Fermilab

SDC SOLENOID DESIGN NOTE #192

TITLE: Automatic Refrigerator Control Systems in KEK

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DATE: Dec. 10, 1992

This design note is one of a series which represents the proceedings of the SDC solenoid subgroup meeting held in Japan on December 8-11, 1992. The plan and purpose of the meeting was to:

- Look at the prototype coil winding and honeycomb vessel R&D in Japan
- Reports of technical progress from each group
- Plan and schedule for the prototype magnet assembly and test
- Discussions on design of the SDC solenoid power supply
- **Discussions on cryogenic design for the SDC solenoid**
- Discussions on responsibilities for the cryogenics fabrication
- Response to the report of the DOE review sub-committee
- Publications and presentations of the technical progress

SDC Solenoid Subgroup Meeting in Japan

Automatic Refrigerator Control Systems in KEK

Y. Makida (KEK)

Dec. 10, 1992

SDC SUPERCONDUCTING MAGNET SUBGROUP MEETING IN JAPAN
8 - 11, dec. , 1992

CONTROL SYSTEM OF KEK PHYSICS CRYOGENICS

- Development of full-automatic operations of He liquefaction systems and refrigerators for superconducting magnets.

Y. MAKIDA (KEK)

Development of Automatic Operation for He Liquefaction System or Refrigerator

1st Step --- Cryogenic System For Tristan Detectors (1987)

- Centum (Yokogawa Elect.Co.) Were Introduced As The Direct Digital Control System
- Automatic Controls In Each Mode, Ex. Compressor Start, Precooling, Magnet Quench And Warming-up.
- Each Mode Starts By Manual Operation.

2nd Step --- Liquefaction System In The East Counter Experimental Hall (1989)

- A Direct Digital Control System Replaced The Analog Controllers.
- Full-automatic Control System Has Been Completed For The Liquefying Operation.

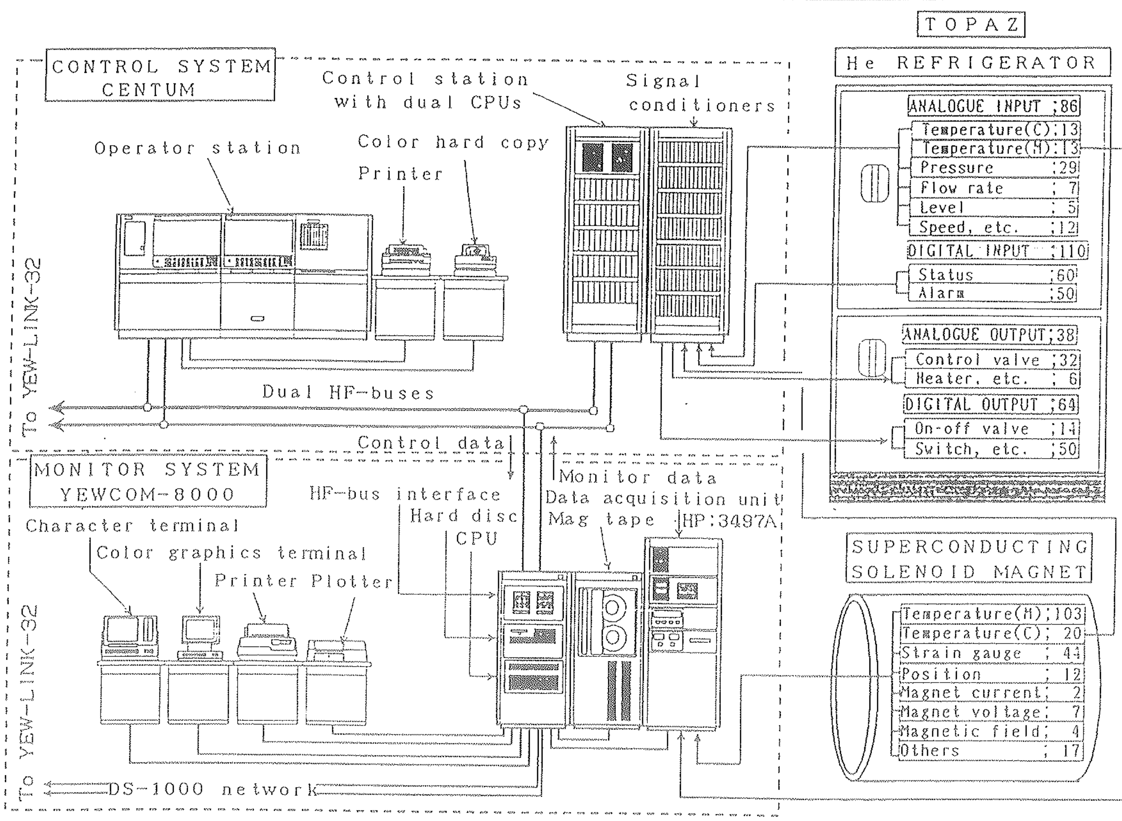
3rd Step --- Cryogenic System For Sks Spectrometer (1991)

