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Abstract

A commercial small refrigerator system has been integrated to a large superconducting spectrometer magnet to cool its thermal shield and anchors. It has been in operation for more than 10,000 hours without major troubles. The refrigerator has cooling power of 60 W for thermal shield at 80 K and 6 W for anchors at 20 K. The magnet is kept below the liquid nitrogen temperature even when the main refrigerator system is turned off, and the cool-down time of the large superconducting magnet is considerably shortened. Operation of the large superconducting magnet has become much easier thanks to the small refrigerator system.

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1 Introduction

A superconducting kaon spectrometer(INS-SKS) has been constructed by Institute for Nuclear Study, University of Tokyo(INS) in collaboration with National Laboratory for High Energy Physics (KEK) and has been installed in the north experimental hall of the KEK 12 GeV proton synchrotron. The spectrometer was designed to meet mounting demand for measuring pions and kaons in the momentum region of 1 GeV/c in nuclear physics research.[1,2] The spectrometer is in full operation for hypernuclear physics experiments by the (π,K^+) reaction and for meson scattering experiments above the Δ resonance region. A large superconducting magnet that can produce 3 tesla in the gap of 50 cm is the most indispensable part of the spectrometer system. The large magnetic volume is required to achieve good momentum resolution of 0.1 % and a large solid angle of 100 msr simultaneously. The superconducting magnet was employed in order to avoid prohibiting electric power consumption if it had been a conventional magnet. A superconducting magnet, however, often introduces difficulties in operation and maintenance since it requires a liquid helium refrigerator and its associated facility. The SKS superconducting magnet was designed so that it can be run as easily as possible without sacrificing requirements as a spectrometer magnet. It is also the experimental requisite that the magnet, when the coils are at helium temperature, can be rotated around the target position so that the angular distribution of the reaction particles can be measured.

A small refrigerator system was concatenated to the SKS superconducting magnet to make the operation of the magnet easy and to meet the experimental requirements. The role of the small refrigerator is to cool the shield and anchors to reduce heat leak, while a main refrigerator supplies liquid helium to the magnet.$^{3)}$ With this small refrigerator, the thermal shield and anchors can be kept at low temperatures without using liquid nitrogen. Since it is mounted directly to the magnet itself, flexible transfer tubes installed between the cold box of the main refrigerator and the magnet helium port became simpler because it is not necessary to install transfer lines for 80 K and 20 K. The magnet can be, then, easily rotated around the pivot, keeping the coil temperature at 4 K. Furthermore, since the temperature of coils is easily maintained below the liquid nitrogen temperature even when the main refrigerator is not in operation, the cool down time of the magnet is considerably reduced. The magnet can reach liquid helium temperature in about 24 hours. It is important for easy use of the superconducting magnet.

In this paper, the structure of the refrigerator system articulated to the large superconducting magnet is described in section 2. The performance of the refrigerator system is explained in Section 3.

2 Structure of the small refrigerator system

A bird eye's view of the small refrigerator system is dipicted in Fig.1, and a schematic diagram of the system is shown in Fig. 2. It consists of a refrigerator unit, compressors, radiation shield, piping for circulation of cold helium gas for thermal shield at 80 K and for thermal anchors at 80 K and 20 K, and a monitor unit. The present system is based on a refrigerator (SRD-220) which is commercially available from Sumitomo Heavy Industry. It was designed so that it can be operated maintenance free for more than 10,000 hours. Each element is described below.

2.1 Small refrigerator

The refrigerator operates on the Gifford-McMahon cycle. The two-stage refrigerator heads are cooled through the alternate compression and expansion of helium gas. The refrigerator itself is installed in the liquid helium reservoir port where helium reservoir and current leads are housed. The two compressors are located on the top of the magnet yoke. They supply high pressure helium gas as shown in Fig. 2. The commercial refrigerator was modified so that it can supply 80 K and 20 K helium gas to the thermal shields and anchors as dipicted in Fig. 3. The cross sectional view of the cryostat is seen in Fig. 4. The thermal shield that surrounds the superconducting coil is cooled by the 80 K helium gas, while the coil supports (not shown) that are made of GFRP are cooled by the 20 K and 80 K helium gases. The helium gas lines are branched to circulate the gas through the thermal shield and anchors as shown in Fig. 5 and 6. Special attention was paid to avoid one-turn eddy current when the superconducting coils quench as seen in the figures. The parameters of the commercial refrigerator when it is used stand-alone are summarized in Table.1.

2.2 Thermal shield and anchors

The radiation shield is extended from the flange of the first refrigeration stage at 80 K of the small refrigerator to the helium reservoir and the superconducting coil vessel.

The radiation shield consists of 2 mm thick copper plate, total weight of which is 440 kg. It is noted that the cold mass of the magnet coil is 4,500 kg. The tubes that circulate the helium gas are made of copper pipe with a diameter of 10 mm and run outside of the thermal shield plate for 80 K and inside for 20 K as shown in Fig. 4. The tube for 80 K is more than 30 m long and is welded to the copper plates of the thermal shield and one for 20K is put on the same plates with thermal insulation. The upper and lower coil vessels are supported by 12 GFRP cylinders from the vacuum vessel at room temperature. These supporting cylinders are thermally anchored both at 20 K and 80 K in order to prevent the heat leak through them. The heat loads to 20 K and 80 K thermal shield and anchors estimated in the design stage is shown in Table 2. Heat loads with the thermal shield and anchors in the case that they are at 100 K and 25 K are also listed in the table. In either case, the small refrigerator has cooling power sufficient to compensate the heat loads to the thermal shield and anchors. Both conduction and gas cooling are utilized for the helium reservoir where the refrigerator head is installed, while only gas cooling power is used to cool the thermal shield and anchors in the coil vessel.

2.3 Monitor unit

The monitor indicators and the control system are installed in one box, which is attached to the side of the SKS magnet yoke. The refrigerator starts operation by turning on one switch. If some alarm is sensed, the refrigerator stops. As is shown in Fig. 7, the monitor unit box has the following functions.

