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DIESEL-ELECTRIC PROPULSION EQUIPMENT FOR THE ICEBREAKER "FUJI", FOR THE ANTARCTIC RESEARCH EXPEDITION

By Keizo Suzuki
Kawasaki Factory

Kazuo Nakamura
and
Kensaku Ihara
Technical Dept.

I. FORWORD

Japan's antarctic research expedition activities which were suspended for a period of time were reopened. "Fuji" was built at the Tsurumi Shipyard of the Nippon Kokan Co., Ltd. and was constructed following the basic design prepared by the Defense Agency which has been responsible for transportation since the fiscal year in which the antarctic research expedition activities were reactivated. "Fuji" was launched on March 18th, 1965, and was completed in July of the same year. "Fuji" is the world's highest class modern icebreaker and is at the same time a first class observation ship.

"Fuji" successfully berthed at Showa Base, and in early April, 1966 returned to Tokyo after her maiden voyage.

Japan's antarctic research expedition activities had been interrupted due to superannuation of the research expedition ship "Soya". However, a strong basis for permanent research expedition activities has been established by the powerful driving force of the new icebreaker "Fuji".

The source of Fuji's powerful icebreaking power is the totally mechanized shaft output, 12,000 ps diesel-electric dc propulsion equipment. This equipment was carefully developed from the basic design, and was manufactured and delivered by Fuji Electric Co., Ltd.

The outline of Fuji's electric propulsion equipment and records of her maiden voyage are briefly summarized in the following description.

II. BRIEF DESCRIPTION OF "FUJI" AND THE ELECTRIC PROPULSION EQUIPMENT

1. Description of "FUJI"

"FUJI" is a special purpose ship. The principal functions of which are: ice breaking, transportation, and observation on board. *Fig. 1* shows the general layout.

Fuji's principal specifications are as follows:

Overall length:	100.00 meters
Length, b.p.:	90.00 meters
Max. breadth, moulded:	22.00 meters
Moulded breadth on water line:	21.50 meters
Depth to No. 1 deck:	11.80 meters
Draught to design water line:	8.12 meters
Normal displacement:	7760.00 tons

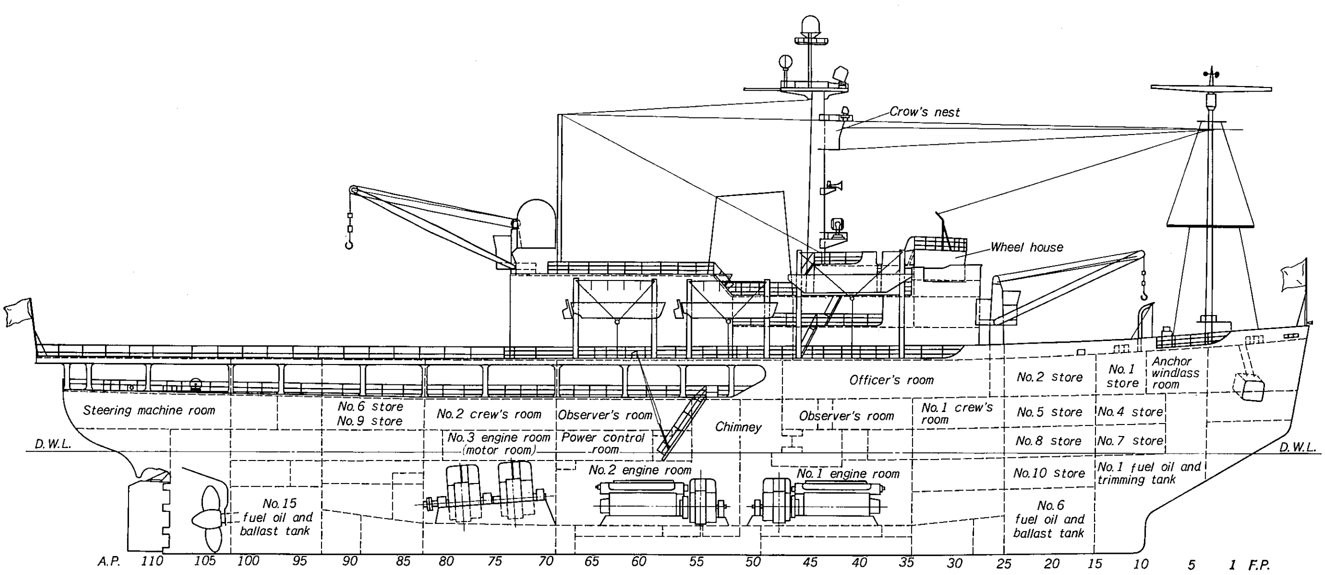

Fig. 1 General arrangement plans

Max. ship speed: 16.50 kn
Machinery horse-power: 2×6000 (metric)
Cruising range at 15 kn: Approx. 20,300 s.m.
Complement:
Number of crew members: 200
Considered number of observers: 40

2. Basic Factors in Design of Propulsion Equipment

Fuji is equipped with two propellers for increased maneuverability on the frozen sea.

The speed-torque curves are shown in *Fig. 2.* Curve *A* shows free running characteristics in which torque is nearly proportional to the square of propeller speed. Curve *B* shows standing pull characteristics which like curve *A* are also proportional to the square of propeller speed. However, the torque compared to the same propeller speed is higher than that of curve *A* since the thrust reduction coefficient of the propeller is minimized. The propeller torque curve moves between curves *A* and *B* depending upon condition from time to time as ship resistance increases while the ship moves through the frozen sea. When the ship is breaking thick ice with a ship speed of almost zero, the load curve of the propeller more nearly corresponds to curve *B*. The torque of the propeller under these conditions should be high to increase icebreaking power. Therefore, utilization of the entire output of the propulsion engine is extremely important in both free running and icebreaking operations. Thus, for an icebreaker, automatic constant output control is ordinarily applied within the range between free running characteristics and standing pull characteristics. This method of controlling constant output within a range between free running and standing pull characteristics is also effective as a load limiting device to prevent the engine from becoming overloaded. When the propeller bites into a large block of ice or when it sinks into a highly viscous muddy slush, it must display as high a torque as possible within such a limit that no unreasonable amount of force is applied to the propeller blades and shaft. This is vital for icebreaker escaping from danger. Therefore, the propulsion system must be designed so that a stalling torque exceeding 200% of the rated free running torque can be displayed for a short period of time. For the reasons outlined above the propulsion equipment for " Fuji " was designed with characteristics shown by curve *C* in *Fig.* 2.

