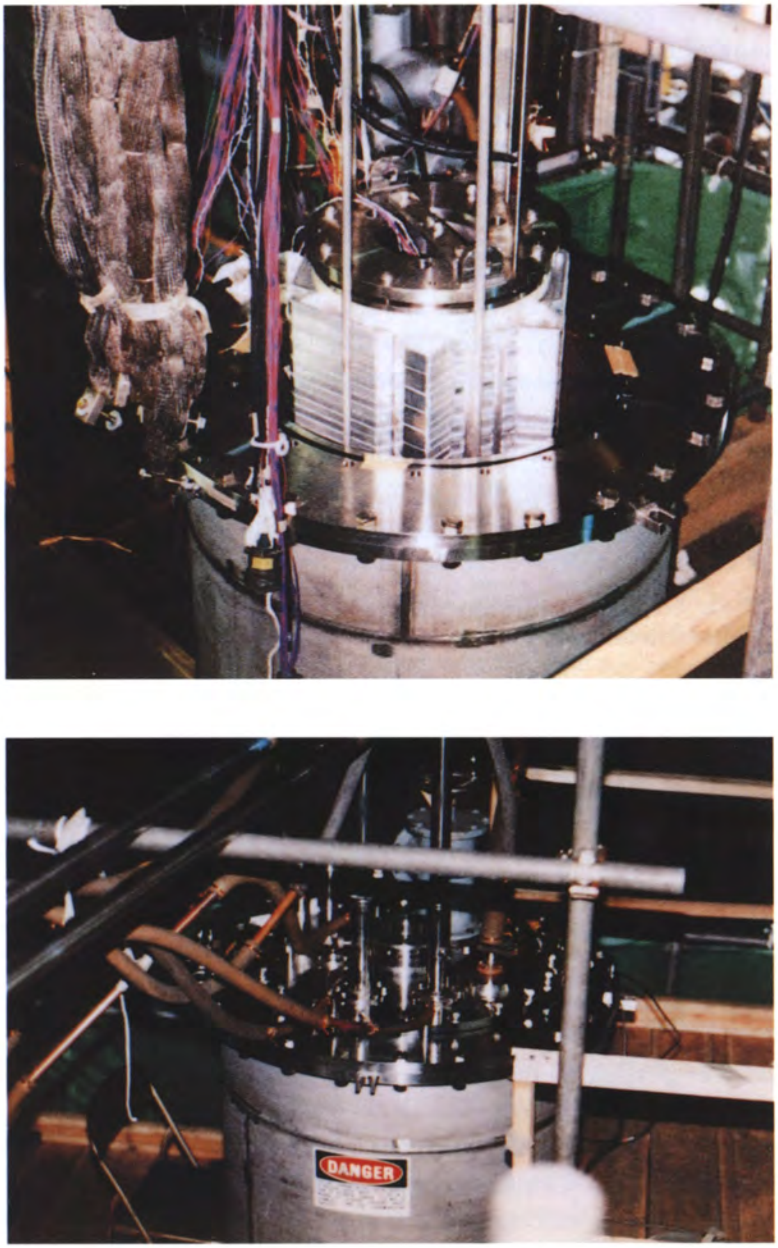


Photo 8.1 Excitation test of unit coil

(a) Unit coil is suspended vertically into the experimental cryostat.

(b) Undergoing an excitation test by conducting the current to the coil in the experimental cryostat.

As an example, the superconducting coil for a unit thruster is hung vertically in the testing cryostat in order to conduct an excitation test, when the coil is completed, (Photo 8.1). The test was conducted by first suspending a coil in the cryostat vertically. Then well cooled helium gas is fed into the cryostat, and the gas is circulated to cool the cryostat's entire interior. When the interior temperature reaches 20 K, liquid helium is poured into the cryostat.

Next, the power supply and protective systems were connected with the coil in the cryostat, and checked to see if these circuits function normally. Then the DC was conducted to the superconducting coil and the amperage was increased gradually by small increments. The amperage was increased until the electromagnetic force induced achieved the design value or better for the annular arrangement of the six coils. If a strong current is conducted right from the beginning, the coil would expand, due to the effect of powerful electromagnetic force suddenly induced, and that may cause a quench. Therefore, the amperage is gradually increased in small degrees.

To simulate the electromagnetic force that a single unit of the coil is subjected to when all six of them are arranged on the same circumference, it was necessary to conduct a nearly 4,000-ampere current to induce a 3.5-tesla magnetic field. Each single unit coil was tested one by one to make sure it achieves the requisite value.

This excitation test was done not only to check and see if there was any problem with the superconducting coils but also to train the coils. Conducting the current to the coil induced the electromagnetic force needed to break-in the coil unit and coil-holder and removes small distortions that might have crept in during the manufacturing process, in order to form the coil shape as close as possible to the ideal design shape. This process is called "training."

The results of the excitation test on all six unit coil are shown in Fig. 8.1. The black circles indicate the occurrence of a quench, and the white circles indicate "hold" — in other words, the achievement of a 3.5-tesla magnetic field which can induce the targeted electromagnetic force. As can be seen, all the unit coils had a quench once or twice before achieving the amperage and magnetic field standards set for the testing.

If a quench occurred, we shut off the electric current to return to

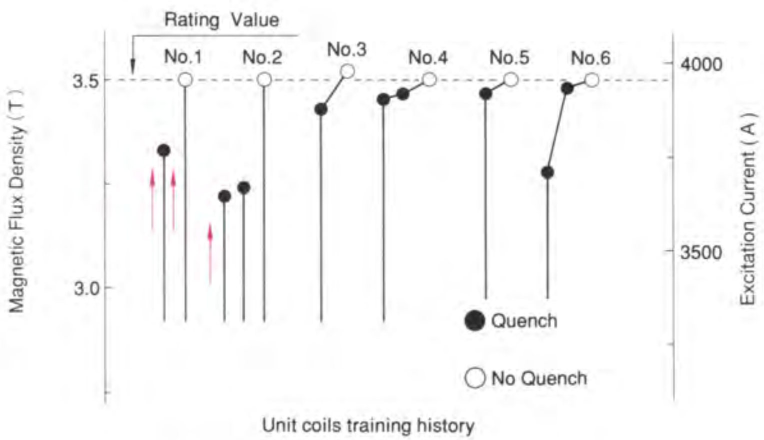


Fig. 8.2 Results of excitation tests on unit coils

Since this figure is a bit difficult to understand, it needs some explanation. The current is conducted to the coil in a superconductive state already cooled in the experimental cryostat, and the current is graudally increased. For example, in the case of No.1, the current is slowly increased on the line heading for the black circle. When the current reaches the black circle, the superconductivity of part of the coil is lost, and the power supply (exciting curent) is shut off automatically. The problem here is the discharge of energy with the disappearance of the magnetic field due to the abrupt power supply shut off. The energy, which was stored in coil to form the magnetic field, is discharged. In other words, a high voltage surge is created in each end of the coil. To prevent burnout damage to the coil itself from a short circuit, a resistor with an appropriate value is inserted in the circuit parallel to the coil. The current flows into this circuit instantaneously, and the magnetic field energy is consumed. When the current is again conducted to the coil circuit, which was shut off once, the current can be increased even higher than where the black circle was and can be conducted uneventfully to the white circle and held there, It is because the coil cable arrangement has been broken by the previous trial current conduction. In other words, this coil can be used at the rated current with no quenching. A coil like No. 2 succeeded in reaching that rating in the third trial. There were also a defective coils which were damaged without reaching the rating.

the initial stage, and restarted from the beginning. Even if a quench occurred in the first test, the coil was able to "hold" by the 2nd or 3rd time. This shows that the coils were trained by the tests. The electric current flowing through the coil at first breaks in the coil and coil-holder to bring the coil to a near-ideal shape. Then the coil can easily withstand the electromagnetic force, and the current amperage can be increased to the required value to achieve the targeted magnetic field.

Only after passing through these tests could the unit coil be used for a thruster. Since the Yamato-1 has two thrusters, a total of 12 unit thrusters are needed. (To be honest, we do not imply that all 12 units cleared the tests. There were several unusable coils that could not pass the tests, due to problems that might have crept in during the manufacturing process. Since this was the first time for the manufacturers to wind such large coils, there were many problems to be solved in production control.)

When two sets of the six unit coils cleared the test, they were assembled in the annular arrangement coil structure. The assembled coils also underwent cooling and excitation tests. After various tests were conducted, we started to install the equipment at the designated spots onboard.

Outfit Procedure

The outfit, itself, is not a very difficult task because it only involves installation of the equipment at specified spots. However, there are mainly two ways to do this depending on when the job is done.

One way is to install the equipment when the hull is completed, before launching, while the ship is still on the building berth or in the dock. Since the outfit is done before launching, this is called "advanced outfit." The other way is to load the minimum items of equipment onboard when the hull is completed, and then launch it for moorage at the quay to start fitting out on the water. This is the conventional outfit.

In short, outfit is done in one of the two ways depending on whether it is are done before or after launching. Outfit timing cannot be determined offhand, because it depends on a ship's type and size. But generally speaking, if the equipment to be installed is light in weight, the outfit is mostly done on the building berth before launching. If the equipment to be installed is heavy, a ship is launched with hardly any equipment onboard. Then it is fitted out gradually on the water while moored to a quay.

The reason for the difference in outfit is that the force acting on the hull is quite different when a ship is in drydock or on a building birth than when it is afloat in the water.

Needless to say, since a ship is meant to be afloat on the water, the hull structure is designed accordingly. Therefore, it is most natural for a ship to be afloat, supported by water, similar to someone lying on a bed.

On the other hand, while the vessel is in drydock or on a building birth, it is supported concentrieally, with large forces always acting on the hull. From the viewpoint of the ship, it is obliged to be patient until it is lowered into the water.