- Start and stop the compressor and the refrigerator.
- Monitor the temperature of the first stage and second stage cold heads.
- Monitor the pressure of the supply and return helium gas.
- Monitor the flow rate of helium gas to the 80 K and 20 K lines.
- Indicate alarms on the cooling water flow and overload of the compressors.

Although the operation status and the alarm signals are also monitored by a computer system that controls the main refrigerator, the functions of the small refrigerator are made completely independent of the operation of the main refrigerator system.

3 Performance

The performance of the small refrigerator system has been tested with a dummy load prior to the installation to the superconducting magnet. After it was shown that the cooling power is as expected, the refrigerator system was integrated to the magnet and the gas flow pipes are connected to each other. Since then, the refrigerator has been in operation for more than 10,000 hours and has shown to be reliable for long-term operation.

3.1 Performance test with a dummy load

The refrigerator system was first tested at the factory using a dummy load. This simulation test was conducted with heaters instead of the 500 kg radiation shield plates installed in the magnet. It is intended to simulate operation for a stationary condition after the shield and anchors are cooled down, but not for a cooling process from room temperature. A schematic diagram for testing the cooling power with the dummy load is shown in Fig. 8. Four heaters , H1 to H4, were setup to simulate the expected heat load and the temperatures were monitored at 6 points. The refrigerator power was measured to be 60 W at 80 K and 6 W at 20 K after the flows of gas helium were optimized. In Table 3, the result of the test is summarized.

3.2 Performance of the refrigerator system

There are two modes of operation for cooling down the superconducting magnet. In an ordinary case, the small refrigerator is on during the main refrigerator is not in operation and the coil is kept below the liquid nitrogen temperature. The mode is usually taken in the intermission period in an experiment. The cool down process starts at the coil temperature below the liquid nitrogen when the main refrigerator is turned on. In this case the coil is cooled down to the liquid helium temperature in about 24 hours. When the magnet is not in use for an extended period, the small refrigerator, as well as the main refrigerator, is turned off. The coil is warmed up to the room temperature. The magnet coil is, then, cooled down from the room temperature by turning on both the main and small refrigerators at the same time. In the performance test of the small refrigerator system, we have measured the cool-down time and the warm-up time of the magnet in these two conditions as shown in Figs. 9 and 10. The helium gas flow rates were typically adjusted to 17 Nm^3/h for 80 K line and 23 l/min for 20 K line.

Figure 9 shows the cool-down trends of the 80 K cold head, thermal shield and 20 K anchor. When the coils are at room temperature in the initial condition, it takes 13 days to cool the thermal shield and the anchors to the saturated values only by the small refrigerator, 159 K and 113 K, respectively. It is because the coils themselves are a heat source in this case. However, when the coil is at room temperature and the main refrigerator is turned on simultaneously together with the small refrigerator, the 20 K thermal anchors and the 80 K thermal shield reaches 24 K and 102 K in 48 hours as summarized in Table 4. Although the achieved temperatures are slightly higher than those of designed values of 20 K and 80 K, they are within a tolerance. As seen in Table 2 where heat estimated loads of the SKS magnet are listed for two different temperatures of the thermal shield and anchors, the difference of those temperatures does not change the heat leak to 4 K drastically. The heat load of the magnet at 4 K was determined to be 3.7 W by measuring the liquid helium evaporation rate in the magnet.

The warm-up curves of the coil vessel are shown in Fig. 10. The curves show the trends of the coil temperature after the main refrigerator is turned off and with and without operation of the small refrigerator. The figure demonstrates the effect of the shield refrigerator after the main refrigerator is turned off. With the shield refrigerator in operation, the temperature of the coils is kept low and does not exceed 60 K for more than 10 days.

4 Summary

The small refrigerator system that is used to cool the thermal shield and anchors of a large superconducting magnet has been in use for more than 10,000 hours. The system cools them to 20 K and 80 K by the cooled helium gas that is circulated through copper pipes. Operating together with a medium size helium refrigerator system, it has been proved that the system performs reliably. By keeping the coil to be at liquid nitrogen temperature with the small refrigerator even when the main refrigerator is not in operation, the cool down time of the magnet is shortened by a factor of 2. The superconducting magnet which has cold mass of 4.5 tons can be excited in 35 hours after the main refrigerator is turned on in this case. It is also shown that the small refrigerator runs stable for extended period over 10,000 hours. The present small refrigerator system provides an efficient mean of cooling the thermal shield for a large scale superconducting magnet and makes the thermal shielding system much simpler.

The authors are thankful to Prof. K. Nagamine for critical advice at the designing stage of the system. Cooperation of K. Morita of Sumitomo Heavy Industry is also acknowledged.

Figure captions

1. Bird eyes view of the SKS superconducting magnet and the small refrigerator system
2. Schematic diagram of the small refrigerator system
3. Detail drawing of the small refrigerator cold heads
4. Cross sectional drawing of the cryostat
5. Helium gas flow line for 80 K thermal shield
6. Helium gas flow line for 20 K thermal anchors
7. Monitor and control box which is attached to the yoke of the magnet
8. Schematic diagram of the refrigerator system for testing the cooling power with the dummy loads.
9. Cool-down characteristics for 80 K cold head (TI-89), 80 K thermal shield (TI-87) and 20 K anchor (TI-86)
10. Warm-up characteristics for coil vessel with (TI76-1) and without (TI76-2) utilizing the small refrigerator

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Table.1 Parameters of the commercial refrigerator (SRD-220)

Refrigeration mode	Gifford-McMahon cycle
Compressor unit	
Charge pressure	15 kg/cm^2
Operation pressure (Supply)	20 kg/cm^2
(Return)	7 kg/cm^2
Power requirement	5.2 kW × 2 units
Cooling water	360 l/h × 2 units
Lifetime of adsorber	10,000 hrs
Flow rate	1,400 Nm^3/h
Refrigerator unit	
Refrigeration power (1st stage)	120 W at 80 K
(2nd stage)	20 W at 20 K
Lifetime of super-seal	10,000 hrs