- Based On The Software Developed In 1st And 2nd Steps, a Full-automatic Control System For A Superconducting Magnet (Sks : Superconducting K-ion Spectrometer) Has Been Completed.
- Centum-xl (Yokogawa Elect. Co.) Was Introduced.

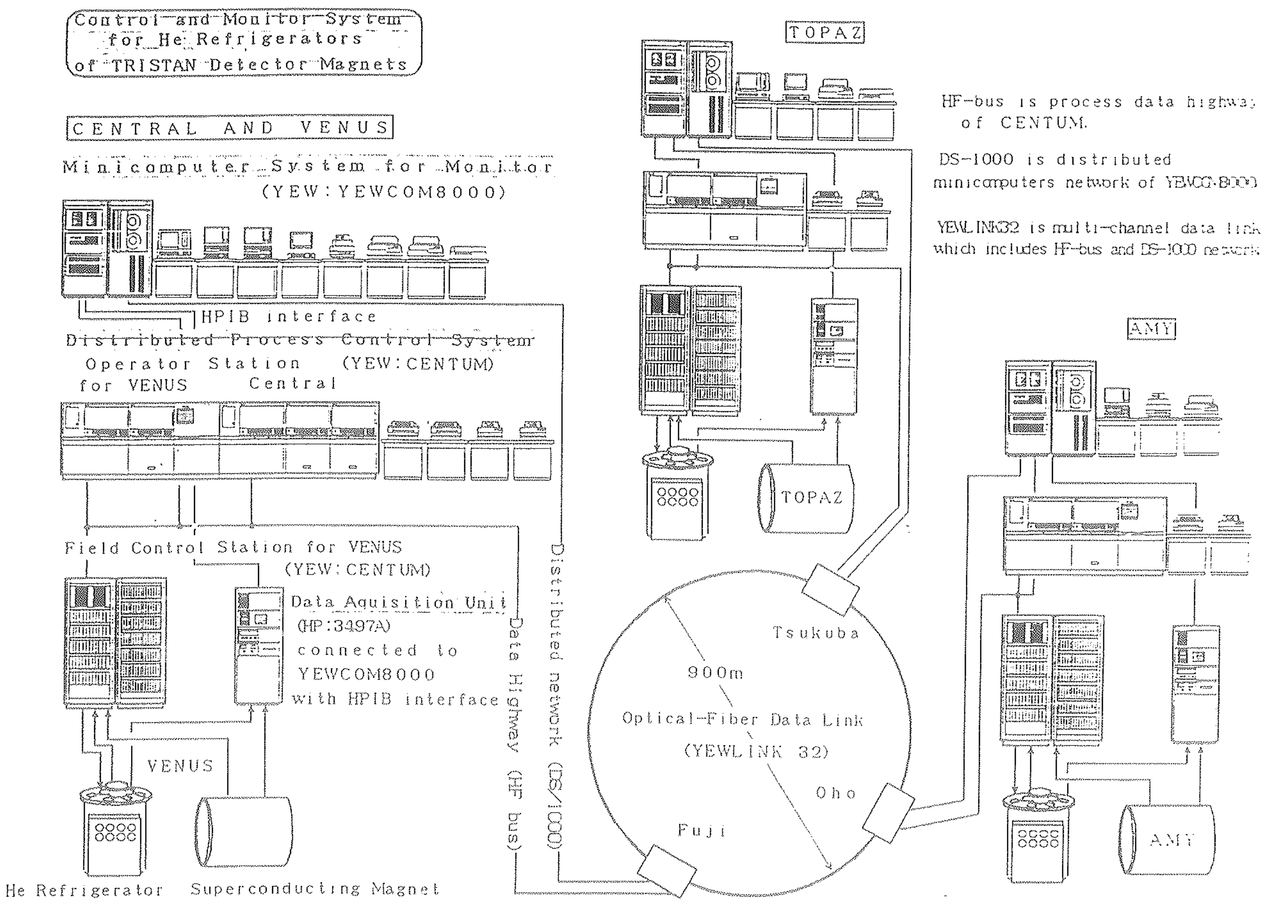
1st Step ---- Cryogenic System for TRISTAN Detectors

