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A LIGHTWEIGHT SUPERCONDUCTING MAGNET FOR A TEST FACILITY OF MAGNETIC SUSPENSION FOR VEHICLES

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I. INTRODUCTION

Since several years ago, magnetically suspended trains have been proposed for high speed passenger trains by many investigators. The Japanese National Railways is developing the magnetic suspension system with superconducting magnet driven by linear motors for the train with the average running speed of 450 km/h. In this system the superconducting magnets have to be designed under the aspect of high safety, small size and light weight.

Several possible magnet structures have been proposed by Powell and Danby(1), and others. We think, however, that the tubular structure is best one. As to structural materials, the stainless steel should be replaced by aluminium or titanium to reduce the weight of the magnets.

We have constructed the magnet for a test facility of magnetic suspension. This magnet has been designed considering to reduce the weight of the cryostat by applying the concept of tubular structure and multifilament superconducting composites as the conductors. However, as the special arrangement of superconducting coils has been required by the test facility, the design of the cryostat has been modified partially. The cryostat is ring-shaped and its cross section is arch-shaped, and a pair of C-shaped modified race-track coils are installed in it. The magnet is designed to be operated in the persistent mode.

The experiments was performed by using the facility of the Railway Technical Research Institute of JNR.

II. SUPERCONDUCTING COILS

Usually the large superconducting coils are completely stabilized with the large quantity of copper. The overall current densities of completely stabilized coils are relatively small. Therefore, the weight of conductor is one of factors increasing the weight of magnet.

To increase the stability of conductor and reduce the weight of it, we have taken account of the criteria of the intrinsic stabilization by multifilament composite wires and of minimum propagation current.

1. Conductors

The conductor consists of 161 filaments of 80 μ diameter Nb–Ti alloy embeded in OFHC Copper matrix, and is coated with polyvinylformal so that the thickness of film is 20 μ thick. The copper ratio of the conductor is 6.3, and the stable current is about 10% larger than the nominal current 855 A.

The diameter of a superconducting filament has been determined from the criterion(2) for the adiabatic stabilization. The insulation thickness has been determined to make the heat transfer coefficient greater than 0.1 W/cm^2·K.

The superconducting wires were developed by cooperation with the Furukawa Electric Co., and Fuji Electric Co.

Fig. 1 and *Table 1* show the cross section and the specifications of the conductor.

Table 1 **Specifications of the conductor**

Cross section	1.8 mm×3.2 mm
Superconducting filament	80 μ diameter Nb–Ti
Number of filaments	161
Twist pitch	100 mm
Copper ratio	6.3
Residual resistance ratio of OFHC	140
Critical current	1780–1910 A at 3 T
	990 A at 5 T
Insulation	PVF 20 μ thick
Unit length	700 m

2. Coil Structure

The coils are wound solenoidally, and each layer of windings is separated by the insulated pieces of 1.5 mm thickness and of 4 mm width, which are placed at 30 mm intervals along the conductor, so as to make the coolant channel vertical. The heat transfer at the liquid helium-conductor interface may be influenced by the design of coolant channels, and the vertical coolant channels is expected to make the performance of the heat transfer better.

The coils are wound as rigidly as possible on the stainless frames with reinforcing ribs, and are tightened with the circular frames and the end sustaining arch-

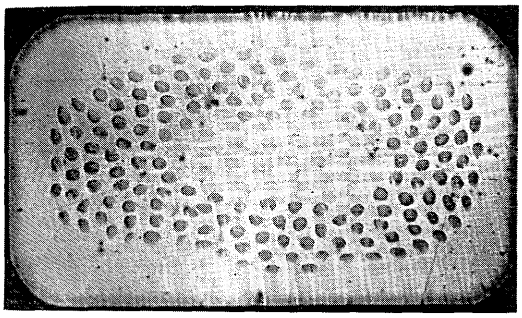


Fig. 1 Cross section of the superconducting composite

shaped frames from the outside. The spacers of the insulated copper have been fastened on the conductors by the cryogenic adhesive so as not to displace.

The coil structure is shown in *Fig. 2* and *Fig. 3*, and the specifications in *Table 2*.