Table.2 Calculated heat loads for two cases of shield and anchor temperatures

CASE I. shield 80 K, anchor 20 K	80 K stage	48.2 W
	20 K stage	3.6 W
	4 K stage	3.4 W
CASE II. shield 100 K, anchor 25 K	100 K stage	44.5 W
	25 K stage	5.1 W
	4 K stage	3.8 W

Table.3 Results of the cooling power test with dummy loads

	Applied heat load	Gas flow rate	Temperature
I. 80 K shield and anchors			
conduction cooling	H1 = 28 W		
gas cooling	H4 = 32 W	F1 = 10 Nm^3/h	T2 = 20.6 K
sum	60 W		
II. 20 K anchors			
conduction cooling	H2 = 3.8 W		
gas cooling	H3 = 2.2 W	F2 = 36 l/min	T2 = 80 K
sum	6.0 W		

where H1 = dummy heat load into 80 K thermal shield and anchors of the liquid helium reservoir to be cooled by conduction utilizing the first stage refrigeration.

H2 = dummy heat load into 20 K anchors of the liquid helium reservoir to be cooled by conduction utilizing the second stage refrigeration.

H3 = dummy heat load into 20 K anchors of the coil vessel to be cooled by helium gas trasnferred from the second refrigeration stage

H4 = dummy heat load into 80 K thermal shield and anchors of the coil vessel to be cooled by helium gas transferred from the first refrigeration stage

T1 = temperature at dummy 20K anchor

T2 = temperature at dummy 80K thermal shield and anchor

F1 = flow rate optimized to dummy 80 K thermal shield and anchor

F2 = flow rate optimized to dummy 20 K anchor

Table.4 Performance of the small refrigerator system

Without main refrigerator

Temperature at stationary state	first stage (80K)	: 120 K
	80 K shield	: 159 K
	20 K anchor	: 113 K
Cool-down time to stationary state	~13 days	

With main refrigerator

Temperature at stationary state	first stage (80K)	: 102 K
	80 K shield	: 139 K
	20 K anchor	: 24 K
Cool-down time to stationary state	~2 days	

Test conditions:

Charging pressure	15 kg/cm^2
Operating pressure (supply)	20 kg/cm^2
Operating pressure (return)	6 kg/cm^2
Coolant flow rate (80 K line)	17 Nm^3/h
Coolant flow rate (20 K line)	23 l/min