Required propeller power is nearly proportional to the cube of propeller speed, and using a fixed pitch propeller the ship speed is approximately proportional to propeller speed. In other words, in designing a ship having a ship speed of 16.5 kn at a maximum continuous rated output, approximately 50% of the rated output will be sufficient to propel the ship at an average cruising speed of 13 kn. To satisfy this requirement, the maximum number of generators is usually provided, with only the minimum number of

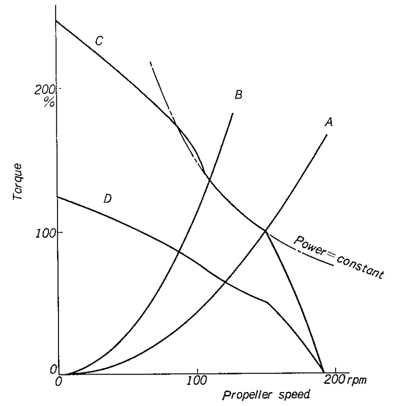

Fig. 2 Torque curves for propeller and propulsion motors

generators required for a partial load operated when cruising with the rest of engines shut down.

Under this system, the equipment can be more efficiently and economically utilized. Moreover, this system has the added advantage of making stand-by set available in case of failure of some sets of them.

However, on the other hand, the number of generators is limited by equipment costs, space limitations, control systems, and other such reasons. Overall consideration was given to these requirments, and it was finally decided that four diesel generator sets would be used to propel " Fuji ". The characteristics when two diesel generator sets are used for propulsion are shown by curve *D* in *Fig. 2.*

" Fuji " operations in which all four engines are employed is referred to as a "Four engine operation", and operations in which two engines (one per propeller) are employed is referred to as a " Two engine operation ". " Two engine operation " is used primarily for normal cruising.

Any icebreaker can continue to move forward while breaking ice up to a certain thickness. However, when the ice is too thick the ship can no longer push forward in continuous icebreaking operation. Under these conditions a so-called " Charging icebreaking " is used in which the ship repeatedly rams against ice belt and then withdraws within an approach distance of one or two ship lengths. Under this mode of operation, the thrust force and inertia resulting from the forward movement of the ship within the short approach distance after having withdrawn contributes significantly to icebreaking ability. Therefore, propulsion equipment must have a high acceleration torque when starting, and the system must be changed quickly and frequently between forward/reverse operations. For this reason dc electric propulsion equipment is used on icebreakers.

Usually, electric propulsion equipment with the most appropriate composition and characteristics should be selected after studying the overall ship conditions under which the electric propulsion equipment is to be used. In the case of " Fuji ", her specific peculiarity had to be fully considered since she was to perform multiple functions as previously described. With respect to these factors, the planning, design, and manufacture of this equipment were guided by four conditions: (1) superior maneuverability when icebreaking, (2) simplified but sturdy construction and ease of operation and maintenance, (3) compact and light weight, and (4) highly economical.

A more comprehensive explanation of these conditions is as follows:

a) Maneuverability for quick and frequent change between forward / reverse operation and speed control down to an extremely low speed were simplified by using a Ward-Leonard control system, so designed that high torque could be generated at low speed.
b) The equipment was so constructed as to withstand an impact of 3 g.
c) The propulsion generator was built as a three-fields generator in order to simplify the control circuit.
d) The two sets of propulsion equipment were arranged so that each set of equipment could be operated independently.
e) Greater operating efficiency was economically accomplished using a completely new main circuit connection and a main circuit changeover system.
f) Automatic constant-power control of the propulsion motor was provided at a range between free-running characteristics and standing pull characteristics.
g) The controls were arranged so that the equipment could be operated from five different locations within the ship.
h) The effects of propeller backpower were carefully studied from the effects of various maneuvers.
i) Various interlocking devices and alarm indicators were provided throughout the system in order to prevent faulty operation.

3. Specifications of Major Components

1) Propulsion generator
   Number of generators: 4
   Rated output: 2420 kw
   Rated voltage: 850 v
   Rated current: 2850 amp
   Rated speed: 600 rpm
   Rating: Continuous
   Exciting system: Three fields exciting system through separate field, shunt field, and differential series field windings
   Type: Self-ventilated closed air-circulation system with water/air cooler
   Class of insulation: Class B
2) Propulsion motor
   Number of motors: 4 (Two motors connected in tandem for each propeller)
   Rated output: 2250 kw
   Rated voltage: 850 v
   Rated current: 2850 amp
   Rated speed: 110 rpm (strong field)/ 150 rpm (weak field)
   Rating: Continuous
   Exciting system: Separate excitation
   Type: Forced ventilated closed air-circulation system with water/air cooler
   Class of insulation: Class B
3) Exciting M-G set
   Number of sets: 4 sets (2 of the 4 sets are for stand-by)
   Construction:
   Propulsion generators exciter: 16 kw 1765 rpm
   Propulsion motors exciter: 40 kw 1765 rpm
   Constant voltage exciter: 10 kw 1765 rpm
   Driving 3-phase induction motor: 75 kw 1765 rpm
4) Propulsson generator diesel drive engine (Manufactured by Mitsubishi Heavy Industry Co., Ltd., Yokohama Shipyard)
   Number of diesel engines: 4
   Maximum continuous rating: 3500 ps
   Rated speed: 600 rpm
   Type: Vee type, single-action, 4-cycle, trunk piston, solid injection, supercharged diesel engine with air cooler.
   Nomenclature: YOKOHAMA MAN V 8 V 30/42 AL
5) Control devices
   Construction:
   Main switchboard: 2 sets
   Main control desk: 1 set
   Wheel house maneuvering stand: 1 set
   Port side deck maneuvering console: 1 set
   Starboard side deck maneuvering console: 1 set
   Crow's nest maneuvering console: 1 set

III. DESIGN FEATURES OF MAJOR COMPONENTS

1. Propulsion Motor

Motor room layout differs greatly from factory layout on the ground. Not only are there limitations with respect to dimensions but also the propulsion motor must be designed so as to minimize the fly-wheel effect for suitability to frequent forward/reverse operation. Two 2250 kw 110/150 rpm motors are installed in tandem for each propeller. This construction was selected as the most effective after overall study of dimensions, fly-wheel effect, effects from distortion of hull of the ship, number of diesel engines, and other related factors. As a result, the length of iron core for the axial direction has been extended, and the flywheel effect has been reduced to half of that of an average 4500 kw motor. Each part of the motor was carefully designed since greater shock and vibration are applied and the motor is placed under more severe operating conditions than ordinary motors. *Figs. 3* and *4* respectively show the external view and internal construction of the propulsion motors.