If heavy equipment is loaded in drydock, even more stressful forces are exerted on the hull. Therefore, a ship is launched when the hull is completed, and the outfit is done on the water.

There is still another reason why heavy equipment outfit is done after launching. When a ship is completed on a building berth, a launching ceremony will take place. A VIP such as the owner cuts the ropes with a silver axe, decorative balls are split open, and the ship slowly slips into the water from the stern. This is an exciting scene for all those involved in the shipbuilding project. However, when a ship is launched and goes afloat, it experiences the greatest force and strain of its lifetime.

If very heavy equipment is already mounted onboard at launching time, the force caused by floating may inflict possible damage or distortion on the equipment, due to the abrupt change in the condition of support for the equipment. In order to avoid that, a ship is launched into the water before it is fitted out with heavy equipment.

However, there are some exceptions. For example, a ship such as a warship must have its hull surrounded by armor plate. No matter how heavy the equipment may be, it has to be installed prior to launching. It cannot be fitted out after launch. Therefore, any such ship as a warship is fitted out as it is built in drydock. When all is done, water is fed into the dock to float the ship without moving it out of the dock. This protects the ship from shock associated with abrupt floating as much as possible.

We have now covered outfit procedures. However, more ship are recently built in drydock and launched by filling the dock with water rather than completing a ship on the building berth before launching it. Accordingly, advanced outfits in an early stage of construction are increasing.

In the case of fitting out the Yamato-1, very delicate equipment such as the superconducting MHD propulsion system had to be loaded onboard, so we adopted a different method of outfit and

launching.

However, the hull of the Yamato-1 is made of aluminum and designed to be very light. Frankly speaking, it is very easily damaged. Therefore, we decided to build the hull on the cradle, and when the hull was complete, we lifted the cradle with the hull on it with a floating crane and lowered it into the water (Photo 8. 2).

Hull Construction

The hull of the Yamato-1 is comprised of a superstructure and a substructure with the deck, which is one meter above the designed load waterline, acting as a border. Only the substructure contributes the strength of the ship. Therefore, the substructure functions as a main hull.

A exterior view of the Yamato-1 is shown in Fig. 8.3.

In order to symbolize the infinite future potential of a superconducting MHD propulsion ship, the appearance of the superstructure was designed under the theme of an "attractive form full of dreams," and its streamlined shape is composed of curved lines.

The ship is uniquely shaped: the forward half section of the main hull has a V-shape bottom with monohull lines, by taking course stability*7) and sea kindliness*8) into account; the aftward half is catamaran-type, with a bulge on each side to encase the

Photo 8.2 The Yamato-1 on the cradle is hoisted by a floating crane prior to launching her in the water

*7) Course stability
Even when a ship is at sea on a certain course, there are forces such as waves and swells acting on it continuously to disturb its motion. This is called disturbance. As long as this disturbance is tolerable, ships in general characteristically hold course steadily without needing any special steering. However, this characteristic varies from one hull form to another, and in some cases there are ships that actually sway left and right while traveling. Such ships as these are said to have a poor course stability. Of course, ships with any such characteristic cannot travel at sea, which requires a modification of the hull form. To clarify such a ship's performance, tank tests of a model ship are conducted in a wide water tank as mentioned in *10) on page 119, but not in a normal towing tank.

*8) Sea kindliness
With exception of special ship, a ship in general has a high and sharp bow. This is for cutting through crashing waves to minimize impact of the wave force as much as possible while a ship is traveling. This performance is expressed as sea kindliness here. As a matter of fact, the shape of the bow section is one of the most important factors in determining performance.

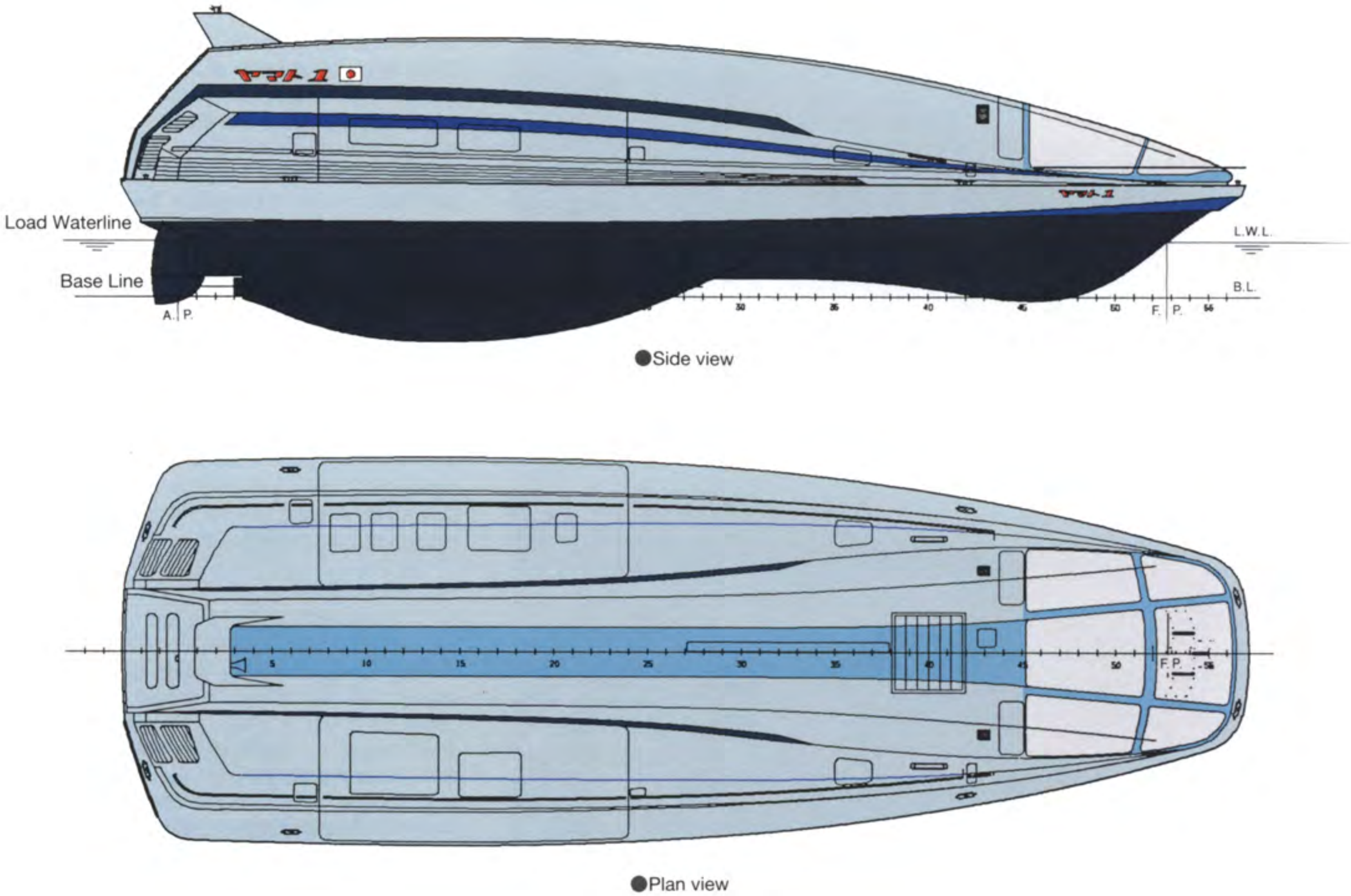
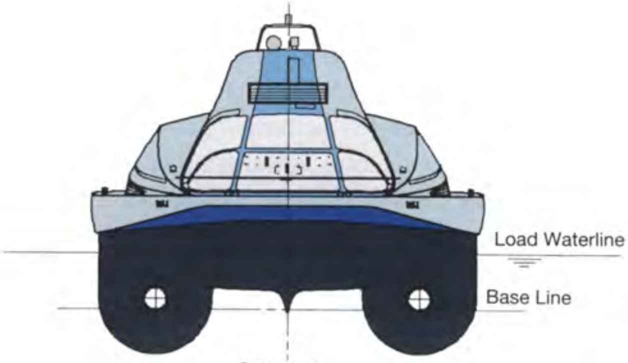


Fig. 8.3 Exterior views of the Yamato-1

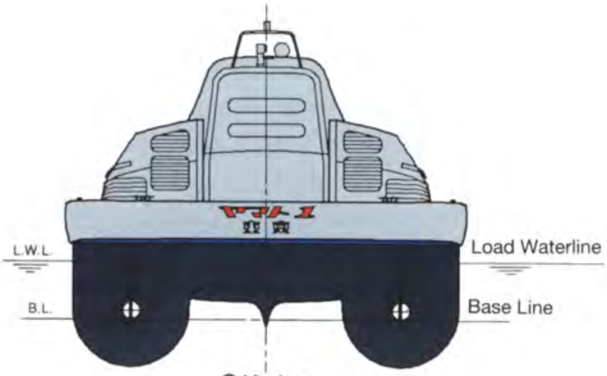
superconducting MHD thrusters.

The hull was constructed at the Shimonoseki Shipyard of Mitsubishi Heavy Industries. Before we began construction, various experiments had been carried out using model ships. Tests using model were necessary to confirm whether the actual ship would function as designed, even though it had been designed with displacement, stability and performance in mind.

It is far more difficult for a ship to maintain a straight-line course than is generally thought. If the ship is longitudinally unstable, even slightly, it may be subjected to the reaction forces



●Front view



●Aft view

created by waves generated by the ship itself under way, or affected by winds or waves. Then the ship will roll and sway, and cannot move in a straight line. Therefore, it is necessary to check to see if the ship can travel on a straight line by model test.

The ship's maneuverability must also be checked to see if it behaves as designed. For example, the ship undergoes tests to find out if it will turn as intended when the rudder is turned, or how much rudder angle is required to return to the initial heading. If the ship had not behaved as designed, an accident could occur. Therefore, it is necessary to check maneuverability carefully by the model experiment.