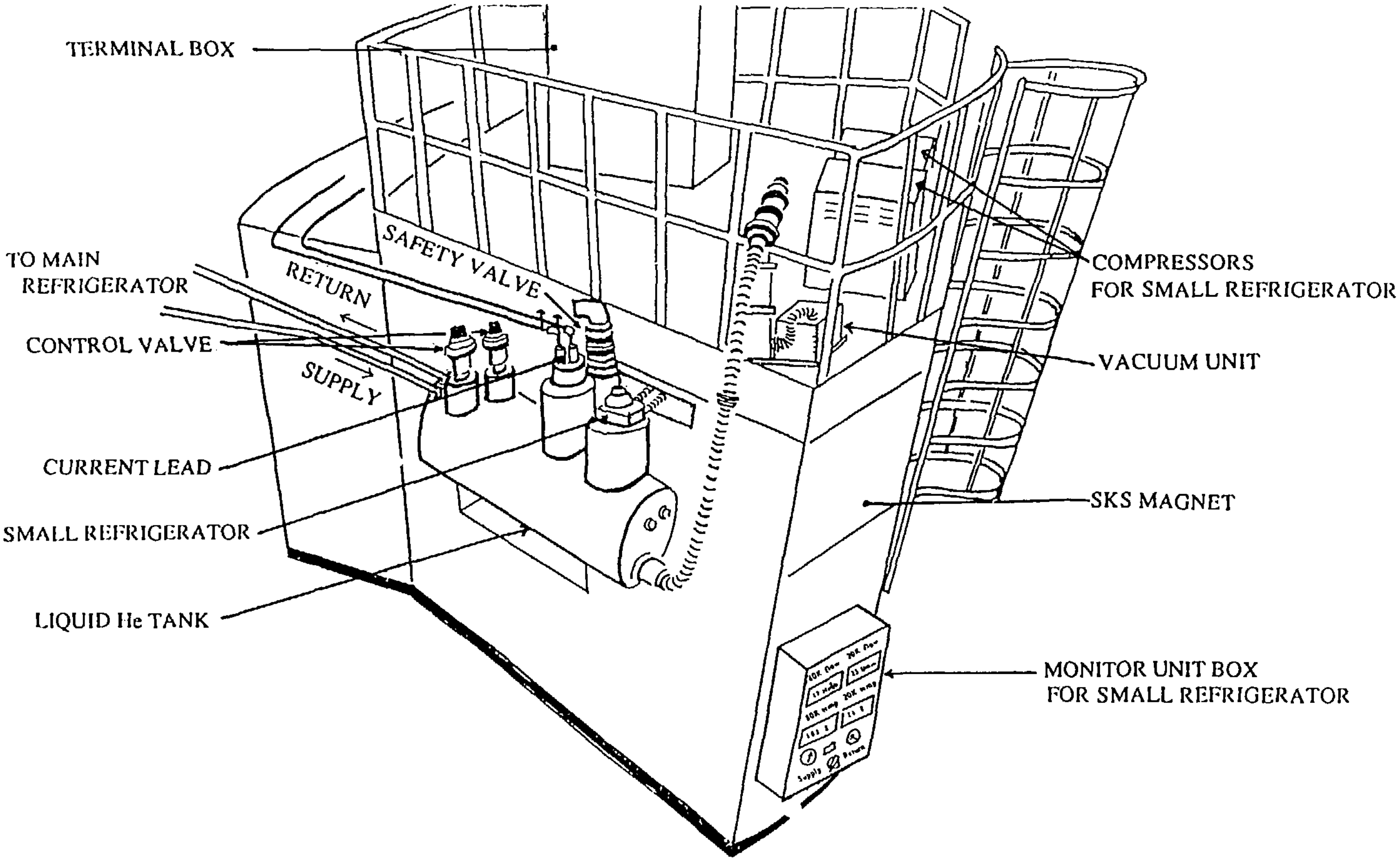

Fig. 1 Bird eyes view of the SKS magnet and the small refrigerator system

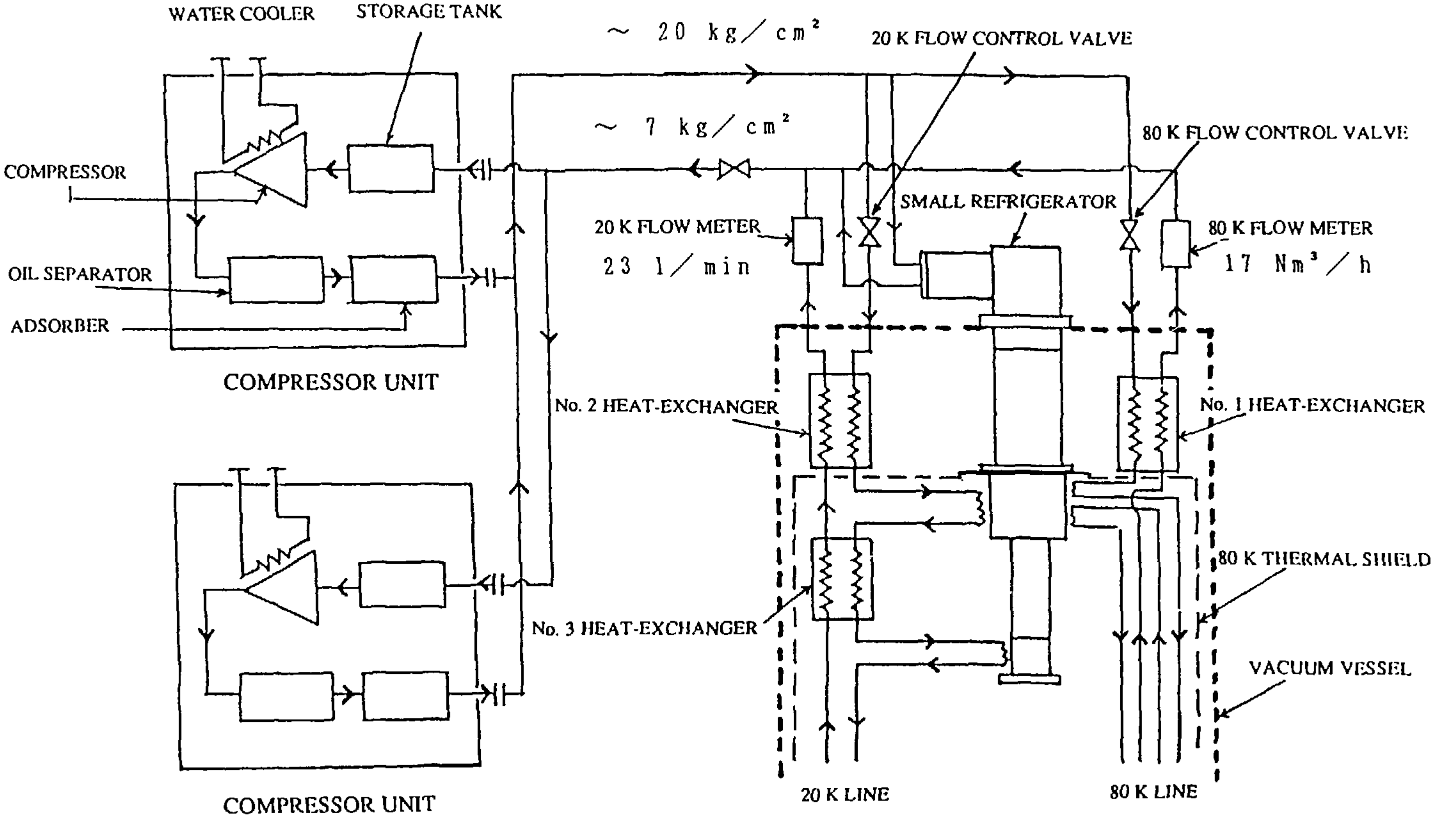

Fig. 2 Schematic diagram of the small-size refrigerator system