The armature is constructed so as to withstand shock and vibration through firm installation of the spider and the core made from half-lapped sectors and connected by a dove-tail joint and with the press ring and spider welded after the core has been firmly secured. The armature winding is insulated by Fuji Electric's special mica foil sleeve method. The neck of the coil end is held in the comb shaped coil support, and the coil is thus firmly installed. The equipment is designed so that the motors will withstand 180% current imposed by propulsion generator characteristics at least one full minute after the propellers are held from rotating by externally applied force. Hard brazing was used on the armature instead of soldering. Thus, the problem concerning rotor coil connections which is one of the weak points in rotating machines was completely solved.

When the propellers stop rotating, current flows only to the commutator segment which contacts the brush on the commutator, and local overheating occurs. However, considering temperature rises based on thermal capacity and expansion, the amount of distortion resulting from thermal expansion was limited to 75μ or less. Thus, local overheating was kept within a reasonable limit. The brush was designed as a constant-pressure tandem type so as to provide proper contact and commutation.

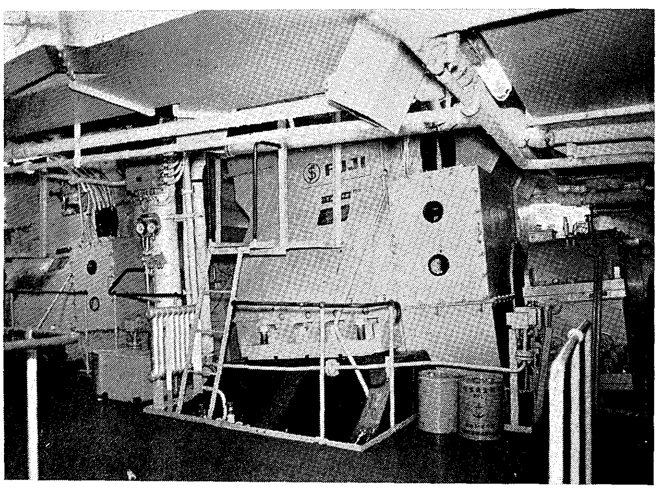

Fig. 3 Propulsion motors

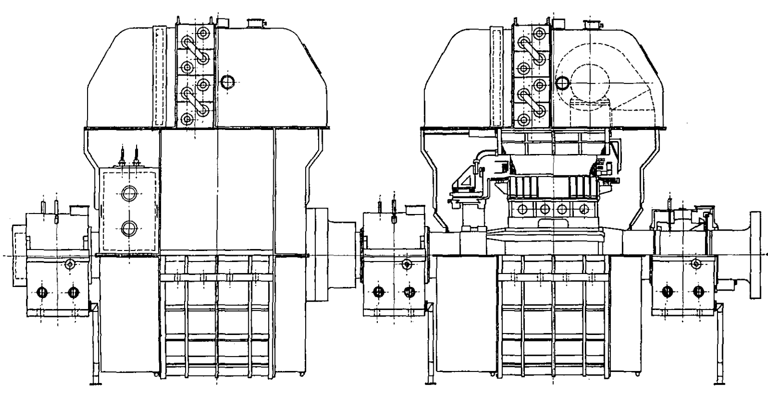

Fig. 4 Construction of propulsion motors

The armature shaft and coupling flange are both made of carbon steel, and made into a unitized forged body. The dimensions are such as to provide sufficient margin with respect to the operation of " Fuji " as an icebreaker. A final study was required on the shaft system consisting of the propeller, propeller shaft, extension shaft, and the propulsion motor shaft. It was necessary to give special consideration to the resonant frequency of the system's torsional vibration. The resonant frequency of torsional vibration should always be higher than the frequency value obtained by multiplying the number of propeller vanes by the propeller speed. Careful studies were made on "Fuji", and as a result the frequency was regulated by adjusting the size of the extension shafts.

It was assumed that the load fluctuation would be extreme running about 1000%/sec. Since permissible load fluctuation is approximately 30%/sec for solid cores, the magnetic circuit was constructed entirely of thin laminated steel sheets. The yoke was constructed in two parts (upper and lower) for shipboard installation. This was reinforced by three thick steel sheets held within thin steel sheets, secured by bolts and welded in the rear so as to provide a sturdy construction.

The lower half of the yoke, together with the covers, are of water-tight construction. Thus, infiltration of bilge water under the motors due to rolling and pitching has been prevented. The center height of the motor is extremely low as shown in *Fig. 4*. Consequently, the center of gravity has been placed in a relatively low position to protect the motors from shocks incurred during icebreaking operations. The propulsion motors which are not installed on their own bases are installed directly on the beams of the ship.

The cooling effect of the main pole coil was increased by dividing each pole coil into three blocks. The interpole coil is a bare copper bar, flatwise coil. Construction is vibration-proof and is tightened in several places on the side of the interpole core with bolts through insulation. The compensating winding is provided with a mica foil sleeve, elliptical copper bar in its slot, and the connectors on both ends are the rectangular copper bars and are firmly secured on the yoke after the connectors are tightened evenly through spacers.

Considering that the propellers are operated continuously for long periods of time at low speed so as to prevent freezing and to maintain position of the ship in the forzen sea, a high pressure forced oil shaft floating system was employed for the bearing so as to provide a constant lubricating oil film. In this system, pressurized oil (30 kg/sq cm) is force fed to the sliding surface by a special oil pump from the lower part of bearing. In addition, an oil disk is used to feed oil from the oil tank in the bearing support so that the motors will continue to operate for a short period of time in the event a breakdown occurs in the lubricating system.

The cooling system is a closed air-circulating type with a water-cooled air cooler. The air filter, the water-cooled air cooler, and the motor fan are mounted on the top of the yoke. Cooling air is fed to the motors from the end opposite the commutator by the fan and, after cooling the motors, is discharged from the commutator end and led upward through a duct, into the air cooler after carbon dust from brushes and other foreign matter is filtered out. Four air cooler units having a capacity of 50 kw are combined as a set, and Alblack is used for the cooling tube so as to resist corrosion from sea water. A double tube construction has been employed to prevent sea water from getting into the motor even if the cooling tube is broken, and the system is designed so that any water leakage is readily detected.