Experiments using a model ship were conducted at the Nagasaki Research and Development Center of Mitsubishi Heavy Industries. Needless to say, a model ship is meaningless if it does not have the same lines as the actual ship. This similarity in form is called geometrical similitude; a 1/8-scale model ship was used for the experiments.

In addition to geometrical similitude, another factor must be taken into account for experiments; that is, the dynamic similitude problem of how the speed should be translated to the model ship.

When checking the maneuverability of a ship using a 1/8-scale model, it is not a simple matter of reducing the speed to 1/8 of the actual speed. When the size and weight of the ship change, wind and wave resistance also change in a complex manner, and even acceleration force can change in a complex way. Determining how much speed should be used to test the model ship, by taking these points into account, is a matter of dynamic similitude.

For a ship, the model speed to be tested is determined by using the following equation:

$$\frac{\mathrm{U}}{\sqrt{\mathrm{L}\times g}} \qquad \frac{\mathrm{u}}{\sqrt{\ell\times g}}$$

where U = Speed of actual ship, L = Length of actual ship, g = Gravitational acceleration, u = Speed of model ship and ℓ = Length of model ship.

Since the actual ship's length and speed are known at the time of design, once the size of a model ship is determined, ℓ is also a known value. Hence the experimental speed of the model ship can be obtained by solving the equation. Based on dynamic similitude, experiments are run by having the model ship travel at that speed. The value obtained from the above equation is called the Froude Number. It is said that the resistance (wave making resistance) of a ship is determined mainly by this Froude Number. The gravitational acceleration g is equal to 9.8 m/s^2 (g = 9.8m/s^2) as widely known.

As to specific details of the experiments, resistance tests are conducted first. The model ship is placed in the water in a long, narrow towing tank*9). The model is towed by a carriage on rails outside the tank to measure the resistance force transmitted on the carriage at various speeds. These resistance tests are conducted in a

*9) Towing tank
The towing tank at the Nagasaki Research and Development Center of MHI, where the resistance tests were conducted, is 165 m in length, 12.5 m in width and 6.5 m in depth, and capable of accommodating up to 10 m/s speed towing. It also has an wave maker capable of generating up to 0.4 m-high waves. See Photo 8.3 (b).

still-water tank where there are no waves(Photo 8.3).

In the case of a high-speed ship traveling at 40 or 50 knots, wind resistance is a major problem. A wind tunnel is used to evaluate the wind resistance of the scale model. However, in the case of the Yamato-1, it was supposed to travel only at a slow speed of 8 knots, so wind resistance was not much of a problem. Therefore, no wind tunnel test was conducted.

Incidentally, wind is a critical for sailing crafts driven by wind. To design a yacht such as one for the America's Cup, scale models are tested to investigate the relationship between wind and water forces using a very special water tank with wind tunnel.

Equally as important as the resistance test is a maneuvering test to examine how the ship behaves. To verify whether the ship behaves as intended in design, we run a model ship in the wide tank*10) to measure its position every moment, and see how much the heading changes in relation to the corresponding rudder angle, and then see how long it takes to return to the initial course. Trying to make the ship run straight often turns it, and trying to make it turn fails when this maneuvering test is conducted.

During the initial tank test of the Yamato-1 scale model (Photo 8.4), it was so unstable that it could not hold its course. This was not unique only to the Yamato-1. It happens often to a ship as fat as a tanker. In the case of the Yamato-1, due to its unique shape with bulges on both sides for housing the two superconducting MHD thrusters, it was especially difficult to gain course stability.

The problem areas detected in the initial maneuvering test were reevaluated by the MHD Ship Design Subcommittee, and design changes were made. After that the maneuvering test was conducted once again. After the second test confirmed maneuvering as intended by the design, we then finalized it and started to build the actual ship.

The procedure for building the Yamato-1 divided the main hull into four blocks and each section of the main hull was constructed upside down with the bottom up. When that was completed, each section was turned over to the right-side-up position and placed on the cradle to join the sections together. Then the superstructure was set on the main hull.

The completed hull was towed to Kobe from Shimonoseki. It was lifted to land for the final phase of construction and outfit of

*10) Maneuvering and seakeeping tank
The tank at the Nagasaki Research and Development Center of MHI, where maneuvering tests were conducted, is called a maneuvering and seakeeping tank with 190 m length, 30 m width and 3.5 m depth, and is equipped with a wave-maker to generate up to 0.4 m waves. See Photo 8.4.

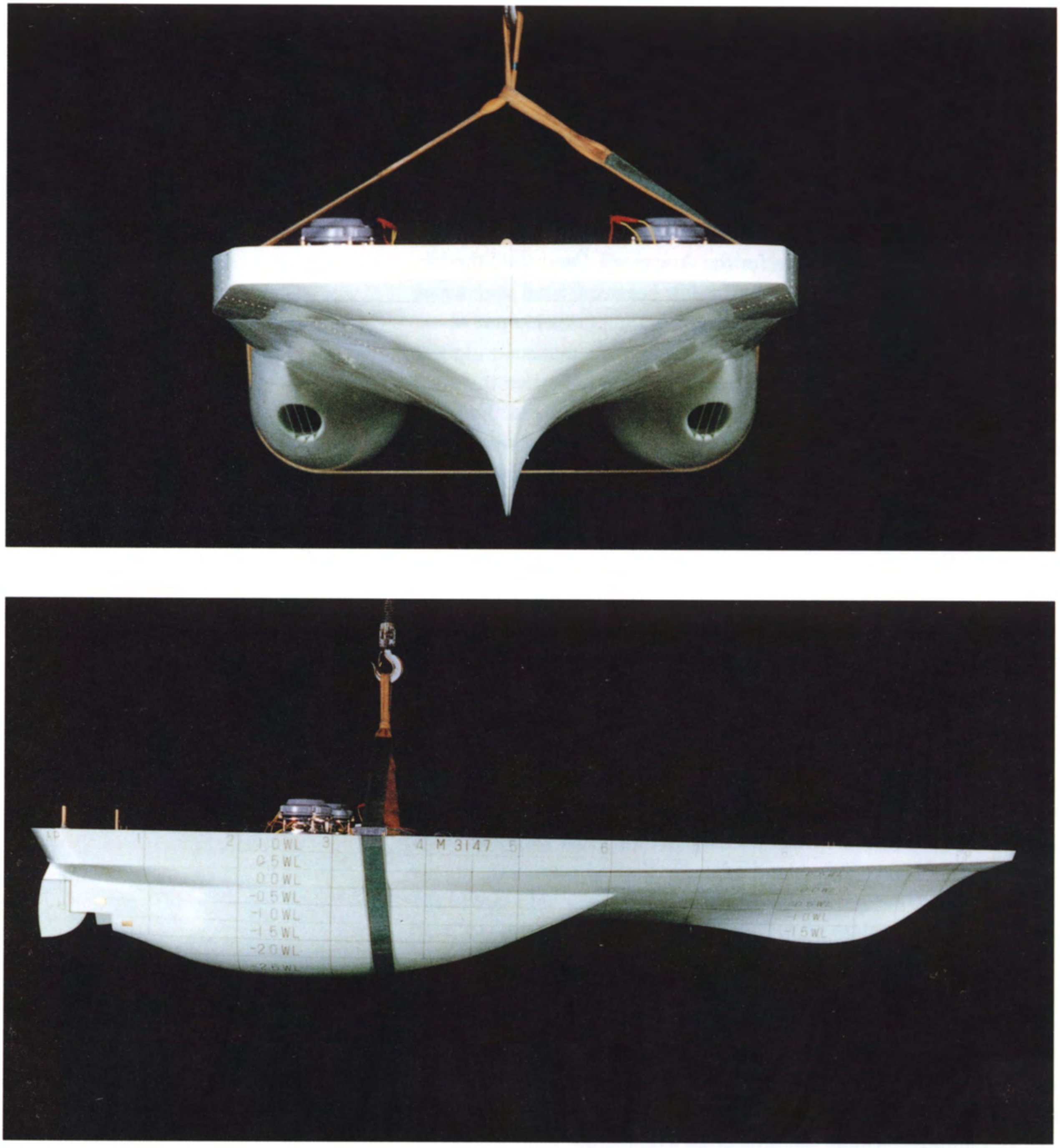


Photo 8.3 (a) The 1/8-scale model of the Yamato-1 used for tank tests

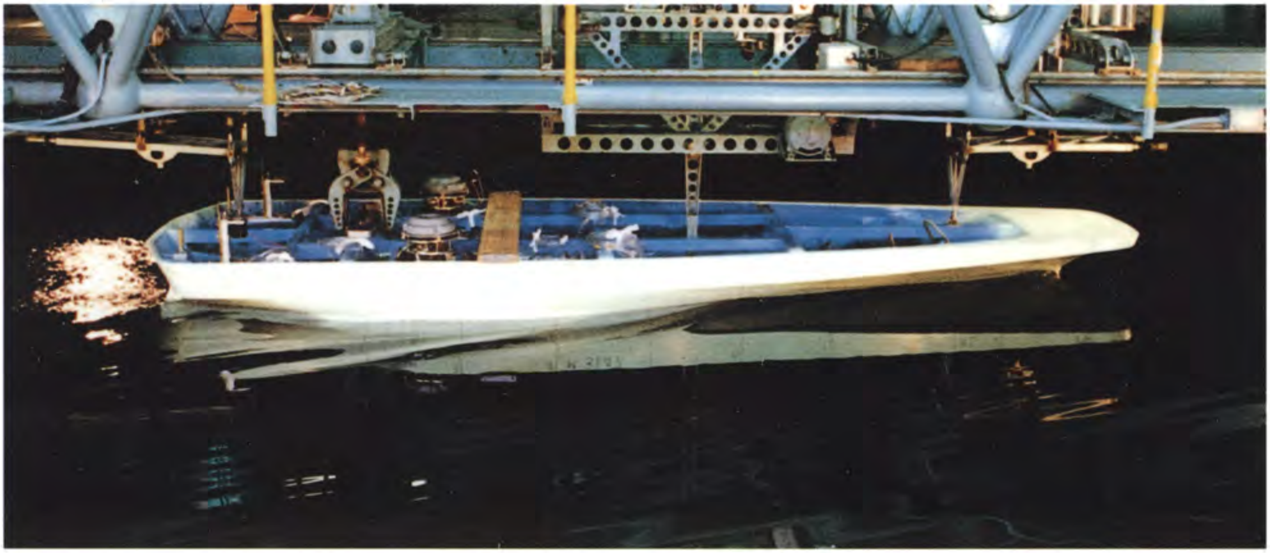


Photo 8.3 (b) A resistance test using a model ship
The model ship is suspended from the towing carriage, and the carriage travels at a predetermined speed on the rails installed parallel to the tank. The force acting on the components which connect the model and carriage during a tow are measured in detail. Based on the low of the hydrodynamic similitude, the resistance acting on the actual ship is calculated from the results.

the MHD thrusters.