Table 2 **Specifications of the coil**

Ampere turns	200 kAT
Nominal current	855 A
Number of layers	18
Number of turns in a layer	13
Cross section	58 mm × 43 mm
Maximum field strength	2.3 T
Center field strength	0.7 T
Weight of conductors	29.5 kg

3. Stability Test of Coil

The stability has been tested by a model coil which has the same cross section with that of the levitating magnet. *Fig. 4* shows the predicted stable region (under the solid line 2) and the observed results (circles denote stable and crosses unstable).

While testings, the heater is set in the model coil. The "stable" means that the normal state induced by the heater in a small part disappears after switching off the heater. In the unstable region the normal state propagates over the other part.

4. Thermally Operated Persistent Switch

Since the electrical resistance is zero in the superconducting coil, the current persists without decay after the terminals of the coil are short-circuited.

Because of the persistent mode operation of the superconducting magnet for the magnetically suspended high speed train, the external power supply is not required so that the equipment weight can be reduced and obstructions due to power failures can be avoided at the same time. In order to realize the persistent mode, the resistance of the switch in the circuit is to be as small as possible. This type of switch is known as a persistent switch.

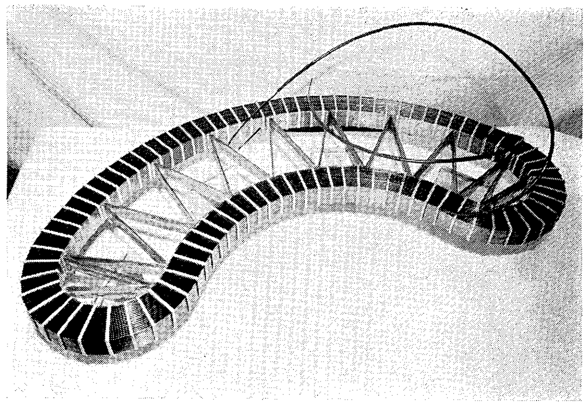
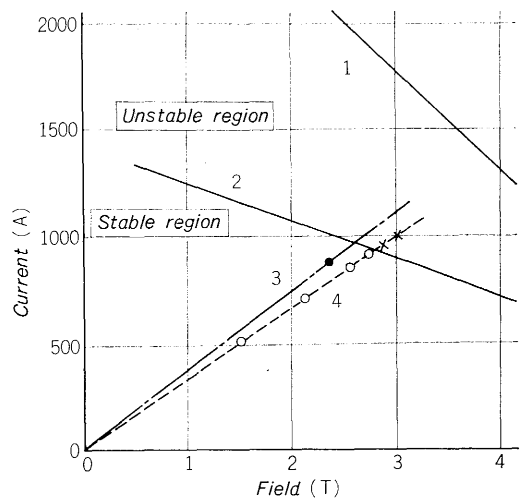


Fig. 2 Superconducting coil



① Critical current
② Minimum propagation current
③ Load line of the magnet for levitation
④ Load line of the model magnet

Fig. 4 Minimum propagation current and load lines of the superconducting magnet for levitation and the model magnet

Fuji Electric has now developed a new thermally operated persistent switch with a current carrying

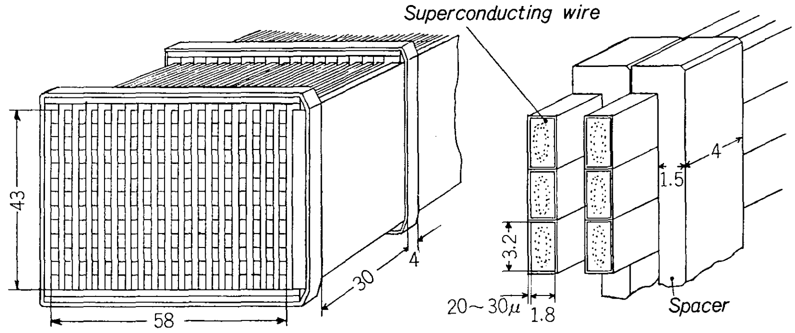


Fig. 3 Sketch of the cross section of the superconducting coil

capacity of 1,000 A for the electro-magnet. These switches consist of bundles of superconducting filaments and heaters and are assembled in a case of 41 mm in height and 60 mm outer diameter. The resistance in the normal state is 60∼70 mΩ at 4.2°K. *Fig. 5* shows the persistent switches.