When the relationship between temperature and humidity within the motor and cooling water temperature exceeds a prescribed limit, condensed water produced on the inside of the cooler could enter the motor. To prevent this, the volume of cooling water must be adjusted. This is monitored by using a thermometer and a psychrometer in the motor, and by checking conditions by visual inspection. For this, an illumination lamp and an inspection window are provided on the upper cover.

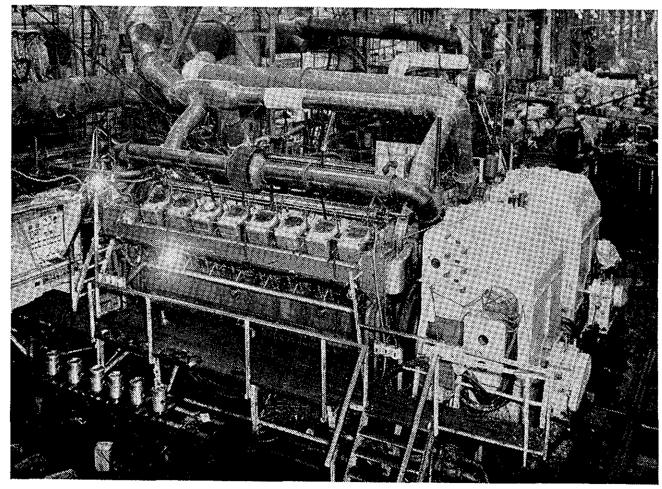

Fig. 5 Propulsion generators

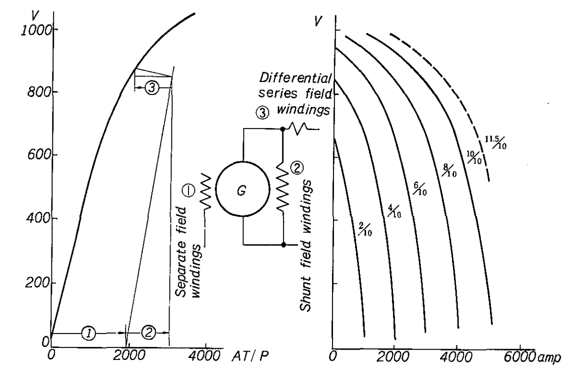

Fig. 6 Characteristics of propulsion generator

2. Propulsion Generator

The diesel engine driven propulsion generator had to have an extremely high capacity and high speed as a dc generator (2420 kw 600 rpm), and yet be compact and light, so as to meet requirements with respect to space limitations aboard ship. Under these special requirements, the equipment had to be carefully and especially designed. *Fig. 5* shows the external view of the propulsion generators directly connected to the diesel engines.

The most significant feature of the propulsion generator is its three-fields arrangement which automatically controls the operation of the generator itself within the load limit of the diesel engine. The three fields consist of separate field, differential series field, and shunt field windings, as shown in *Fig. 6*, giving drooping characteristics. The system is designed so that voltage corresponding to rated voltage of 850 v is approximately 1000 v when no load is applied and the current is 180% of rated current at the time of motor stalling. In addition, the system has been designed so that the operation of the generator is limited to within 115% of the permissible overload of the diesel engine at any point on the load characteristics curve. This type of characteristic is obtained by applying three fields to the generator exciter or by using an amplifier. However, use of three fields in the generator provides an extremely reliable and simple control circuit. The construction of each unit is almost identical to that of the propulsion motor. However, the generators are installed in a common base with the applicable diesel engines. The shaft has a single support so as to provide shorter shaft length in an axial direction. The bearing is an ordinary forced-lubrication type and is used together with an oil ring.

The cooling system is a closed air-circulation type with a water-cooled air cooler. A self-ventilated fan, installed in the commutator end, blows air to the filter and the water-cooled air cooler mounted on the top of the yoke. Three 50 kw units are used in this air cooler, and the individual units are interchangeable with the air cooler units in the propulsion motor. The brush and brush holders for the generator are also the same as those used in the propulsion motor. Thus, these parts can be used interchangeably.

The engines are sometimes operated at low speed to save fuel through highly efficient diesel engine operation and conserve engine. To satisfy this operating requirement sufficient capacity is provided for fan ventilation so that full engine power can be provided even when the speed of the propulsion generator itself is decreased to approximately 500 rpm.

3. Exciters

One set of exciting motor-generators consists of an exciter for the propulsion motors, an exciter for the propulsion generators, a constant voltage exciter, and a driving induction motor. One set of exciting motor-generators is used for each propeller.

Each exciter and induction motor are coupled with the flexible couplings on a common base. Ball bearings are used for each bearing, since pitching and flaking may occur on the bearing due to shock and vibration applied to the hull of the ship when the machines stall. To prevent this, preload spring force is applied in the axial direction so that the rotary unit does not move even when a shock force of 3 g is applied.

4. Control Devices

1) Main switchboard

The main switchboard consists of main circuit changeover panels, propulsion generator control panels, propulsion motor control panels, field resistor panels, and auxiliary panels. All of these panels are installed in the power control room in a block " U " arrangment as shown in *Fig. 7*. These panels are arranged bisymmetrically, with those to the right to the center used for the starboard side propeller and those to the left of center for the port side propeller.

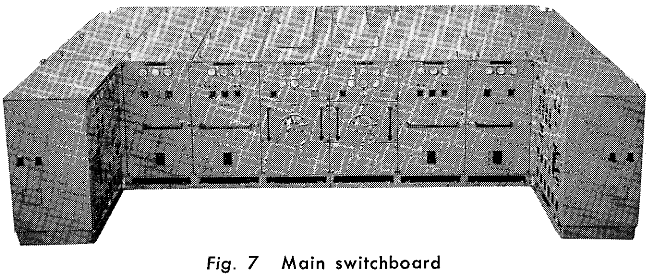

Fig. 7 Main switchboard

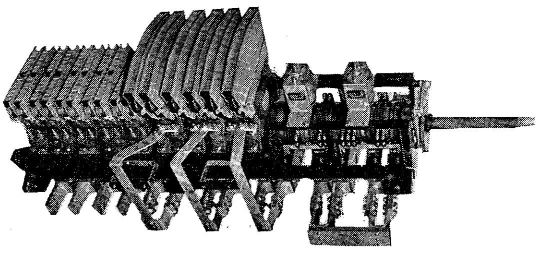

Fig. 8 Main circuit switch

The steel framework and steel sheet of all of the panels have sufficient size and thickness to withstand extreme vibration and shock. In addition, handrails were provided on the front of the panels for use by crew members as safety hand grips when the icebreaker is pitching and rolling. An aisle is provided inside the panels for inspection. The resistors which generate heat inside the panel are located behind the aisle, and heat is discharged to the outside of the room by ventilation through the air duct on the rear of the panel. A partition is provided between the panels on the left and right sides so that even if a breakdown occurs on one side the other side is not affected.