- A CENTUM system (Produced by YOKOGAWA Electric.Co) was introduced for each cryogenic facility of each ditector magnet as a direct digital control system.
- A YOWCOM process computer (YOKOGAWA)was intorduce to control a data acquisition unit and to analize magnet characteristics.
- Important analog or digital signals for control are directly scanned by the CENTUM. While other many signals, which are not referred to feed back loop, are connected into the data acquisition system.
- The CENTUM and the YOWCOM exchange their data through a local network "HF-bus". So operators, who normally are in front of operator stations of the CENTUM, can monitor signals gathered by the YOWCOM.
- Three conyrol unit composed by the CENTUM and the YOWCOM for each cryogenic system comunicate each other through an optical fiber data link (YEWLINK32). Normally operators stay in the Fuji experimental site and remotely keep watch every three cryogenic facilities.
- Software of the CENTUM writen by C-language. Programers need not modefy it, but just input parameters or tables.
- Many sequences has been developed to make operation more reliable and easy. Most sequences don't start automatically but are triggerd by operator 's command.

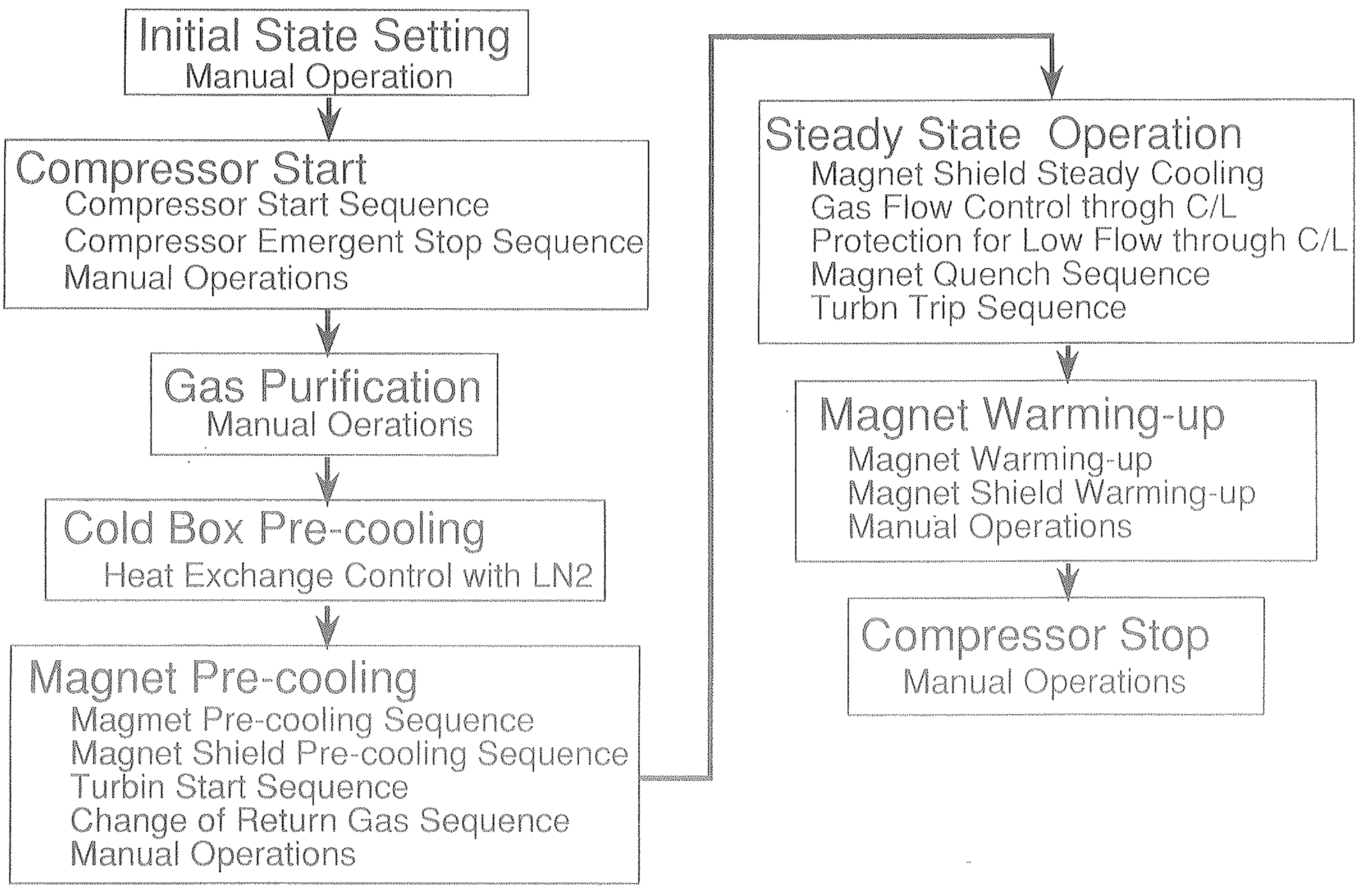
Control and Monitor System for TOPAZ Cryogenic System