Incidentally, every part of conventional Japanese ships, including the main hull and superstructure configuration, has been designed by naval architects most of the time. However, we commissioned industrial designer to design the superstructure, emphasizing appearance. Most often, Japanese naval architects place priority on function, ignoring formative arts such as appearance and color. Naval architects of other countries are not always like their Japanese counterparts. For ages they have been designing vessels emphasizing artistic appearance as well as practical function. This is the reason why there are so many handsome ships in other countries.

However, with the exception of traditional Japanese wooden ships built by Japanese shipwrights, Japan had very few in which artistic appearance was taken into account. This may have been due to the influence of Japanese naval architects who designed

Photo 8.4 A maneuvering test using a model ship
In a tank as wide as a swimming pool, unlike the one used for the resistance tests, a model ship travels by means of onboard battery-powered propellers. The behavior of the ship is measured through telemeter while she is in motion. The performance of the actual ship is estimated based on the dynamic relations from the analysis of the results.

function-prioritized warships much of the time.

Only recently have the shipbuilding-related colleges and departments of universities started teaching industrial design. Before that, these schools had given courses only in engineering and functions. Ship appearance was largely ignored. That was why ships formerly designed by Japanese naval architects somehow looked more dull and crude than foreign vessels.

Although the Yamato-1 was an experimental ship, it had an unlimited future potential. There was no pretext to design it to make it appear as dull as conventional Japanese ships. The ship form was intended to look modern and artistically styled. Since the person most ardent to emphasize design happened to be the Chairman of the Research and Development Committee, Yohei Sasakawa, we made a bold decision to commission industrial designers to design the superstructure.

We made the right decision. We are proud that the Yamato-1 turned out to look like a ship with a modern form and color scheme that had never been seen in conventional Japanese ships. In fact, when the sea trials were conducted with invited guests from shipbuilding interests in Japan and overseas, the ship form and color scheme were highly praised.

CHAPTER 9

THE ENTIRE PROPULSION SYSTEM

The cradle with the outfitting completed Yamato-1 sitting in it was lifted and then lowered into the water. To place a ship in the water for the first time is called "launching," and generally speaking, this is the time for a ceremony to celebrate. However, since the launching was unconventional in the case of the Yamato-1, a christening ceremony was held before the launch.

The "godfather" of the Yamato-1, the Chairman of the Research and Development Committee, Yohei Sasakawa (the current President of the Nippon Foundation), cut the tape, wishing for success in the Yamato-1 sea trials (Photo 9.1). There was no ceremony when the ship was physically launched.

After the Yamato-1 was afloat, we docked it at the quay broadside to conduct adjustment operations for the main generator system, electrode power supply panel, and so forth, except for the thrusters. Once confirming there was no abnormality in the systems, the Yamato-1 was lifted from the water back to land again.

After adjustment operations on equipment were completed, it should have been time to pour the liquid helium into the MHD thrusters to cool the coils. But considerable time is required to cool the superconducting coils. If a storm hits the area in the interim, the

Photo 9.1 Christening ceremony
Chairman of the Research and Development Committee,
Yohei Sasakawa, names the ship "Yamato-1"

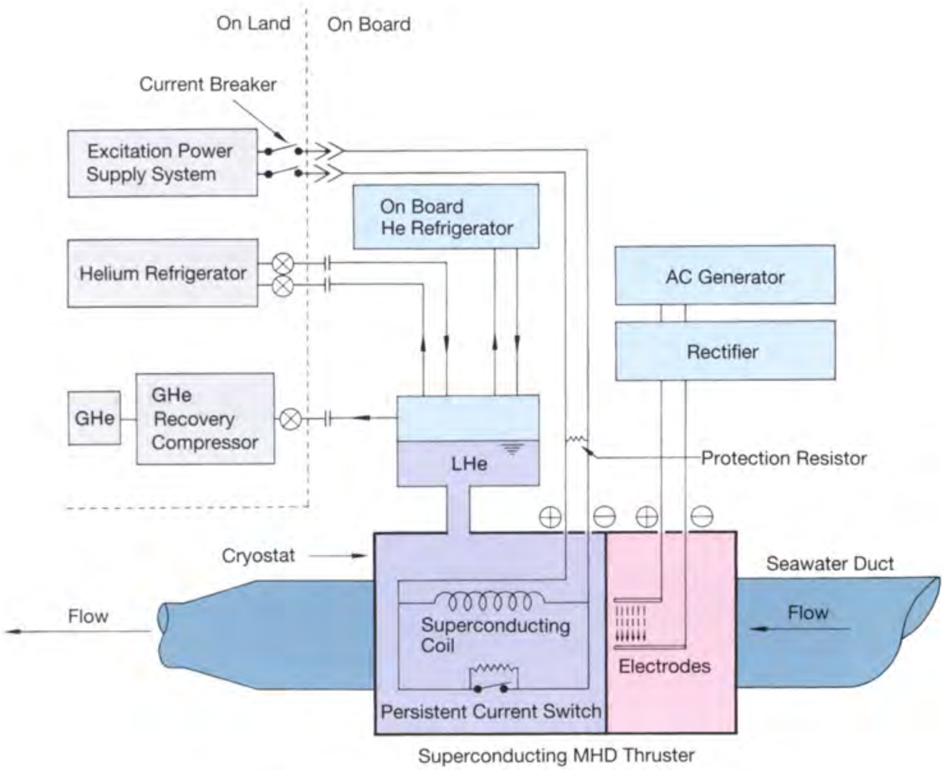


Fig. 9.1 Schematic diagram of the superconducting MHD propulsion system and land-based support facilities
The excitation current from the land-based facilities is conducted to the ship through heavy cables, and helium in liquid phase as well as in vapor phase from land is sent to the ship by using a kind of hose with outstandingly high insulation capability called a transfer tube.

ship would be in peril because it could not escape the storm and that was why the ship was lifted out of the water.

There were the support facilities on land such as helium refrigeration system and the power supply system for excitation of the superconducting coils and for supplying persistent current to the coils. First, the helium gas was injected into the MHD thrusters of the Yamato-1 on land from the helium refrigerator to cool down the superconducting coil sufficiently. This operation required very careful, time-consuming execution.

The procedure for the operation is as follows.

The configuration of the propulsion system and the land-based

support facilities, and the connections between them all are shown by diagram in Fig. 9.1.

The superconducting coil in the figure has to be cooled down to 4.2 K (-269℃). Incidentally, the PCS, or persistent current switch, is the device used to shift persistent current mode. Although the mechanism of the PCS is covered in detail later, it is made of superconducting material like that of the superconducting coil.

Although the superconducting coils needs to be cooled to 4.2 K, no 4.2 K liquid helium can be put into the helium vessel right from the start. Since air is present in the helium vessel initially, both the oxygen and nitrogen contained in air liquefy at about -196℃, and if cooled further they solidify. Therefore, if liquid helium is poured into the vessel suddenly, solidified air would block the places which should be filled with liquid helium. The water moisture

contained in air is also a great impediment*1).

In order to prevent air and water moisture condensation, highly purified helium gas at room temperature is fed into the helium vessel first, and forced-out helium gas containing air and water moisture from the helium vessel is recovered for removal. Helium gas is then fed repeatedly into the helium vessel to remove all moisture and air.

Next, helium gas is cooled by using the helium refrigeration system at the land-based support facilities with a 100-liter-per-hour liquefying and a 300-watt refrigerating capacity. The cooled gas is fed into the helium vessel of the thrusters by using the transfer tube*2). The helium gas is circulated in the helium vessel to cool its interior temperature gradually down to become 20 K (approx. -253℃) uniformly throughout the helium vessel by using the helium

*1) Boiling and melting points of substances such as helium
It is known that a material generally takes three phases of vapor, liquid and solid. The conditions for a material to shift from one phase to another — in other words, the relationship between pressure and temperature — are fixed. The temperature at which a solid changes into liquid when the pressure is one atmospheric in that relationship is called the melting point and that at which liquid changes into vapor is called the boiling point. Of course, these processes are reversible from vapor to liquid and liquid to solid, respectively. The following table is an example of the boiling and melting points.

(unit:℃)

Substance	Melting point	Boiling point
Water	0	100
Mercury	-38.86	356.72
Iron	1535	2754
Oxygen	-218.4	-182.97
Nitrogen	-209.86	-195.8
Hydrogen	-259.14	-252.8
Helium	-272.2	-268.9

As can be seen from this table, if the temperature of helium is lowered to -268.9℃, its melting temperature at one atmospheric pressure, then not only water but oxygen and nitrogen also solidifies. Therefore, if the vapor is left in the cryostat, it would solidify as hard as a rock and disturb the liquid helium flow.