Since this switching method can be performed by heating the bare superconductor with a heater, there are no contacts and the only resistance is that in the coil connection part so that the value can easily be made sufficiently low. Therefore, the switch can be very compact and light weight. These are the main features of this device. These switches was previously used only in cases of small current and no persistant switch for large current was developed.

The response of the persistent switches has been so quick as to work within few seconds after switching off heater. The decay of the persistent current has been too slow to be detected in about one hour. The evaporation rate of liquid helium due to the heater of a persistent switch is about 5 liters/h, but the quantity of liquid helium evaporated by the heater over a operating cycle of the magnet is less than one liter per a switch, because the working period of the heater has been about 9 minutes which is the period to excite the magnet.

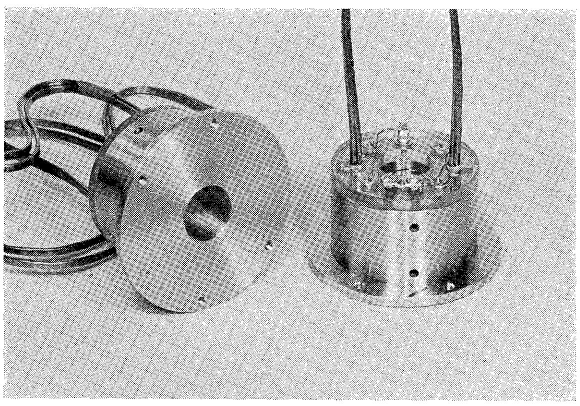


Fig. 5 Thermally operated persistent switches

III. CRYOSTAT

1. General

The superconducting magnet for the high speed train is required to be light in weight, short in height and small in the consumption of liquid helium. Considering these requirements, we have designed conceptually the cryostat to be installed on the high speed train, as shown in *Fig. 6*. The features of this cryostat are as follows:

a) By adopting the tubular structure, the thickness of the wall of cryostat is reduced as compared with the cylindrical or rectangular structure, and the reduction of the weight is expected.
b) The inner vessel is placed eccentrically against the outer vessel and the superconducting coil is located on the lower part of the inner vessel to increase the field at the level of ground loops and the lift force.

Due to the calculation based on the following test results, it is confirmed that 8 superconducting magnets weighing 700 kg are able to suspend a 32 ton high speed train travelling of 500 km/h at the height 100 mm.

2. Structure of the Cryostat

The magnet has been designed on the basis of the above concept. However, some modifications of design were necessary to apply the magnet to the experimental facility. *Fig. 7* shows the cross section of the cryostat and the coil arrangement in it and *Table 3* gives the specifications of the cryostat. The cross

Table 3. **Specifications of the cryostat**

Outer diameter	1540 mm
Diameter of bore	260 mm
Height	560 mm
Weight (coils and cryostat)	650 kg
Liquid helium	140 liters