In the main circuit changeover panel contains devices to switch the main circuit according to the number of propulsion motors and generators used, and other such devices. As shown in *Fig. 8*, the main circuit switch is a hand operated rotary type having seven main switches and several auxiliary switches assembled on a common shaft. The main switch has a capacity of 3000 amp. Three main switches with a breaking capacity of 250 v 3000 amp are provided. The propulsion generator control panel and the propulsion motor control panel each contain devices and instruments required for the Ward-Leonard control and the motor field control.

The motor operated field rheostat which is electrically interconnected with the propulsion control lever is installed in the field resistor panel. The auxiliary panel contains a field regulator for the constant voltage exciter and changeover switch for the standby exciting motor-generator set. Control devices for distribution of the ac power supply for the propulsion equipment and transformers are also contained in the auxiliary panel.

2) Main control desk

The main control desk is the control center for all electric propulsion equipment, and is installed in the power control room. The main meters and changeover switches are assembled in the instrument panel. Propulsion control levers for both port and starboard sides are installed in the center of the operating panel. Sequence lamps and fault pilot lamps are provided on both sides of the center. The vertical propulsion control levers move the variable resistors through gears. An electromagnetic brake is provided so that the equipment is not operated in error due to vibration.

3) Wheel house maneuvering stand, side deck maneuvering consoles, and crow's nest maneuvering console.

The wheel house maneuvering stand is shown in *Fig. 9*. The propulsion equipment can also be operated and supervised from the wheel house. The ship can be operated using the side deck maneuvering consoles while carefully and closely observing the condition of the frozen sea during icebreaking operations. These maneuvering consoles have water-

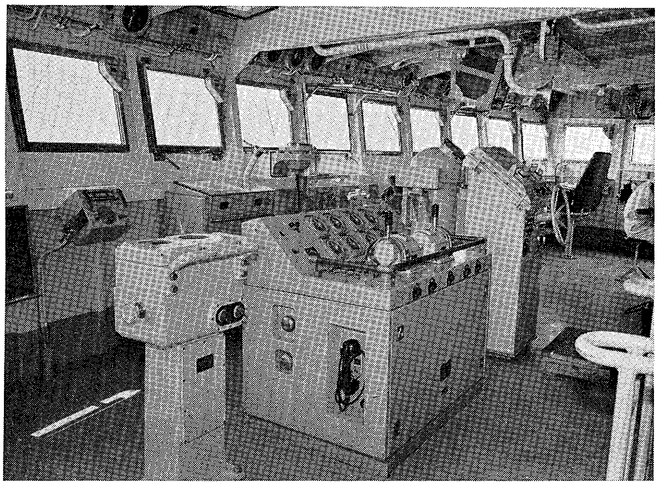

Fig. 9 Wheel house maneuvering stand

proof construction and are installed on the open deck. The crow's nest maneuvering console is used when operating the ship by observing overall conditions of the frozen sea.

4) Air circuit breaker

Two air circuit breakers for each side or a total of four air circuit breakers are contained in boxes, installed in the engine room.

The breakers have an especially designed vibration and shock-proof construction.

Their breaking capacity is dc 900 v 30,000 amp, and arc supression is accomplished by dividing the arc into many small arcs by a multiplicity of steel sheets. This circuit breaker will withstand 500 load opening/closing operations, and it is operated by a dc 220 v motor or manually.

IV. CONTROL SYSTEM

Fig. 10 shows the basic circuit diagram of the electric propulsion system. The figure shows only one side of the system. The same circuit is also used on the other side. These two circuits are completely separated to prevent electrical trouble in one side from affecting the other side. The main circuit is constructed in an alternate series of wire connections for two propulsion motors and two propulsion generators. A special circuit arrangement is provided, with various switches installed in appropriate positions within the main circuit to permit " Two engine operation " described in the foregoing paragraph.

The propulsion generators are excited by a special exciter (EX_1). The voltage of the propulsion generator, and, in turn, propulsion motor speed, is controlled by the exciting input adjustment. To be more specific, as the propulsion control lever is operated, the magnetic amplifier speed setter detects