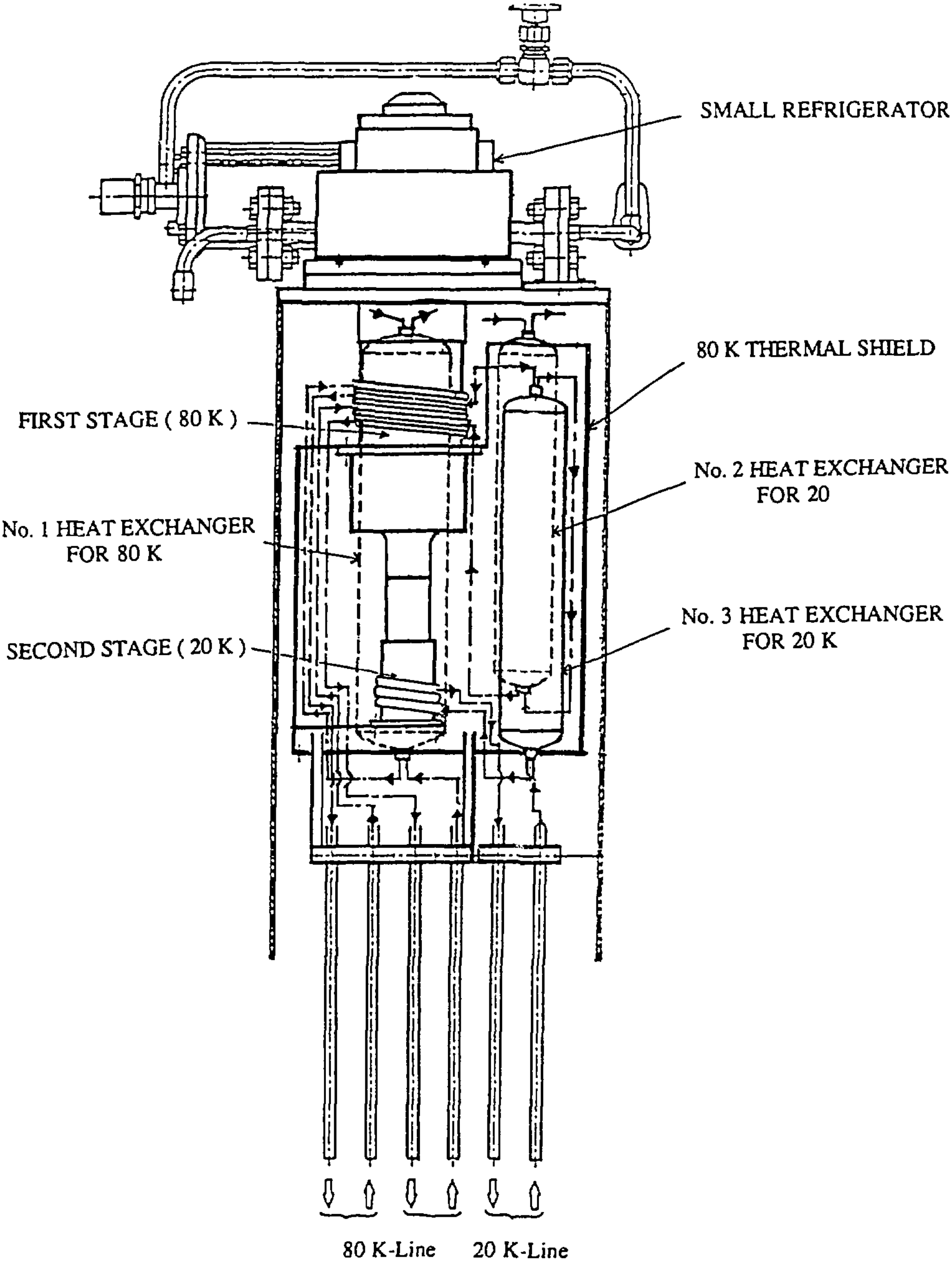

Fig. 3 Detailed drawing of the small refrigerator

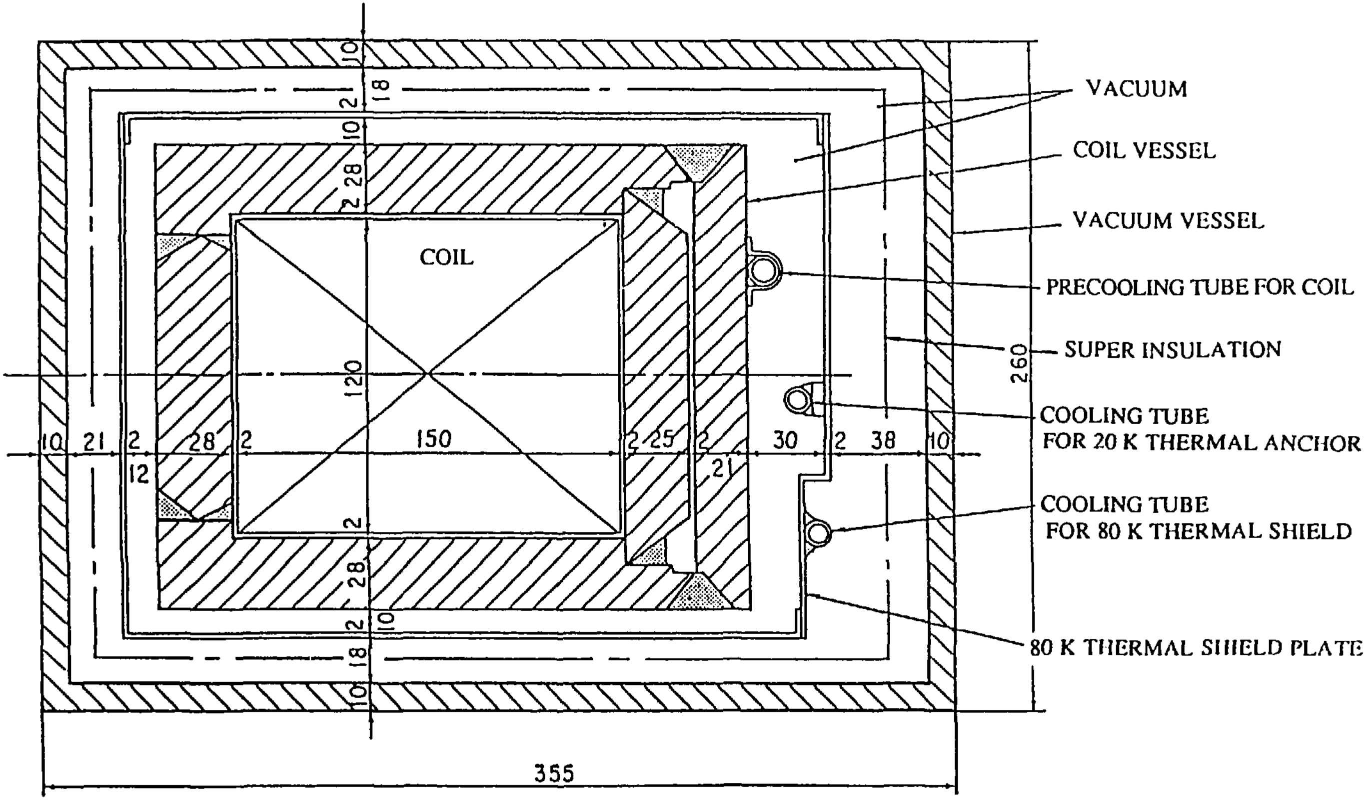

Fig. 4 Cross sectional drawing of the cryostat

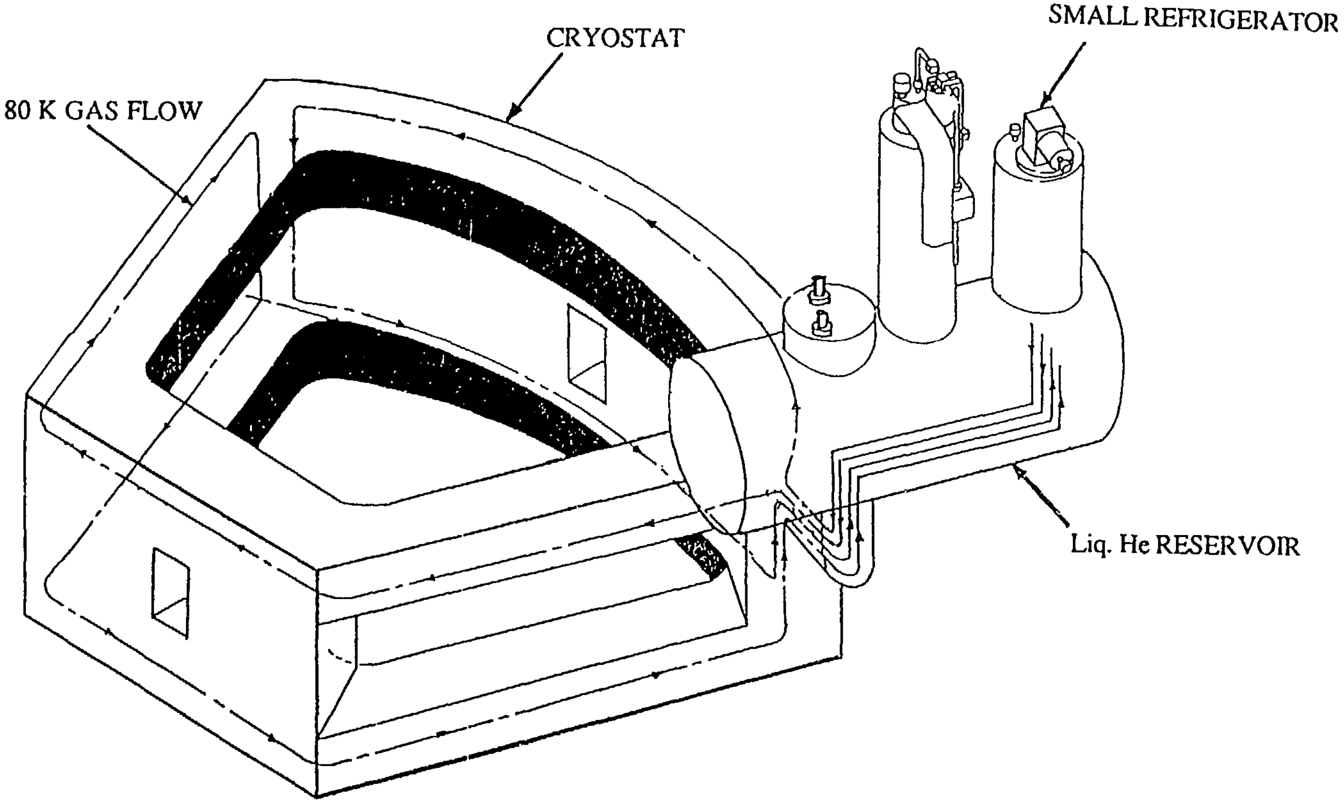