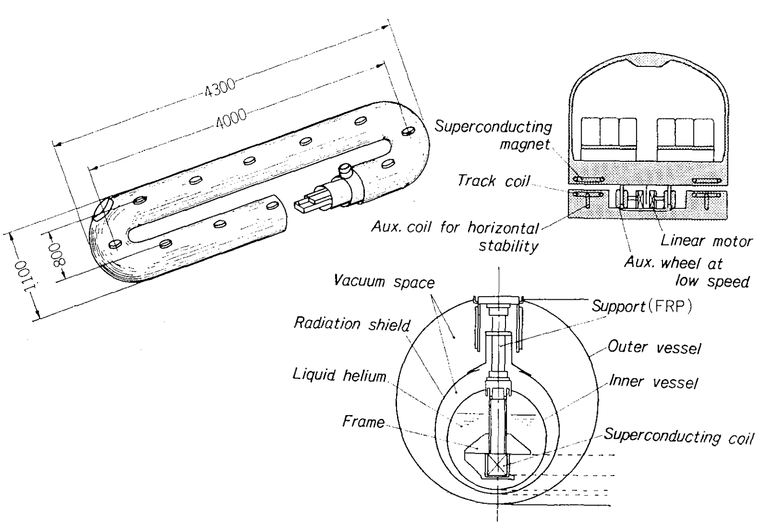
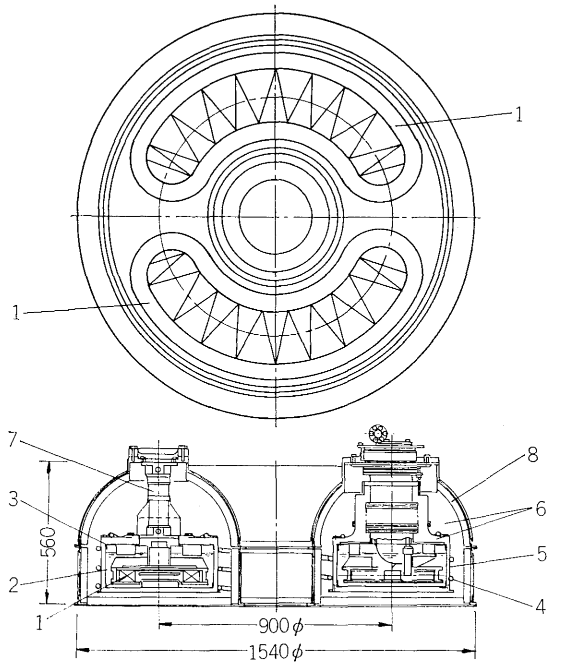


Fig. 6 **Conceptual design of the magnet for high speed trains**



1. Superconducting coil
2. Liquid helium
3. Inner vessel
4. Liquid nitrogen
5. Radiation shield
6. Vacuum space
7. Support
8. Outer vessel

Fig. 7 Cross section of the superconducting magnet

section of the outer vessel has the semicircular upper part and the rectangular lower part to reduce the distance between the superconducting coils and the lifting coils. The cross section of the inner vessel is rectangular. The outer vessel is made of 1.6 mm thick stainless steel plate, and inner vessel is made of 2.0 mm thick plate. The radiation shield is located between the inner and outer vessels, and made of 0.8 mm thick copper plate with the exception of the bottom plate and cooled by liquid nitrogen flowing in the copper tubes soldered on the shield. The bottom plate is made of 3.2 mm thick aluminium plate to shield the alternating field from the lifting coils.

3. Tower of Bellows Structure

The cryostat has two towers with the lid. The tower wall introduces heat from the outer vessel to the inner vessel. Excepting the heat inleak through the power leads, a major portion of the heat inleaks into the cryostat depends on the tower wall. The bellows has the thin wall and prolongs the heat conduction path, and so we have adopted the bellows structure as the tower to reduce the heat inleak. Furthermore, to improve the reduction of the heat inleak, the bellows have been attached a heat sink controlled at the nitrogen point.

The rubber 0–ring has been used for the vacuum seal in the tower. The sealing part has been designed so as to be maintained at the room temperature by separating thermally the flange for 0–ring from the flanges for ports, through which cold gas flows

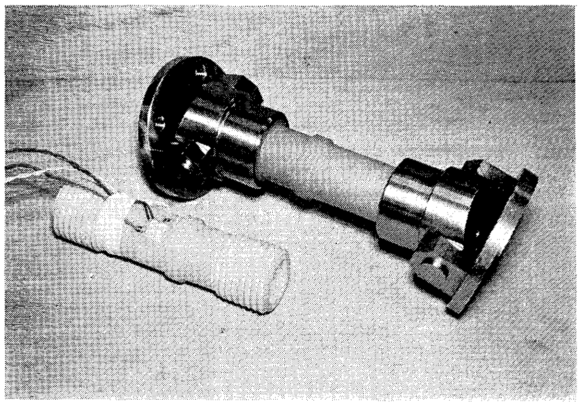


Fig. 8 FRP support

by the steel bellows.

4. Supports of Lift Force

Superconducting coils and the inner vessel must be carried the magnetic force caused by the interaction between the magnet and lifting coils. The FRP tubes have been used for supports because of the large ratio of the mechanical strength to the thermal conductivity. The supports have hinge structures at the both ends to prevent the stress caused by the thermal contruction.

Fig. 8 shows the supports with hinge structures.