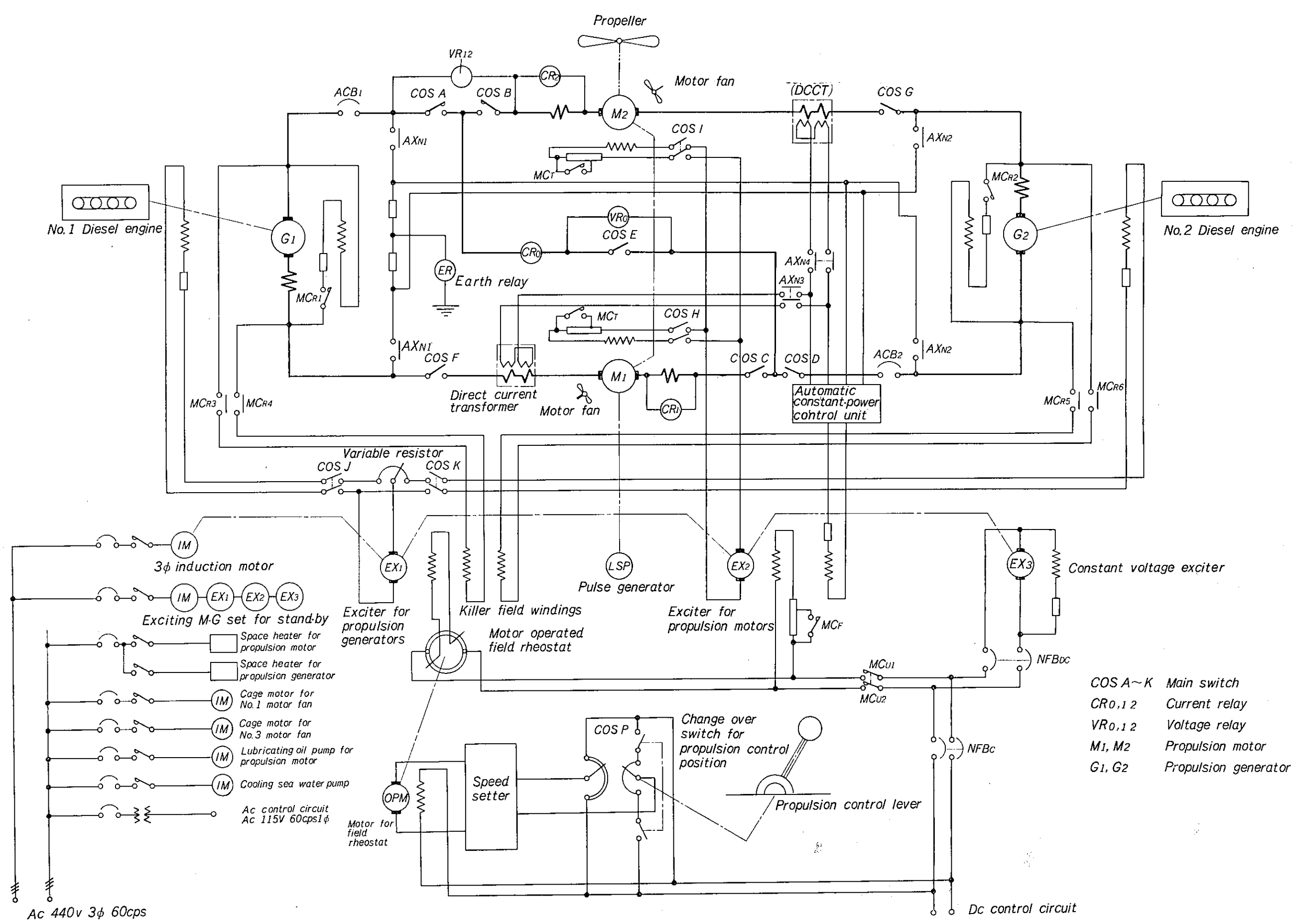

Fig. 10 Basic circuit diagram of the electric propulsion system

the direction and degree of lever motion, operating the motor driving the field rheostat for input of the EX_1, and exciter output is changed. A variable resistor is applied to balance the exciting currents of both generators by adjusting the difference in voltage between the two propulsion generators when switching the main circuit. To suppress residual voltage, when stopping the propulsion motor, propulsion generator voltage is returned to the exciter by $MC_{R3\sim6}$ under reverse polarity.

The propulsion motors are excited by special exciter EX_2. The excitation is shifted to strong, medium, or weak fields according to operations such as normal cruising, icebreaking, full engine operation, two engine operation, etc. In addition to the design features already described, an automatic constant-power control is also provided. A description of this device is provided within the subsequent descriptive information. Two identical sets of exciting motor-generators are provided on each side. One set is for stand-by.

In event major trouble occurs requiring quick protection of the electric equipment the output of EX_3 is interrupted by MC_{u1} and MC_{u2}, and, matching the magnetic flux attenuation of the fields of the propulsion motor and generator, the fields are quickly cut off to protect the equipment.

1. Main Circuit Changeover System

The main circuit changeover system is used to switch from " Four engine operation " to " Two engine operation " or vice-versa.

The main circuit switch is a cam rotary type consisting of seven main switches assembled on a single shaft. This switch prevents erroneous connection during complicated circuit switching, and detects conditions under which propulsion motor power is not properly applied to the propeller and changes the main circuit connection while the ship is in motion. To be more specific, the current relay installed in the main circuit detects conditions under which no power is applied by the propulsion motor to the propeller, and immediately and effectively switches the main circuit. Due to this design feature a high breaking capacity is not required on the main switch, and the switch can, therefore, be made compact. The system is protected further by interlocking mechanisms using lock magnets so that the equipment is not switched unless certain conditions prevail. However, prevailing operating conditions for switching may vary during rough weather. To provide for this variation in operating conditions, various conditions are provided and necessary breaking capacity for various conditions has been predetermined by computer.

2. Automatic Constant-Output Control

The automatic constant-output control is a device by which propulsion motor output is constantly maintained between free running characteristics and standing pull characteristics.

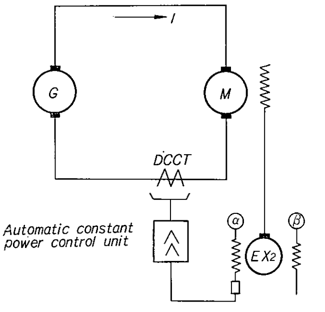

Fig. 11
Automatic constant-power control system

To be more specific, the propeller operates at a point between free-running characteristic *A* and standing pull characteristic *B* in *Fig. 2*. This point is determined or is moved depending upon external conditions. On the other hand, the torque characteristic of the propulsion motor connected to the three fields generator is, as shown by curve *D*, a so-called " Drooping characteristic " in which the generated torque increases in line with the increase in load torque and finally stalls at a some designed torque. If the field of the propulsion motor is constant (strong field), the speed of the propeller will not increase sufficiently when released from standing pull, even though the propulsion motor is generating a rated output for standing pull. As a result, the motor can be used only with a partial load. By using a weak field for the propulsion motor and increasing propeller speed to apply the rated load, the full power of the propulsion equipment can be utilized. In this equipment the field of the propulsion motor is automatically regulated in the manner described so that the propulsion motor always generates rated output between the two characteristics as described above.

That is, in *Fig. 11, DCCT* in the main circuit detects the current, and compares it in the automatic constant-power control unit with the standard value. If the main circuit current exceeds the rated value, output is generated at the automatic constant-power unit, control current flows into winding α for constant-power control of exciter EX_2, and the propulsion motor field is automatically strengthened.

3. Switching Ship Operating Locations

The propulsion control levers are installed in five different locations on this ship: (1) mian control desk, (2) wheel house maneuvering stand, (3) port deck maneuvering console, (4) starboard deck maneuvering console, and (5) crow's nest maneuvering console. Propulsion control can be switched so that propulsion control can be performed from any of the five locations, as appropriate.