Fig. 5 Helium gas flow line for 80 K thermal shield

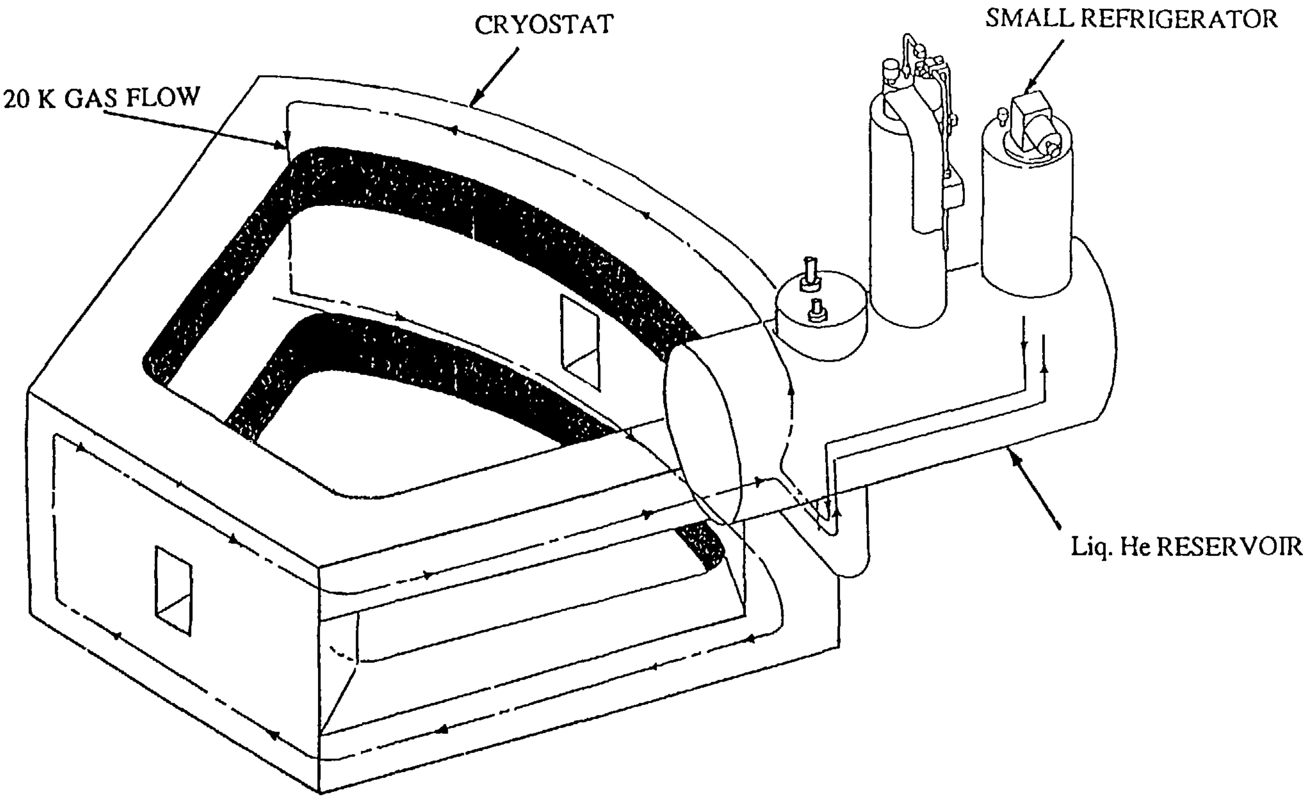

Fig. 6 Helium gas flow line for 20 K thermal anchor

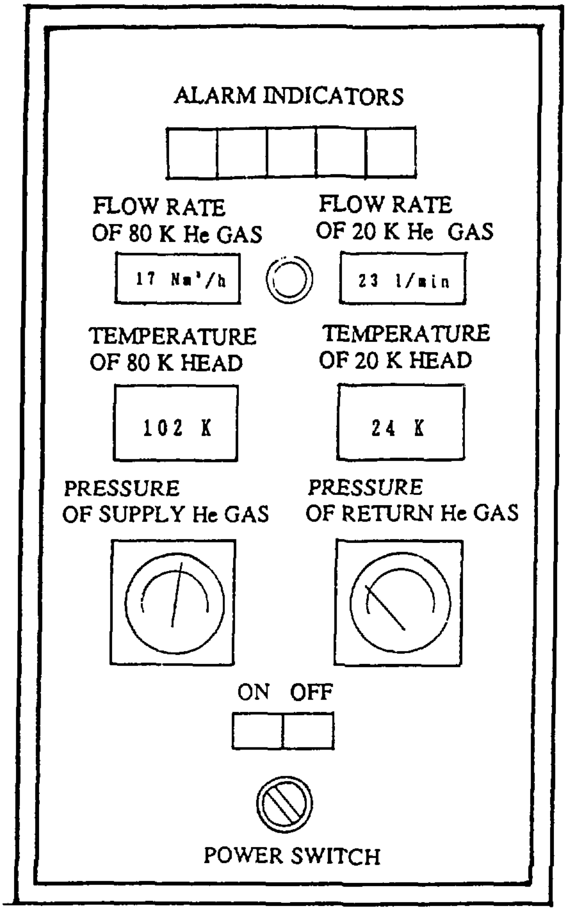

Fig. 7 Monitor unit box