5. Liquid Helium Level Gauge

A continuous-reading level gauge using superconductor[3] has been developed to monitor the level of the liquid helium in the cryostat. The structure of this level gauge is shown in *Fig. 9*. The superconducting state is present in the superconductor below the liquid helium level when a certain current is flowing. In the part above this level, the normal conducting state can be achieved by self heating. The level is measured by reading the voltage drop proportional to the length of this normal state part under such conditions.

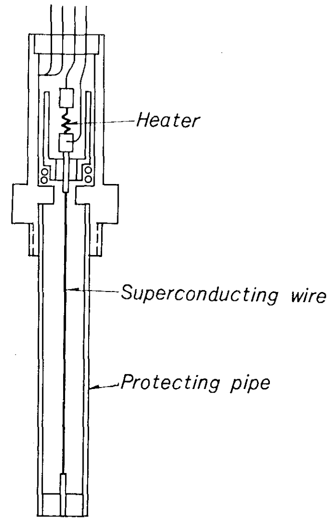


Fig. 9 Schematic structure of liquid helium level gauge

IV. MAGNET PERFORMANCE

1. Excitation and Persistent Mode Operation

The excitating circuit is shown in *Fig. 10*. The diode in the circuit has a role to protect the coils and the persistent switches. Even if the current supply is accidentally interrupted, the terminal voltage of coils is limited to the forward blocking voltage of diode and then the coil current is prevented to change rapidly. At the same time it is prevented for the excessive current to flow into the persistent switches in the resistive state.

The maximum excitation current experienced was 875 A (2.35 T) which was about 90% of the minimum propagation current 960 A. During the excitation, the flux jumps were not observed in the records of the terminal voltages of the superconducting coils and the search coils beneath the superconducting coils. Even when the current supply was interrupted at 855 A, the coils did not quench but discharged in about one minute.

2. Test Record of Excitation in Persistent Mode

Fig. 11 shows an oscillogram of the process of excitation and transfer to a persistent mode. The coil current in persistent mode remained without any detectable decay in one hour test.

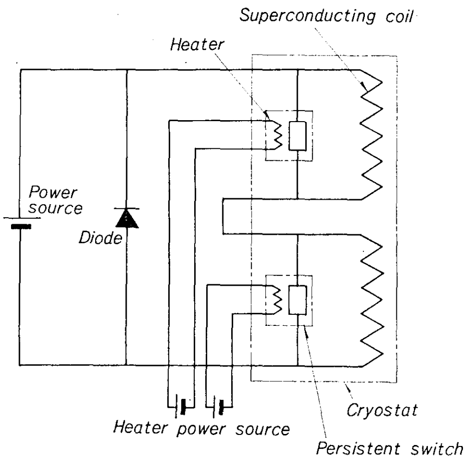


Fig. 10 Exciting circut for the superconducting magnet

A typical process of the persistent mode operation is as follows:

a) exciting the coils up to 855 A by the current supply at the rate of 100 A/min.
b) switching off the heaters in the persistent switches to make the switch conductors superconductive.
c) reducing the supplied current with the rate of 100 A/min from 855 A to 450 A, 40 A/min from 450 A to 200 A and 20 A/min from 200 A to 0 A.

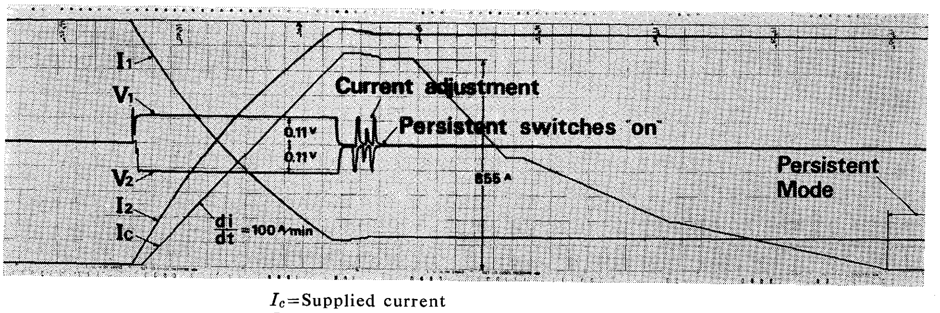
In the process to reduce current we choosed three steps of the rate to protect the switches from the destruction of switch conductors caused by excessive current change, because the switch conductor was not stabilized with the copper substrate. It needed about 30 minutes to complete the process. The excess helium loss due to the persistent switches in the excitation process was about 0.8 liters per a switch.