The sequence for shifting propulsion control is: Main control desk→wheel house maneuvering stand (port and starboard deck maneuvering consoles)→

crow's nest maneuvering console. The propulsion control levers on the wheel house maneuvering stand can be connected to the port and starboard deck consoles by selsyn motors.

4. Protection and Trouble Indication Devices

When trouble occurs, a bell alarm sounds and pilot lamps on the main control desk and individual maneuvering stands and consoles, as applicable. All major and minor trouble is indicated on the main control desk in the power control room by individual pilot lamps for each type of trouble. Serious trouble may include suppression of the propulsion motor fields, excessively slow operation of the diesel engines, excessive main circuit current, excessive main circuit voltage, and extended stalling of the porpulsion motor. If such serious troubles occur, the exciting circuits of the exciters for both the propulsion generators and propulsion motors are cut off with the same attenuation time constants, so that damage to the main circuit from rapid field change is prevented and the electric system is, thereby, protected.

The air circuit breaker in the main circuit has been used to insure continued capability of operating the ship under extreme operating conditions. It has been so designed that, even if breakdown does occur, the air circuit breaker is not cut off by signal. Rather, an instantaneous self-tripping of the air circuit breaker occurs. For example, the overcurrent rate established for fast cut off of excitation is approximately 220%, and that of self-tripping of air circuit breaker is approximately 250%.

5. Reverse Power

The relationship between propeller speed and required torque when the direction of propeller rotation is reversed is indicated by Robinson curves (*a* through *a''*) as shown in *Fig. 12*. The ship speed *Vs* is used as a parameter for this purpose. For example, in curve *a* (when the ship speed is equal to *S* kn), point *B* represents the point at which the propeller rotates at continuous speed, as shown in the *Fig. 12*, like a water turbine. This is due to water flow at a velocity of *S* kn even when no torque is applied to the propeller by propulsion equipment. To reduce propeller speed from point *B*, reverse torque exceeding the torque applied by water flow must be applied to the propeller by the propulsion equipment. The torque required by the propeller changes according to the change of speed from point *B* to *C*, *C* to *D*, *D* to *E*, etc., as illustrated in the figure.

Therefore, when the propeller is quickly reversed while the ship is moving forward at a speed of *S* kn, and the time required to reverse the rotation of the propeller is comparatively short (approximately 10 to 20 seconds), it is concluded that ship speed is maintained at a speed close to *S* kn for a short period of time after the order is given to reverse

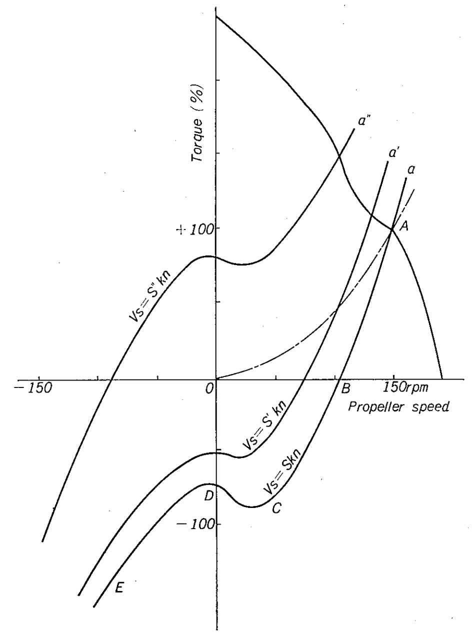

Fig. 12 Robinson curves

rotation, which is due to the extreme force of ship inertia, and the required propeller torque remains close to curve *a*.

In dc electric propulsion, the voltage (rotating direction) of the propulsion motor is positive and the current (torque) is negative within the ranges between *B* to *C* and *C* to *D* in the reversing process. Thus, electric power reverses from the propeller toward the propulsion equipment, the engine moves from an unloaded condition to a braking loaded condition, and in exceptional cases, becomes over speed. This reverse power value varies depending upon the size of the ship, propeller specifications, reverse rotation time, and ship speed at time of reversing.

For icebreakers, more emphasis is placed on thrust in designing the propeller than in ordinary commercial vessels, and therefore, the inclination of the Robinson curve, as described above, is more pronounced. Accordingly, the reverse power value is also greater. Moreover, in an icebreaker, it is desirable to shorten the propeller reversing time as much as possible due to special ship operational requirements (e. g., charging, etc.). For this reason, the ship speed cannot be appreciably reduced before reverse power is applied. Consequently, in a dc electric propulsion ship, especially an icebreaker, over acceleration of the diesel engines requires a great deal of careful consideration.

When planning the design of "Fuji", based on the block diagram shown in *Fig. 13*, the Robinson curve described in the foregoing paragraph was combined with the friction function k_1 (n), and analysis was performed by a digital computer (IBM 7090) on the effects of quick reverse rotation upon the electrical system. As a result, the conclusions

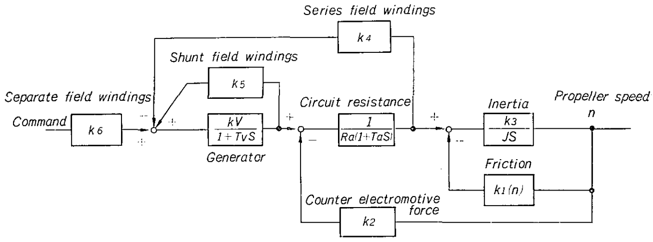

Fig. 13 Block diagram

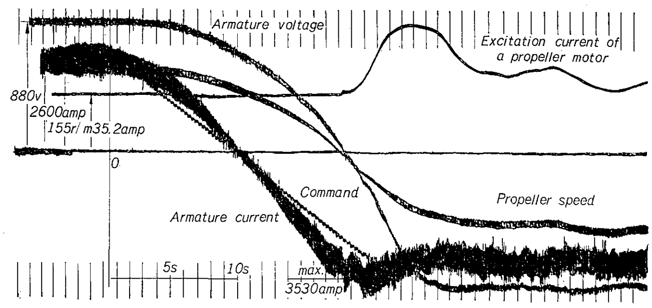

Fig. 15 Oscillogram of a reversing maneuver from Full-ahead to Full-astern

of the analysis were generally in agreement with results of actual measurement.