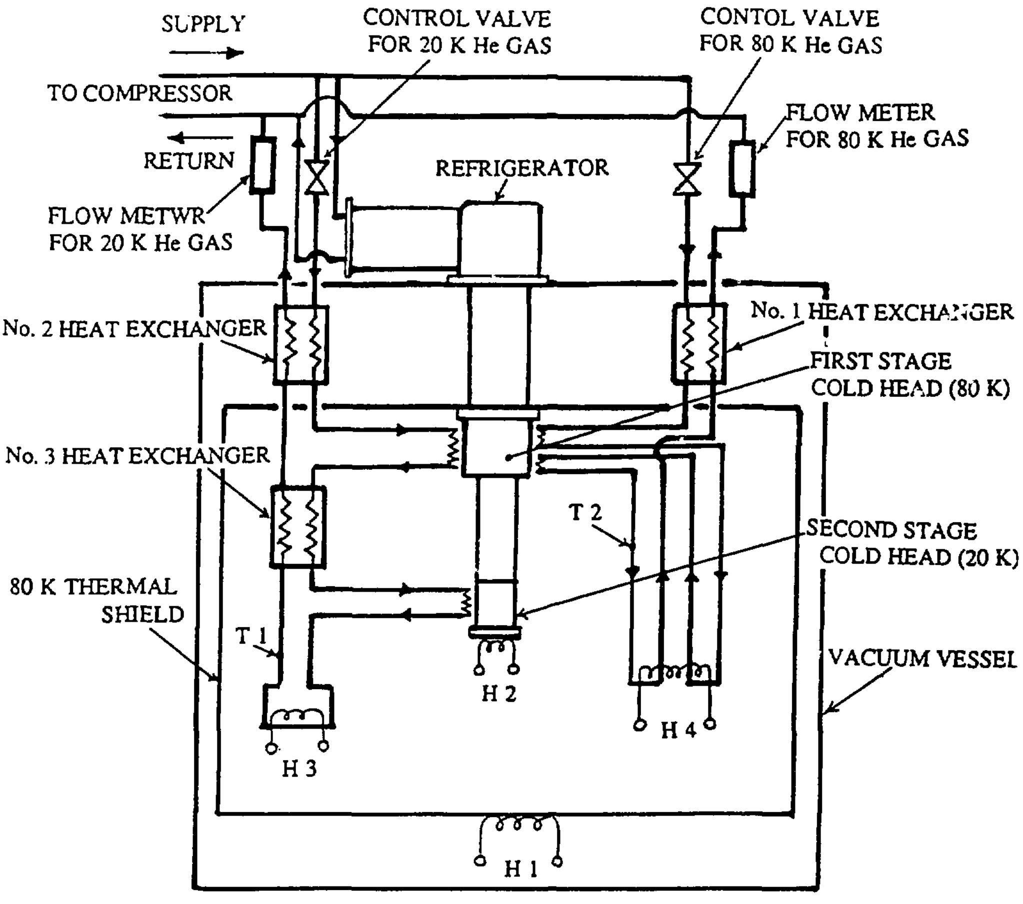

Fig. 8 Schematic diagram for testing the cooling power with the dummy load

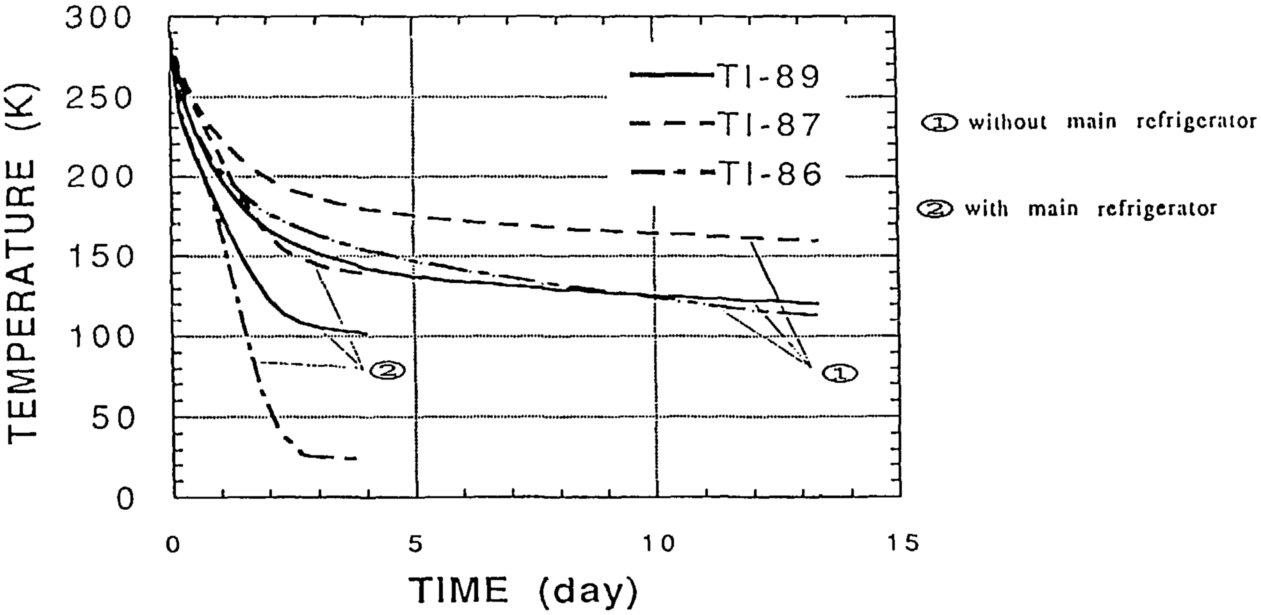

Fig. 9 Cool-down characteristics for 80 K cold