*2) Transfer tube
A water hose is frequently used to transfer water from one tank to another. Cryogenic liquid such as liquid helium is also transferred by using a hose. But to perform that operation in the atmospheric environment, the hose wall must have structure that does not permit heat invasion. The hose for such use is called a transfer tube, and has an incomparably more complex structure than an ordinary hose. Each of those used to pour liquid helium into the cryostat of the Yamato-1 was a stainless hose with an overall length of 30 m and internal diameter of 32 mm at the

innermost wall, where liquid helium flowed. In addition, this 32 mm internal-diameter walled tube was housed in a stainless, triple-layer structure tube. The space between the internal tube and external tube was kept in a vacuum. Furthermore, liquid nitrogen flowed inside the triple-layered tube and its exterior side was also kept in a vacuum to minimize heat invasion as much as possible. All in all, it was structured similar to the cryostat. The only major difference was that the transfer tube had to perform like any other ordinary hoses. Therefore, all of the above-mentioned tubes comprising a transfer tube have flexible walls, and they could be bent considerably and freely as an entire tube. The ones we used were German-made and very expensive, as it can easily be understood from their complex structure. We used a total of two transfer tubes.

*3) Thermal stress
Metals expand and contract considerably, depending on the temperature. Due to this, force-exerted areas occur sometimes in a metal structure as the environmental temperature varies. Such an internally generated force is called a thermal stress. For example, let us suppose a metal ring is attached lightly around a cylindrical rod made of another metal at room temperature, and the assembly is attached to; naturally, internal force is acting on both the ring and rod in the form of the former being stretched outward by the latter and the latter being pressed in by the former. This force is called thermal stress. When the temperature environment returns to the initial state, the thermal stress vanishes. But, if the temperature is further lowered instead, the stress would increase and it could cause damage to the engagement areas of the assembly. Such a thermal stress phenomenon is one of the criteria that require the most attention when it comes to designing a structure to be used in an environment with severe temperature fluctuations.

refrigeration system.

The process up to this point is called "pre-cooling." This pre-cooling needs to be done slowly, taking time, and carefully. If this is done hurriedly in a short time and results in an uneven temperature distribution inside the helium vessel, then thermal stress*3) is created locally and could cause damage to the helium vessel or coil. In order to avoid that, about 10 days are required to cool down to 20 K.

When pre-cooling is over, the liquid helium is fed in to fill the helium vessels and the reservoirs, which are mounted on the top of the thrusters, with 4.2 K liquid helium. This operation requires about two days.

When the procedure is completed, the transfer tube is disconnected to remove it. The Yamato-1 is lowered into the water again to be moored at the pier. Now the running of the onboard helium refrigeration system begins. Since the liquid helium evaporates easily hit by invasive heat from outside the system, cooling is continued by re-liquefying helium gas evaporated with the onboard refrigerator to maintain the interior cryostat temperature at 4.2 K.

Only when these operations are completed at long last can the electric current be conducted to the coils.

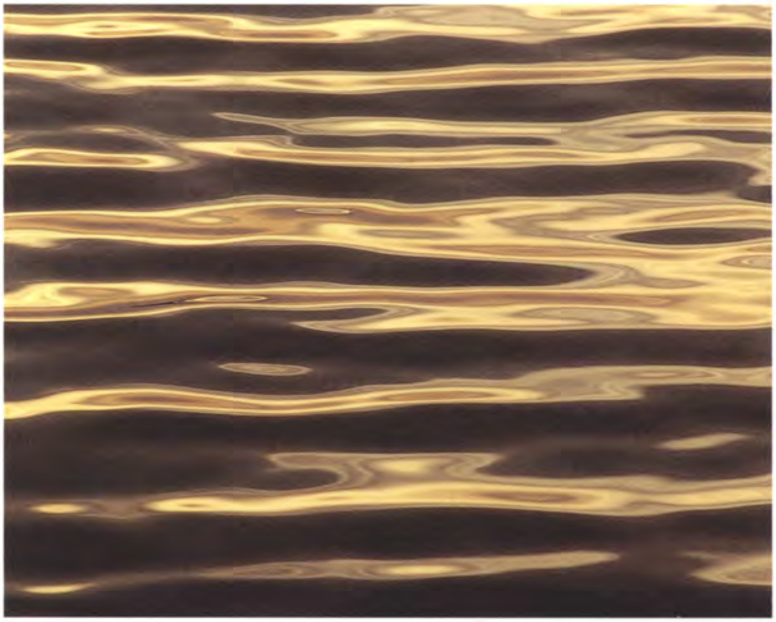
We next explain how the persistent current mode, or the state in which persistent current flows, is created by conducting the current to the coils.

Direct current is conducted to the superconducting coils to increase the current value gradually from the "EPS" (Exciting Power Supply) (Fig. 9.1). Although each of the coils experiences conduction in the excitation test in the single-coil stage and also in the stage when all the coils are assembled into the annular arrangement of the six-unit thruster structure, it is still possible that coil strands may move, resulting in a quench if a massive current is fed in abruptly. Therefore, time is taken to gradually increase the current value to the target level.

Although the superconducting coils are already in the superconducting state at this point, they are still connected to the external power supply. In other words, the persistent current switch (PCS) is open and is not turned on. While the superconducting circuit is connected with the power supply, the current flows through the six coils in a series in the cryostat before returning to the external power supply.

This is somewhat like an experiment with a battery using a miniature lamp. The current flows through a closed circuit, including the battery, when each end of the lead wire of the lamp is connected to the positive and negative poles. A closed circuit is created between the external power supply and the six coils, and the current flows through this circuit over and over. In this stage, since the PCS is not yet turned on, the current does not flow into the PCS circuit at all.

The current is increased in this stage to finally reach the targeted current value. Then the PCS switch is turned on to close the circuit. Since the PCS circuit material is the same as that of the superconducting coils, the resistance in the PCS circuit itself is also nil. The current which has been flowing through the superconducting coils is able now to flow in the PCS circuit. If the current value from the external power supply is decreased, a difference will occur between the power supply current and coil current. The difference in the two currents will flow into the PCS circuit automatically.



When the current from the power supply falls to zero, all the current as set flows in the closed circuit comprised of the coils and PCS, and the persistent current mode begins.

Once the coil system of the thruster goes into the persistent current mode, this coil system circuit does not need current from the external power supply. Therefore, the ship is able to leave the quay for a voyage without being connected to the land-based support facilities.

To cancel the persistent current mode, by the way, all it takes is reversing the operation just described. That is, connect the coil to the power supply on land to increase the current from the power supply. Although the current flowing into the coil circuit remains the same, the current flowing in the PCS then decreases by the amount of increased current from the power supply. When the value of the current from the power supply reaches that of the set value, the current flow in the PCS becomes nil.

When the PCS is turned off to create resistance, the closed circuit of the PCS vanishes, with the result that the electric current is flowing only in the coil and the power supply circuit. When the current from the power supply is lowered in this state, the current in the coils also drops. When the current from the power supply is cut off, the current in the coils is nil, canceling the magnetic field and stopping propulsion system function.

When a sea trial is over and the ship returns to the quay for moorage, exactly that procedure is carried out. These are the processes for operating the propulsion systems in principle. You can see how much time is required to prepare the Yamato-1 to cast off for a cruise.

CHAPTER 10

SEA TRIALS

At last the time came to start the sea trials. The operation schedule for the day of the trials is shown in Table 10.1. As indicated in this table fuel and oil for the onboard diesel generators of the ship moored at the quay is supplied first. Next, the transfer tubes for pouring the liquid helium into the helium vessel of the thrusters and the cables for supplying the electric current to the coils are connected. Then the liquid helium and liquid nitrogen are supplied to the MHD thrusters via the transfer tube. The liquid nitrogen is for cooling the cryostat heat shield to prevent heat invasion. Next, the current is conducted to the superconducting coils to shift them into the persistent current mode. Then the transfer tubes and cables are disconnected. After these operations, the ship is ready to leave the quay for various trials at sea.

Table 10.1 Operation procedure for the Yamato-1 sea trial

YAMATO-1
Preparation work
(1) Connecting long transfer tubes (while the experimental ship is on land)
(2) Precooling of superconducting magnets by helium refrigerating system (20 K)
(3) Pouring liquid helium into the superconducting magnets
(4) Disconnecting the long transfer tubes
(5) Launch the experimental ship and moor it
Operation on the sea trial day
(1) Filling fuel, lubrication oil, fresh water, etc.
(2) Connecting excitation cables and transfer tubes
(3) Replenish liquid helium and liquid nitrogen
(4) Excitation of superconducting magnets
(5) Disconnecting the excitation cables and transfer tubes
(6) Leaving the quay
(7) Sea trial
(8) Returning to the quay
(9) Connecting the excitation cables
(10) Demagnetizing superconducting magnets

The time required up that point was five to six hours. Therefore, workers and researchers in charge alike gather by 3 am on the quay and at the ship on the day for the sea trials to start at 9:00 a.m.

A mooring trial, bollard test, sea trials and performance evaluation tests of the Yamato-1 are carried out.

The mooring trial to run the propulsion system is conducted while a newly built ship is at the quay or in the dock. Naturally, the moored ship does not travel, only water out of the propulsion system is thrust aft powerfully. In the case of a newly built ship, it is the first official running of main engine (engine for propulsion) after the outfit. In the case of the Yamato-1, the trial was conducted to confirm if the superconducting coils and electrode power supply system are operating normally by excitation of the superconducting coils and charging up to a 2,000-ampere electric current to the electrodes while the ship is moored at the quay. After the functions of all systems and equipment pass muster in the mooring trial, the bollard test is conducted.

The bollard test measures the towing force of the Yamato-1 by pulling a Tetoron (polyester fiber) towline tied to the bollard on the quay at 1 and 2 teslas magnetic field. Naturally, this is different from the propulsive force when the ship is under way. However, it is very difficult to measure the value of propulsive force while a ship is under way, so the data obtained from this bollard tests is used to analyze the propulsion performance of the ship. A kind of spring scale called a "load cell" is inserted between the bollard and the rope to measure the towing force.