The above process is reversed for the deexcitation. When the persistent mode was switched off, the discrepancy between the supplying current and the persistent current was allowed up to 6 A without any trouble.

When the magnet levitate the coil current in the persistent mode might increase so as to maintain the total magnetic flux constant against the reaction field from the lifting coils. We observed the current increase of 1–2% for the total current of coils.

3. Magnetic Suspension Test

The test facility is shown in *Fig. 12*. The magnet is suspended over the six lifting coils on the rotating disk and free to displace vertically. The rotation of the magnet is arrested by the stoppers on which the load cells are installed to measure the drag forces. The lifting coils are fastened on the rotatable disk with the revolution velocity of 600 rpm which corresponds to the linear velocity of 100 km/h of the track coil. *Fig. 13* shows a test scene.



I_c=Supplied current
I_1=SC coil current measured by Hall probe (1)
I_2=SC coil current measured by Hall probe (2)
V_1=Terminal voltage of SC coil (1)
V_2=Terminal voltage of SC coil (2)

Fig. 11 Test record of excitation in the persistent mode

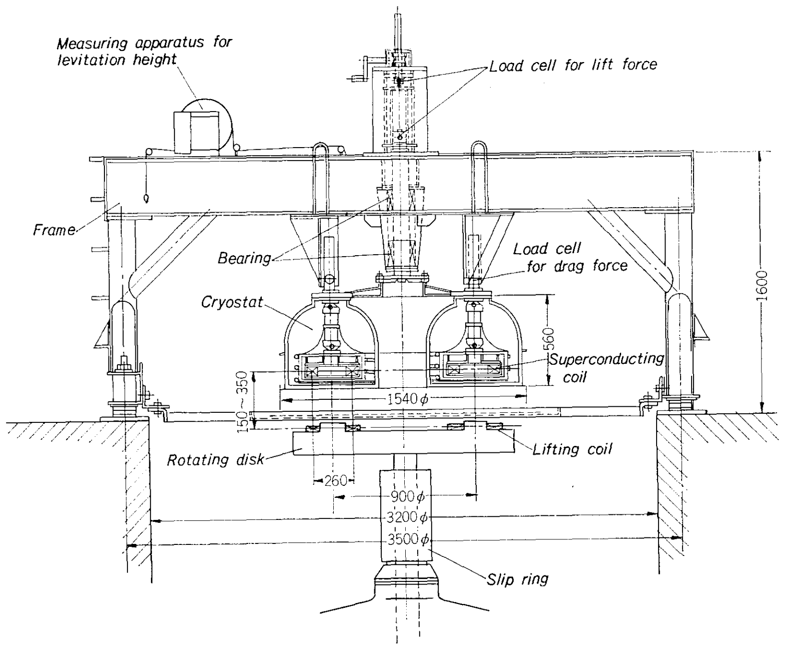


Fig. 12 **Test facility of magnetic suspension**

The magnet was levitated to the height of 80 mm at the lifting coils velocity 100 km/h and the superconducting coil current 800 A in the persistent mode. An example of the test data is shown in *Fig. 14* where the solid lines are the calculated values and the dashed lines are the measured results.

The AC component of the reaction field from the lifting coils was detected by the search coils installed beneath the superconducting coils. The amplitude and the frequency of the AC component were respectively 50 gausses at most and 60 Hz. Any trouble by such a reaction field was not observed as to the superconducting coils. The increment of the evaporation rate of helium was about 25–37 liters/h, most of which could be evaluated as the joule loss (20 liters/h) caused by the eddy current in the copper substrate.