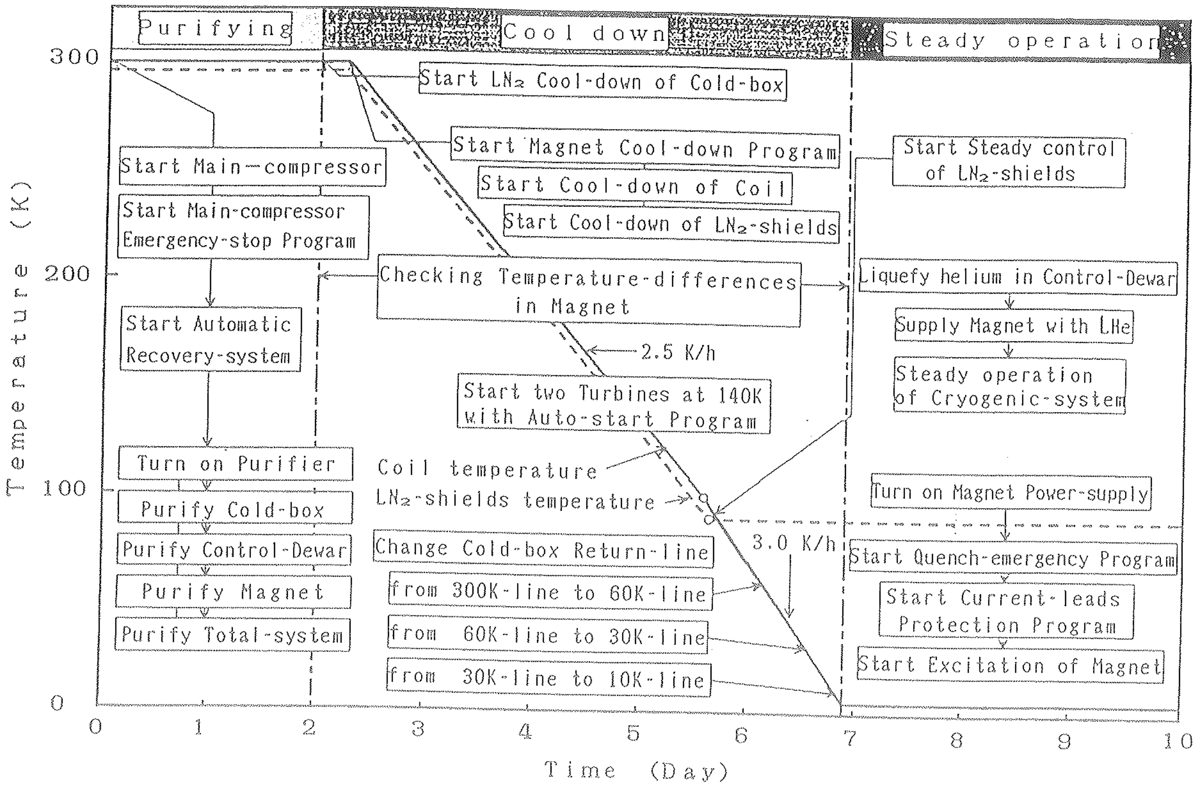
HF-bus is process data way of CENTUM. DS-1000 is mini-computers network of YEWCOM-8000.
YEW-LINK-32 is multi-channel data link which includes HF-bus and DS-1000 network.


Control and Monitor System for He Refrigerators of TRISTAN Detector Magnets
CENTRAL AND VENUS
Minicomputer System for Monitor
(YEW:YEWCOM8000)
HPIB interface
Distributed Process Control System
Operator Station (YEW:CENTUM)
for VENUS
Central
Field Control Station for VENUS
(YEW:CENTUM)
Data Aquisition Unit
(HP:3497A)
connected to
YEWCOM8000
with HPIB interface
VENUS
He Refrigerator
Superconducting Magnet
Data Highway (HF bus)
Distributed network (DS/1000)
TOPAZ
TOPAZ
HF-bus is process data highway of CENTUM.
DS-1000 is distributed minicomputers network of YEWCOM-8000
YEWLINK32 is multi-channel data link which includes HF-bus and DS-1000 network
AMY
AMY
Tsukuba
900m
Optical-Fiber Data Link
(YEWLINK 32)
Oho
Fuji