Coming next, the sea trial is conducted by actually running the ship on water. The purposes of the trial are to receive the ship inspection certificate, which is required for navigating at sea, and to understand the basic performance of the ship. Speed, steering, turning, and astern tests are conducted in the presence of inspectors from the Ministry of Transport.

The evaluation tests are also conducted while the ship is under way. The tests on speed, hull resistance and so forth are conducted by changing the test conditions for evaluation as an MHD propulsion ship.

The above tests were conducted on the water as shown in Fig. 10.1. As shown in this chart, the trial area was set in the harbor of

Kobe Port. Although testing the ship outside the harbor was considered, we decided to set the test site in the harbor because various measurements and monitoring needed to be conducted not only onboard but also from tender boats*1), as well as from land, and in the event of a problem, we would be able to respond immediately.

*1) Tender boats
The Yamato-1 was an experimental ship, and fully loaded with various measuring instruments and personnel. In addition, various observations and monitoring had to be made offboard while the ship was test-cruising. Also, many other people who had been involved in designing and building the ship alike needed to observe it, while it was underway, with their own intentions and purposes. There was also a direct necessity to secure the sea trial lanes safely for this important ship. Therefore, a few boats were arranged to accompany the Yamato-1 on the water during the sea trials. These boats were called tenders and, of course, there were many journalists aboard.

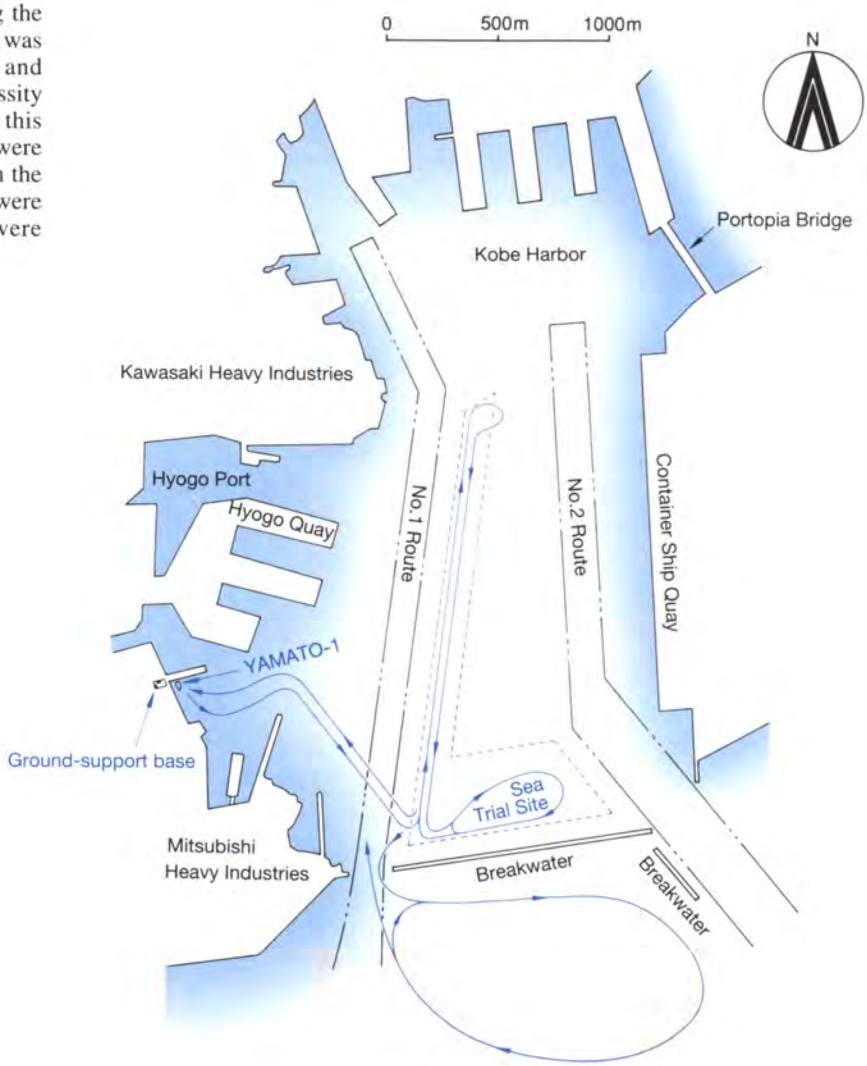


Fig.10.1 Yamato-1 sea trial site

Initially, the Research and Development Committee intended to conduct speed trials by keeping the superconducting coil-induced magnetic field magnitude, starting with 1 tesla, at an increment of 0.5 tesla at a time to reach the final target value of 4 teslas. However, regretfully, the speed test at the final 4-tesla value could not be conducted due to a PCS breakdown. (The cause of the PCS breakdown is covered later.)

The relation between the electric current and ship speed with varied electrode current at a constant magnetic field magnitude is shown in Fig. 10.2. The vertical axis indicates ship speed and the

Magnetic flux density (T)	Seawater density (kgf/m^3)	Seawater conductivity (S/m)	Marks	Date of trial
1.0	—	—	○ ——	Jun. 9, '92
1.5	1019	4. 59	△ — —	Jul. 7, '92
2.0	1019	4. 49	□ —·—	Jul. 16, '92
2.0	1022	4. 69	■ —·—	Jun. 24, '92

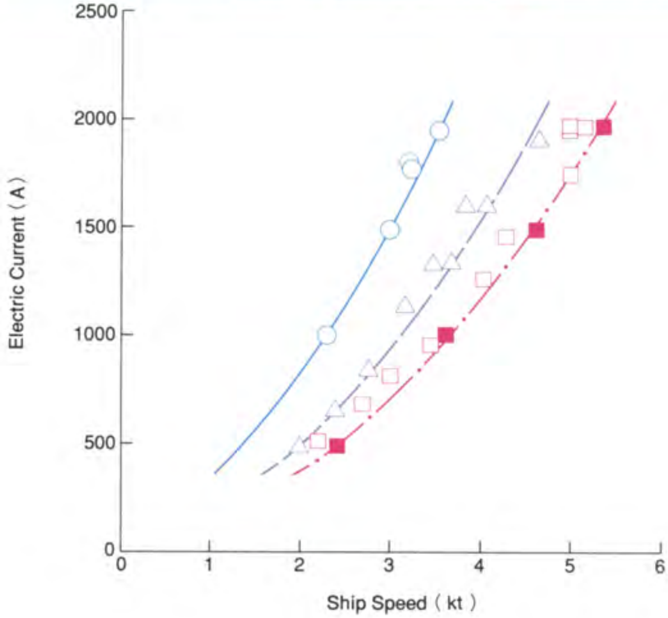


Fig. 10.2 Ship speed vs. electrode current at constant magnetic field intensity

horizontal axis indicates electrode current.

Initially, the magnetic field magnitude was set at 1 tesla to examine the relationship between the electrode current and ship speed. Then the relationships for 1.5 tesla, and 2.0 teslas were examined.

The ship speed depends on the magnitude of both the electrode current and magnetic field. But when keeping the magnetic-field magnitude constant, as shown clearly in the figure, a very smooth relationship between the current and ship was observed. This suggests that extremely smooth cruising can be achieved through control of the current.

The magnetic field magnitude induced when leaving the quay cannot be changed during navigation on the test day. If a 1-tesla magnitude magnetic field is created when leaving the quay, it cannot be increased or decreased during the cruise. But in the future, the magnetic field magnitude may be changed as desired during navigation. Theoretically, there is a method to connect the coil circuit to the electrode-current circuit in a series in order to feed the magnetic field-inducing current to the electrodes. If this is realized, it seems that different characteristics of the relationship among current, magnetic field and ship speed may be clarified.

Moreover, if this method is possible, the PCS will not be needed any longer, and that will eliminate PCS malfunction, which did occur during the sea trials. In that sense, this conjectural method is very rational. But if we need to resort to it, many other problems will arise. Even simply thinking about how to remove invasive heat into the cryostat by conduction through lead wire becomes a major issue. Therefore, for the time being, we have no alternative but to run the ship with the magnetic field magnitude induced when it leaves the quay.

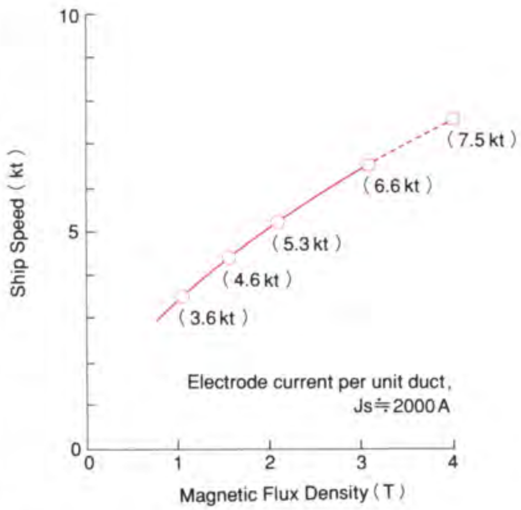


Fig. 10.3 Ship speed vs. magnetic field magnitude at 2,000 ampere electrode current

Fig.10.3shows the relationship of magnetic field magnitude and maximum ship speed when the maximum inter-electrode current capacity of 2,000 amperes is reached. In brief, this means that when 2,000 amperes in electric current is conducted to the electrodes at the magnetic field magnitude of 1 tesla, the ship speed is 3.6 knots, and similarly at 1.5 teslas it is 4.6 knots.