head (TI-89), thermal shield (TI-87) and 20 K anchor (TI-86)

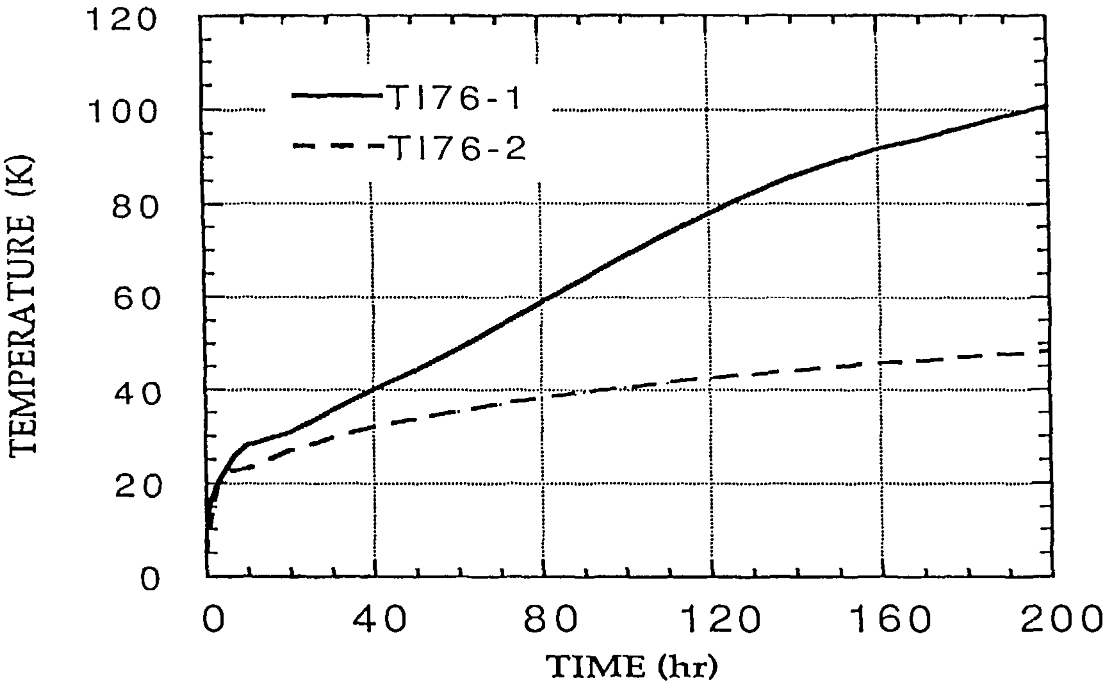

Fig. 10 Warm-up characteristics for coil vessel with (TI76-1) and without (TI76-2) utilizing shield refrigerator