Flowchart of the Control System for TRISTAN Detector

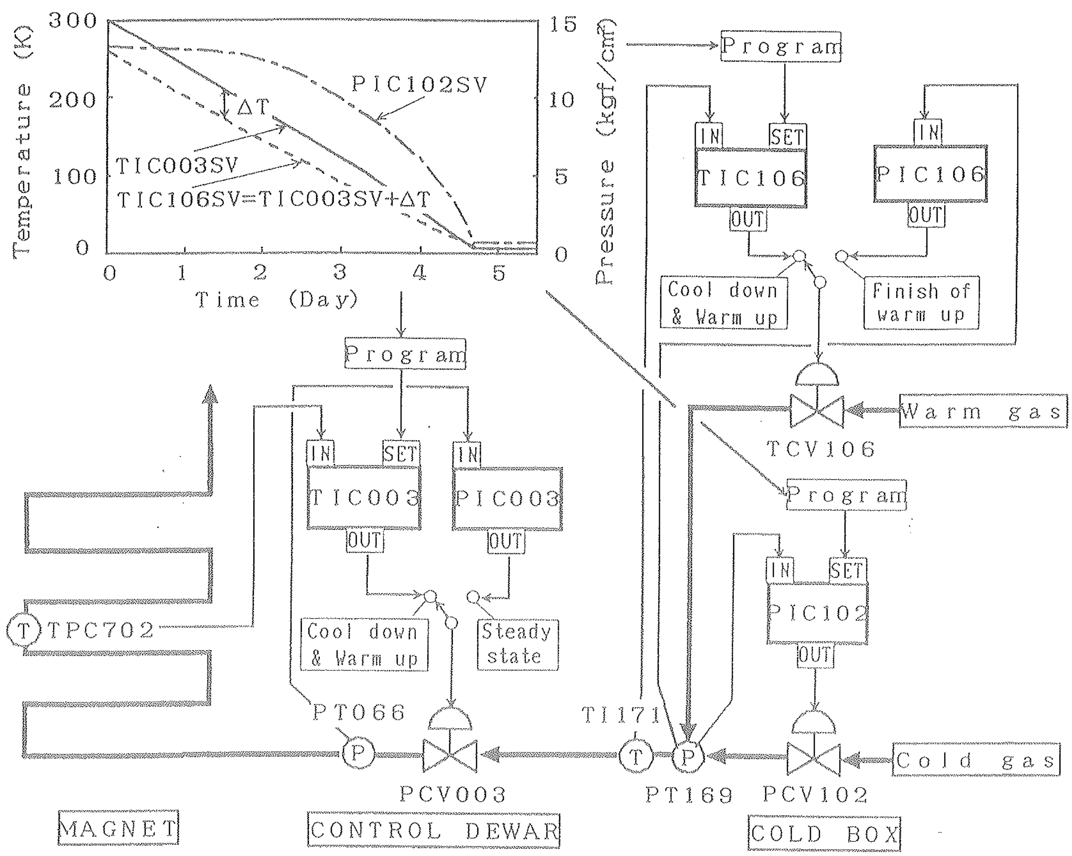


Example of Sequence (1) Pre-cooling

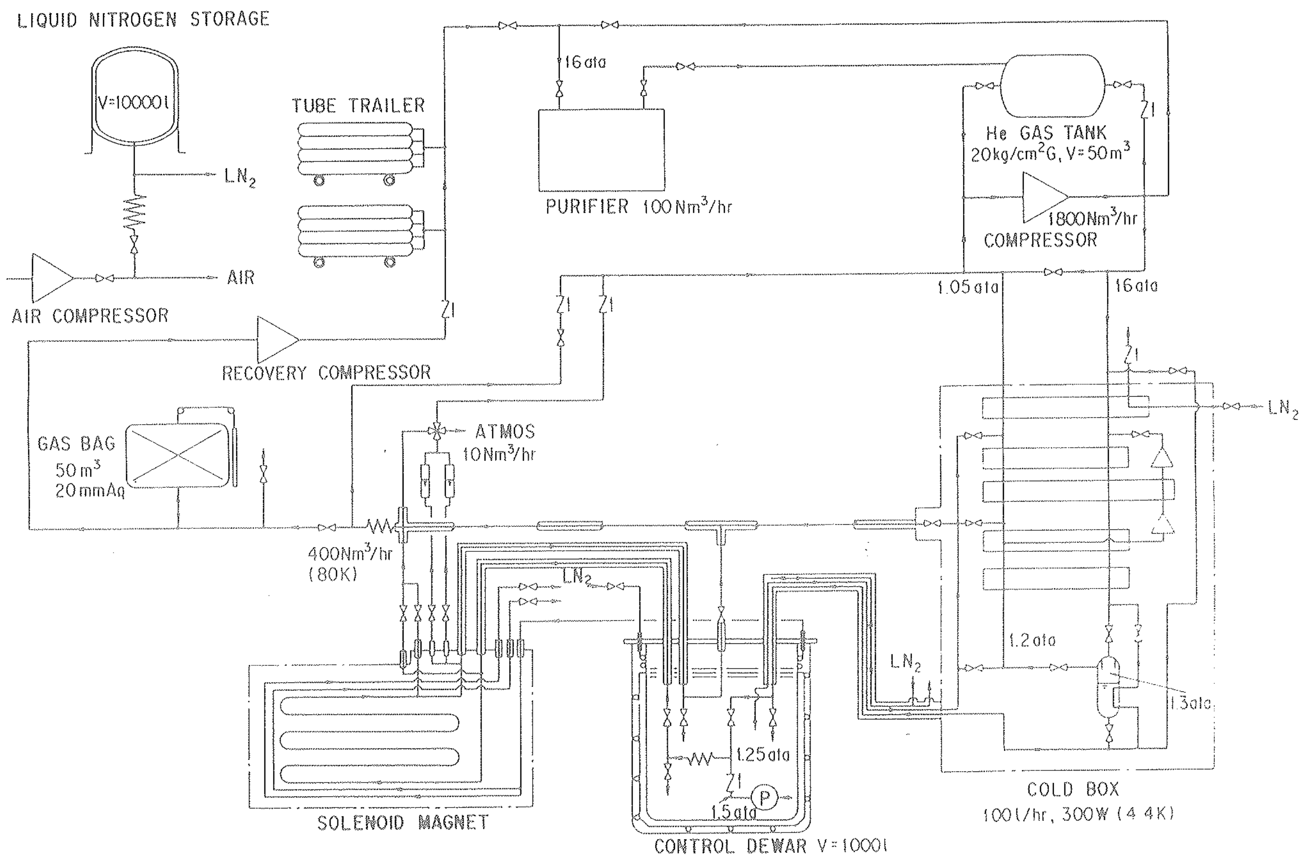


TOPAZ CRYOGENIC SYSTEM OPERATIONAL FLOWCHART