V. RECORD OF OPERATION

1. Factory Test

The various electrical devices were assembled at the Kawasaki Factory of Fuji Electric Company after various individual tests were completed. After assembly, the overall tests were performed primarily to verify that inter-related operations between individual devices were correctly performed.

Following the above test, the propulsion generators were coupled with the diesel engines, and a 100-hour continuous endurance test, a quick load variation test, and other related tests were performed at the factory where the engines were manufactured. In addition to these tests, a combined plant test was made by actually applying a load to the propulsion motor. To be more specific, one set of propulsion equipment, for the propellers on one side, was assembled in the factory, the propulsion equipment was hooked up, and a water brake was used in lieu of a propeller. (Refer to *Fig. 14.*) This test was significant. During this test, the equipment was adjusted and the performance was verified. The data obtained from this test was extremely useful for reference during tests and adjustments subsequently made aboard ship.

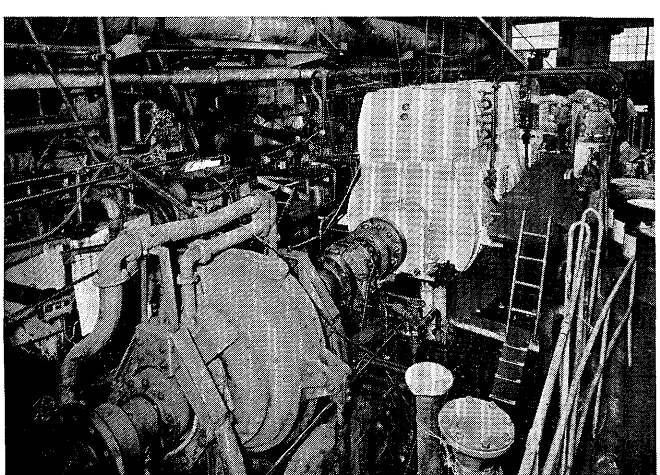

Fig. 14 Combined plant test for propulsion motors using water brake

2. Tests under Actual Operating Conditions

Results of tests made during actual operations at sea, performed after ship construction was completed, proved to be completely satisfactory to all concerned.

After the ship was put into commission, a quick reversing test was performed through the cooperation of the Defence Agency, the shipyard, and the manufacturer of electrical equipment, and tests were performed and measurements taken from every viewpoint with regard to the effects of propeller reverse power. The oscillogram made during the quick reversing test is shown in *Fig. 15*. The measured reverse power energy satisfactorily matches the value forecasted during initial planning as described in Chapter IV, above. It was proven that the various assumptions and computations made during the study were correct. Based on these test results, the coursing time from +100% to −100% for the motor operated field rheostat was determined to be 25 seconds. With the ship placed under normal displacement, a reversing order of " Full-astern " was issued while the ship was running under a full speed of 17 knots. The ship stopped in approximately 79 seconds after issuance of the order, and the distance from the position at which the order was issued to the position at which the ship stopped was approximately 407 meters.

3. Record of the Maiden Voyage (activities to support and transport the 7th Antarctic Research Expedition Team)

The activities to support and transport the 7th Antarctic Research Expedition Team began from the departure of " Fuji " from Tokyo Port on November 20th, 1965 and ended on April 8th, 1966. During the operation in the frozen sea (December 27th, 1965 to February 13th, 1966), the ship anchored for 16 days while positioned alongside the permanent ice formation near Showa Base to transport materials. Fuji engines were operated at all other times during which normal icebreaking was performed in the frozen sea and continuous icebreaking was performed in the area of the permanent ice cap. Except during charging operations two engines were usually employed when moving about in the frozen sea, and the measure of maneuvering was not propeller speed, but

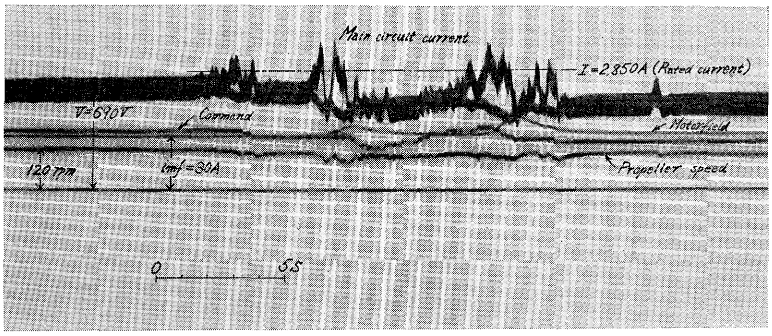

Fig. 16
Oscillogram showing the current fluctuations when ship sailed backward during charging maneuver

electric power (current). On the return trip from the Molodyzhnaya Base (USSR), movement of the ship was retarded by areas of compactly frozen ice and it became impossible to move forward continuously. The ship performed charging operations in which the ship was repeatedly rammed forward and withdrawn. Under those operations, all four diesel engines were operated, and the operation was controlled from either the wheelhouse or the crow's nest. With quick handling of the control lever position while charging, since the ship's speed was slow, the reverse power, its continuing time, and overspeed of the diesel engines were respectively limited to approximately 300 kw, 3 to 4 seconds, and 4 to 5%. Insofar as these factors are concerned, no problems were encountered. While moving about in the frozen sea, all four propulsion generators were simultaneously operated for a total of approximately seven hours. During the time the ship was engaged in normal icebreaking and when charging... especially when reversing... many blocks of broken ice struck the propellers, and a considerable fluctuation in main circuit current was experienced as shown in the oscillogram in *Fig. 16*. However, the ship was carefully operated since this was her maiden voyage; thus, the extent of curren tfluctuation was minor compared to that envisioned during planning. Maximum shock measured during normal icebreaking and charging was 0.04 g. This is also minor in comparison to the data considered in planning.

VI. CONCLUSION

The electric propulsion equipment has continually performed satisfactorily without failure ever since the "Fuji" was completed in July 1965. The performance of this equipment was fully displayed, and the superiority of the electric equipment was proven by transporting the 7th Antarctic Research Expedition Team. On the other hand, much of the success in actual performance of this equipment is attributed to the fact that ice and weather conditions had been previously thoroughly investigated and that proper judgement was applied in maneuvering the ship very carefully. It is assumed that in future voyages the ship will be operated under conditions for more severe than those encountered during this voyage. However, judging from actual performance during this voyage, it is expected that the electric propulsion equipment will display even greater power.