Up to 3-tesla magnetic field magnitude is shown with a solid line, but the line between 3 and 4 teslas is dotted in this figure. This is because we were not able to conduct the trial at 4 teslas, due to the PCS breakdown, so we extrapolated and drew it based on several measured values up to 3 teslas. This means that, judging from various conditions, 7.5 knots could have been achieved if a trial at 4 teslas had been conducted.

We set the speed target for the Yamato-1 to achieve 8 knots at a 4-tesla magnetic field magnitude. But this extrapolated value came short of our expectation by 0.5 knots. This is interpreted as the actual resistance of the ship exceeding that of our estimation, which was based on such data as the model tests.

This is unavoidable to a certain extent. Although tests using a scale model were conducted with geometrical and dynamic similitude taken into account, it is very difficult to establish a

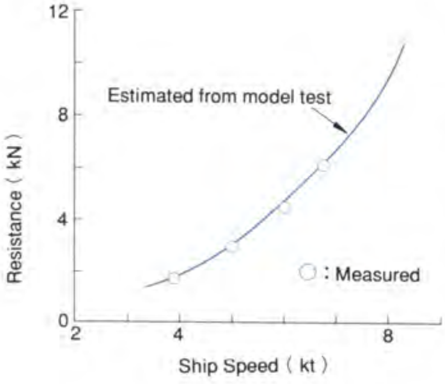


Fig. 10.4 Results of hull resistance measurements

A comparison of the hull resistance values of the Yamato-1 towed by a tugboat for measurement using a load cell vs. the values measured in tank tests using a model. Both conform very well.

perfect similitude.

An easy-to-understand example of this is dressing a 1/5-scale doll of a man with a jacket. In this case, although the jacket can be made to fit exactly the 1/5 scale of the man, the seams of the jacket cannot be reproduced as 1/5 of the original. Therefore, strictly speaking, the 1/5-scale jacket is not in perfect similitude geometrically.

The same can be said of dynamic similitude.

In other words, even though the model test has been conducted, it does not reveal everything about resistance, ship speed and so forth that needs to be solved for operating an actual ship.

A comparison between the measured resistance value of the Yamato-1 towed by a tugboat and the result of the tank test using the model ship is shown in Fig. 10.4. They match very well. This is because the model test was conducted with the same Froude Number, which is the decisive factor in a wave-making resistance. Therefore, an excellent estimate of hull resistance was obtained as a result of the tank test.

However, the Yamato-1 sucks a large volume of water into the thrusters and accelerates the water electromagnetically to discharge it through the nozzles. The flow resistance in this process is also a load on the thrusters. The hydrodynamic mechanism of this resistance induction is different from that of the hull, and is primarily governed by a factor called the "Reynolds Number*2)." It was practically impossible to match the Reynolds Number to the duct model for this resistance evaluation and that of the actual duct of the ship. It was also impossible to make a perfect geometrical similitude. Therefore, it is believed that flow resistance was heavily underestimated. As a result, a slight difference was created between the design speed and the actual ship speed.

At any rate, the relationship between the magnetic field magnitude and ship speed was extremely smooth when the inter-electrode current was constant, and it was found that the ship speed increased smoothly in proportion to the magnitude of the magnetic field. This verified that a superconducting MHD propulsion ship has very easy to-control performance.

A very regrettable event for us was the PCS breakdown, which did not permit us to complete the experiment at 4 teslas. Although the PCS function was explained earlier, we will go into more detail.

*2) Reynolds Number
Equipment such as pumps which transfer fluid, and objects such as aircraft and ships that travel through fluids create friction. In other words, resistance force caused by fluid friction is created between the fluid and the channel surface of the equipment, and between the object surfaces and fluids. This fluid friction is caused by the fluid's viscosity.
The factor that governs the law of similitude in the fluid-friction-related phenomenon is called the Reynolds Number, after Osborne Reynolds (1723-1792), the British scientist who discovered it. Along with Froude and Mach Numbers, it is one of the very important factors in fluid-related phenomena.

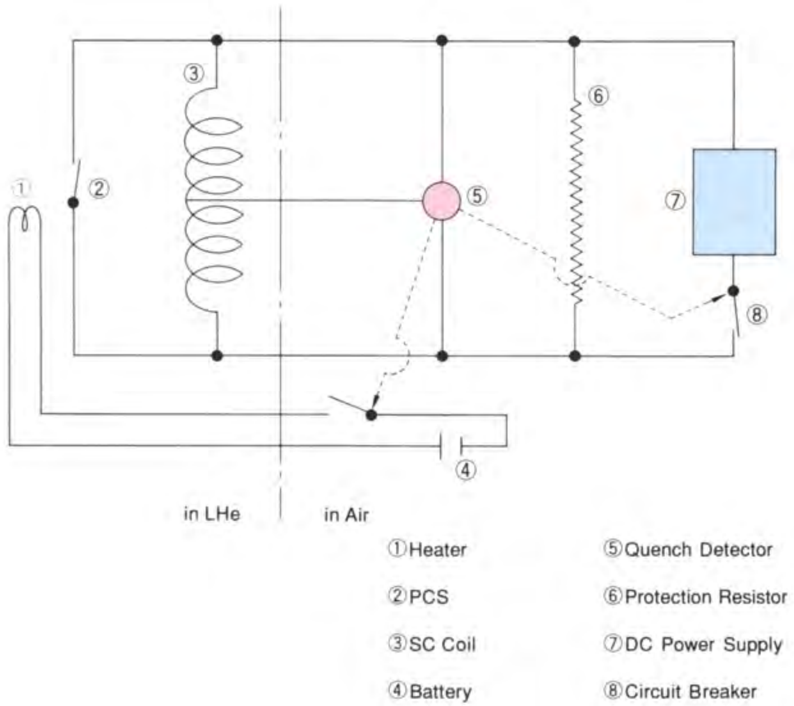


Fig. 10.5 Superconducting coil circuit
Since the persistent current switch (PCS) is made of superconducting wire, turning the heater on changes the switch to open mode, which is the normal conductive state with resistance. When the heater is turned off, the PCS goes into a superconductive state to produce the switch closed mode. That is, the PCS is turned on and off by turning the heater off and on.

To turn the persistent current circuit on and off, the PCS used was not devised to turn on and off manually like an ordinary switch. It consists of the superconducting wire and the heater wire. The PCS is devised to be turned on and off by means of heating the heater wire.

The relationship between the PCS and heater is shown in Fig. 10. 5. When current is conducted to the heater, the PCS heats up. Since the PCS is made of the superconducting material, the PCS is never in the superconducting state when it is heated. In that case PCS is open, in other words, the PCS is turned off. In this state, the superconducting circuit is shut off.

To turn on the PCS the next move is to turn off the heater. Doing so lowers the PCS temperature to -269℃, which is the same as the liquid helium temperature. When the PCS temperature reaches -269℃, the PCS is turned on the superconducting state to turn the section consisting of the PCS and coils into a superconducting circuit.

In short, switching on and off the PCS, which shifts from the normal conducting state to the superconducting state, is done by warming and cooling the heater. In a sense, this is a very unreliable method. However, there is no other method available. It is very difficult to develop even a normal conducting switch to bear a massive electric current at thousands of amperes. The method we tried was probably the first attempt of its kind to develop a large-capacity switch to be used in a superconducting circuit.

It is a fact that this method functioned well, at least up to 3-tesla magnetic field magnitude, so we think we have proved out this method in principle.

When the superconducting coil quenched in 3-tesla persistent current mode, the PCS failed. Why did it fail? It is likely that there were some inadequacies, structural or otherwise, even though it was correct theoretically. The Research and Development Committee has been conducting research to pinpoint the cause since the PCS broke down at the 3-tesla test. But we still have not pinpointed the cause clearly.

The PCS is functionally a very outstanding mechanism, since it is superconductive. In spite of being the switch for a massive electric current of thousands of amperes, it is enclosed in a compact cylinder with only a 300 mm diameter and 365-mm height. If it were a case of normal conductivity, the size of the switch capable of withstanding thousands of amperes would be on the order of 1 meter. That indicates how functionally superb the PCS switch is.

Unless a PCS with sufficient capability to withstand practical usage is not developed, full-scale development of a superconducting MHD propulsion ship will be delayed. PCS research and development therefore is a very important factor. The Research and Development Committee has continued PCS research activity since fiscal 1995*3).

*3) The Ship & Ocean Foundation has continued superconducting MHD propulsion system-related research and development since the completion of the Yamato-1 project. In 1996, its research group succeeded in the development and production of a rated 3,000-ampere PCS using Nb_3Sn. This result is scheduled to be announced at an appropriate international conference in the near future. Furthermore, this group is currently working on the development of a PCS capable of turning on and off a current on the order of 10,000 amperes flowing in the superconducting coil, which induces an over 10-tesla magnetic field.

CHAPTER 11

CONCLUSION

Achievements and Problems

The Research and Development Committee has been working on development of a superconducting MHD propulsion ship since 1985. The mission of the experimental ship Yamato-1 was to prove that, equipped with the necessary systems and equipment onboard, it was capable of traveling at sea by means of electromagnetic force. In June 1992, the ship succeeded in the world's first sea trials to achieve that initial objective. In that sense, this project has been a success.

In the process of development, we found the essential conditions required and solutions to problems such as the superconducting coils and helium refrigerating system comprising the superconducting MHD propulsion system. We were able to

achieve various successful results in several aspects of related theoretical research.

The successful results obtained from the process of research and development of the Yamato-1 are summarized as follows:

(1) When it was confirmed that the Yamato-1 satisfied all the specified performance requirements through various tests of the onboard equipment and sea trials, certificate of ship's nationality and ship inspection certificate were issued by the Ministry of Transport. (The certificates are shown in Photo 2.4 Chapter 2).

The Yamato-1 is now officially recognized as the world's first seagoing superconducting MHD propulsion ship. This project also proved that the superconducting MHD thrusters can be used as a ship's propulsion system.