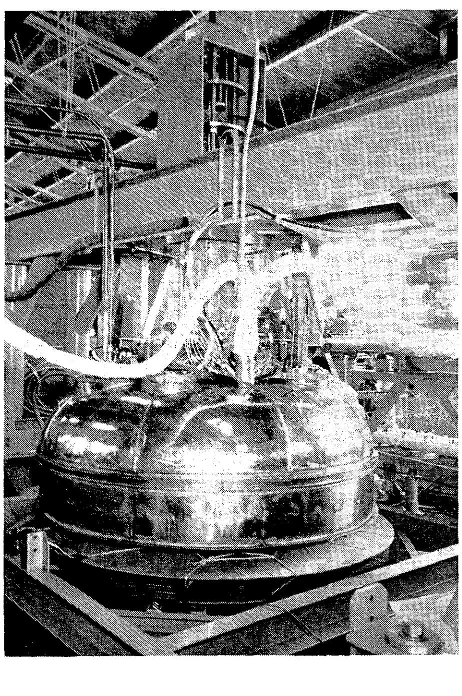
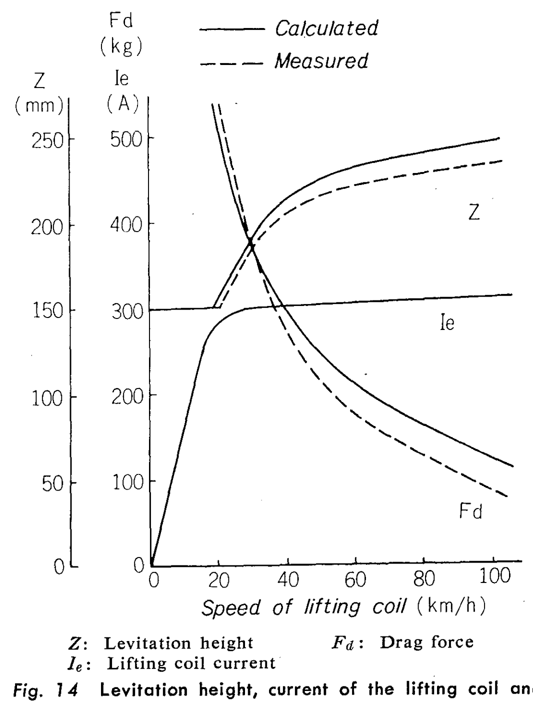


Fig. 13 **Scene of the magnetic suspension test**

4. Evaporation Rate of Helium

The vacuum space of the cryostat has been evacuated by the 1200 liters/sec diffusion pump and maintained at a pressure of 3×10^{-7} Torr. The radiation shield was supplied the liquid nitrogen at the rate 26 liters/h. The evaporation rate was measured by the float type gas flowmeter and the liquid helium level gauge[(3)]. The mean value of the rate was 15 liters/h in the persistent mode.

The major portion of the heat inleak may be carried through two pairs of short power leads. Although the heat inleaks through various parts could not be measured separately, calculated values are listed *Table 4*. The application of the FRP tube for the



Z: Levitation height F_d: Drag force
I_e: Lifting coil current

Fig. 14 **Levitation height, current of the lifting coil and drag force versus speed of the lifting coil**

Table 4 **Calculated heat inleaks in the cryostat except two power leads**

Parts	Materials	Temperature difference	Heat inleaks (kcal/h)	Helium loss (liter/h)
4 supporting columns	FRP	80 to 4.2 K	1.03	1.66
3 supports for radiation shields	FRP	80 to 4.2 K	4.48×10^{-2}	0.072
2 towers	SUS	81 to 4.2 K	5.02×10^{-2}	0.081
Leads for measurement	Cu	300 to 4.2 K	0.277	0.447
Helium gas in the towers	He	300 to 4.2 K	0.491	0.79
Thermal insulation plugs	urethanform	300 to 4.2 K	0.603	0.97
Guide for helium transfer	teflon	300 to 4.2 K	0.107	0.172
Radiation	vacuum	80 to 4.2 K	3.21×10^{-2}	0.052
Vacuum space	rarefied gas	80 to 4.2 K	5.5×10^{-2}	0.137
Total			2.98	4.38

supports and the bellows structure for towers might be able to reduce the evaporation rate of helium by 5 or 7 liters/h.

Testing results of the superconducting magnet produced by us confirm that the application of twisted multifilament wire, the design concept of tubular construction for cryostat and the use of FRP supports improve the stability of cryostat and are effective for making the cryostat compact and light weight as well as for reducing helium evaporation.

Acknowledgment

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