(2) We were able to establish an operational procedure unique to

a superconducting MHD propulsion ship, quite different from that of a conventional propeller-driven ship. This procedure included cooling, excitation and demagnetization of superconducting coils and operation of a helium refrigeration system.

In addition to understanding actual operations, such as cruise preparation work, ship-handling procedure and cooling operation after the trials, the problems to be resolved in the future were also found.

(3) The most important result was gaining the manufacturing technology for a lightweight but large-size superconducting magnet with a stable and strong magnetic field of 4 teslas with 23 megajoules (MJ)*1).

Although we have set the target value of the magnetic field magnitude of the Yamato-1 at 4 teslas, it was not an easy task to generate a 4 tesla magnetic field magnitude with sufficient spatial expansion for a sufficient period at the time during the research and development phase. This remains true even today. The method adopted to achieve that difficult task was to assemble six coils in a concentric arrangement by holding each saddle-shaped coil in place with hexagonal collars. Using this method, we succeeded in

*1) Megajoule (MJ)
The SI unit of work, or energy, is the joule.
1 joule (J) = 1 newton-meter (Nm)
The megajoule (MJ) is a 1,000 kilojoule (KJ), or 1 million joules. The scale of a magnet, in other words how large a magnetic field magnitude it has, is expressed in the amount of energy spent to induce this magnetic field. Therefore, the energy unit MJ is used. Naturally, KJ or J is sufficient to express the scale of a magnet if it is small.

increasing the magnetic field magnitude of the thruster while minimizing the magnetic field leaks to the outside.

(4) It was possible to ascertain the characteristics of the internal magnetic field type superconducting MHD thruster. When the magnetic field and current act uniformly and mutually intersect at right angle, the Lorentz force induced is almost identical to that theoretically predicted.

(5) It was also confirmed that the magnitude and direction of propulsive force can be easily controlled by changing the magnitude and direction of the electrode current.

(6) As for the PCS for shifting persistent current mode, we plan to find out the cause of the breakdown and to conduct research to improve the PCS performance.These are important issues for the future.

The results achieved from research and development of the Yamato-1 are considered to make a great contribution not only to engineering progress in the field of a future superconducting MHD propulsion system but also in the fields of superconducting coil applications such as for the magnetic levitation train.

Issues for the Future

It will be most crucial to determine whether it will be commercially feasible to operate ships with such a propulsion system in the future. According to the results reached by our group, it seems that ships with such propulsion systems would be justified for commercial operation, if we could raise the magnetic field magnitude of the MHD thruster to 20 to 30 teslas*2).

Currently, the 4-tesla magnetic field magnitude we achieved as the magnetic field for the ship's thruster with the spatial expansion and time span continuity seems to be the highest magnitude of that kind in the world, with the exception of the momentarily achieved high-magnitude magnetic fields in the community of experimental physics. It is hoped that a large and strong superconducting coil will be developed. A program of development of such aspects as a superconducting coil material capable of withstanding a high-magnitude magnetic field would be necessary. The pace of progress is rapid today. We believe that this important development will likely be realized in the not too far future.

Although we used the superconducting coils to create such a

*2) This is discussed in "The Superconducting magnetohydrodynamic propulsion system of Yamato 1: Design, Sructure and Performance" (see Chapter 4).

magnetic field, it may be possible eventually to use a magnetic field in the form of a permanent magnet if science and technology make progress in this area. Then the hoop stress problem we had to deal with painstakingly in the case of the Yamato-1 would be solved a more easiely.

A superconducting MHD propulsion ship has no propeller and shafts to cause noise or vibration. The ship speed including forward and astern movement, can be controlled smoothly by varying the magnitude or direction of the electrode current. When the propeller turns at high speed in the case of the screw-propeller drive, cavitation occurs to lower propulsive efficiency. But since the cavitation problem is sparse in the case of the MHD propulsion system, it has characteristics more suited to high speed ships. These characteristics were verified through the Yamato-1 sea trials.

Therefore, demand for superconducting MHD ships would seem to be certainly on the increase in the future.

The Research and Development Committee hopes that the achievements of the Yamato-1's research and development will make a great contribution to speed up construction of superconducting MHD propulsion ships for practical use.

At the same time, several problems associated with production, performance and function of the superconducting magnets that were clarified in the process of developing the Yamato-1 are very important in using superconductivity. Therefore, the countermeasures we developed and the data we clarified are extremely useful to superconducting engineering. We expect that these will be utilized to the fullest to help yield outstanding results in superconducting engineering. Also, the Research and Development Committee of the Ship & Ocean Foundation is continuing several research themes that arose during the development of the Yamato-1, such as the stability of a PCS and related research. (Part of those results are described in the last section of Chapter 10.)

APPENDIX

MEMBERS LIST OF RESEARCH AND DEVELOPMENT COMMITTEES ON SUPERCONDUCTING MHD PROPULSION SHIP

Chairman of Steering Committee
Yohei Sasakawa (President,The Nippon Foundation)
Chairman of the MHD Ship Design Subcommittee
Seizo Motora (Professor Emeritus,University of Tokyo)
Chairmanof the MHD Thruster Subcommittee
Kensaku Imaichi (Professor Emeritus,Osaka University)

[Members of Steering Committee]

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Kensaku Imaichi (Osaka University)
Shigeo Onishi (Ministry of Transport)
Mitsutoyo Okada (Ministry of Transport)
Eifu Kataoka (Ministry of Transport)
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Hiraku Tanaka (Ship Research Institute)
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Noboru Hamada (Japanes Marine Equipment Association)
Jiro Hoshino (Nippon Kaiji Kyokai)
Seizo Motora (University of Tokyo)
Atsuo Yazaki (Ship&Ocean Foundation)

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Tomomasa Uemura (Osaka University)
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Masayoshi Wake (National Laboratory for High Energy Physics)

History of Superconducting MHD Propulsion Ship Yamato-1 Development

1985	1986	1987	1988
● Configuration of EMT ship investigation ● Design of hull form; model tests [Monohull, single thruster; W = 95 tons]	● Research on propulsive efficiency of an EMT ship ● Design of hull form; model tests [Monohull, single thruster; Monohull, 2 thrusters; W = 150 tons]	● Conceptual design of the experimental ship ● Design of hull form; model test (catamaran type) ● Design of seawater duct system (6-branching and 6-joining) ;model test	● Basic and detail designs of the experimental ship ● Design of hull form; model test (Modified mono-hull) ● Design of seawater duct system (intake and nozzle); model test
● Investigating superconducting magnet and cryogenic technology	● Basic design of superconducting magnet ● Basic design of helium refrigeration system ● Design of power supply system	● Detail design of superconducting magnet · Production of unit coil prototype ● Detail design of refrigeration system · Production of prototype expansion turbine ● Overall design of power supply system	● Production of coils and cryostats ● Production of refrigeration system ● Production of power supply system ● Design and production of electrodes
			● Investigating designated sea trial area
			● Design of land-based support facilities
● Production of circulating water channel	● Construction of MHD research laboratory ● Installation of circulating water channel	● Construction of test tank	
	● Production of superconducting MHD thrusters ● EMT performance test	● EMT performance test	● Self-propulsion test of the MHD model ship
	● Electrode test	● Electrode test ● Research of magnetic shield	● Endurance test for electrodes ● Research of magnetic shield

EMT:Electromagnetic thruster W:Displacement of ship

1989	1990	1991	1992
● Detail design, construction and outfit of the experimental ship	● Completion of the experimental ship hull ● Christening ceremony	● Loading and outfit of superconducting MHD thrusters ● Adjustment of inboard equipment and apparatuses	● Sea trials and evaluation tests of the YAMATO-1
● Assembly and adjustment of superconducting magnet ● Assembly and adjustment of refrigeration system ● Assembly and adjustment of power supply system ● Production of electrodes	● Assembly of superconducting magnets and performance tests ● Assembly of electrodes into the superconducting magnets		
● Investigation of evaluation test method ● Preparation of measuring instruments			
● Construction of support base (at Mitsubishi Kobe shipyard)	● Adjustment of support facilities on land		
● EMT performance test			
		● Hosting international symposium (MHDS91)	

INDEX

YAMATO-1

The World's First Superconducting Magnetohydrodynamic Propulsion Ship

First Printing, March,1997

Supervised by Yohei Sasakawa
Book design by Kan Suganuma

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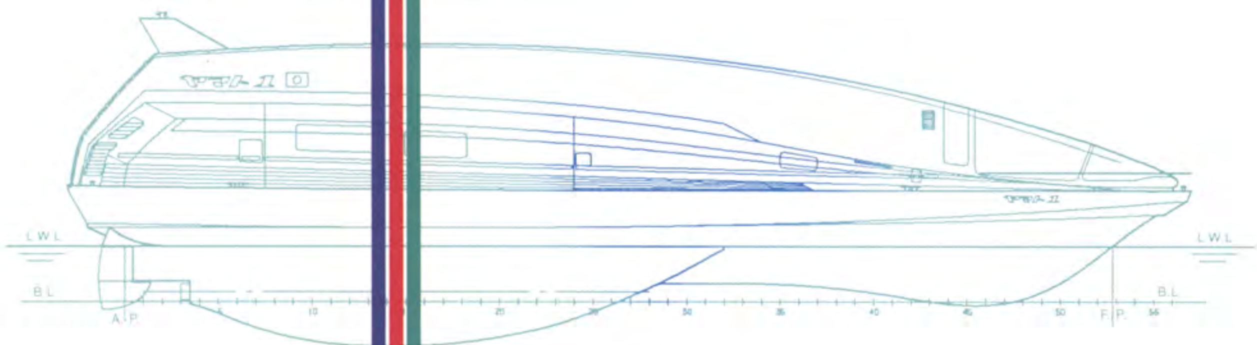
YAMATO-1

World's First Superconducting Magnetohydrodynamic Propulsion Ship



"YAMATO-1" SIDE VIEW