Example of Sequence (1) Pre-cooling



Example of Sequence (1) Pre-cooling

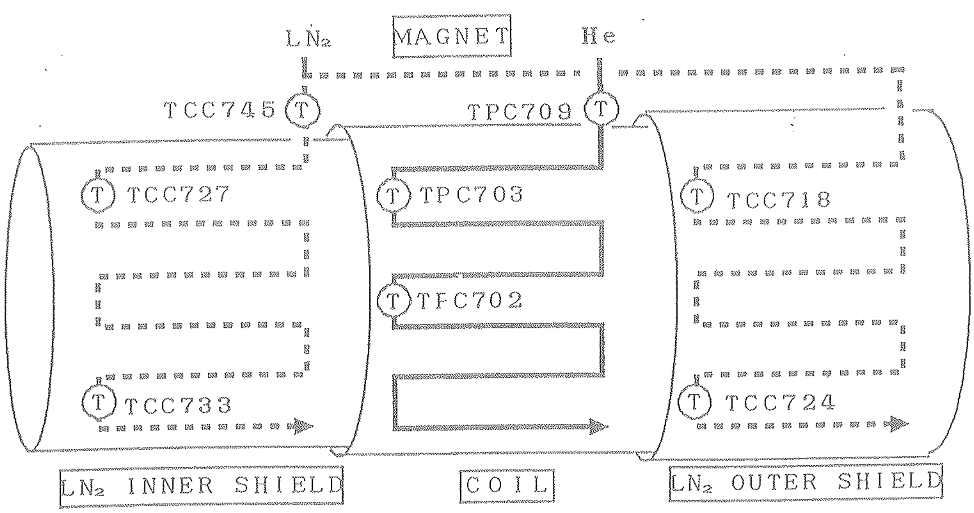


CRYOGENIC SYSTEM OF THE TOPAZ SOLENOID MAGNET

Example of Sequence (1) Pre-cooling

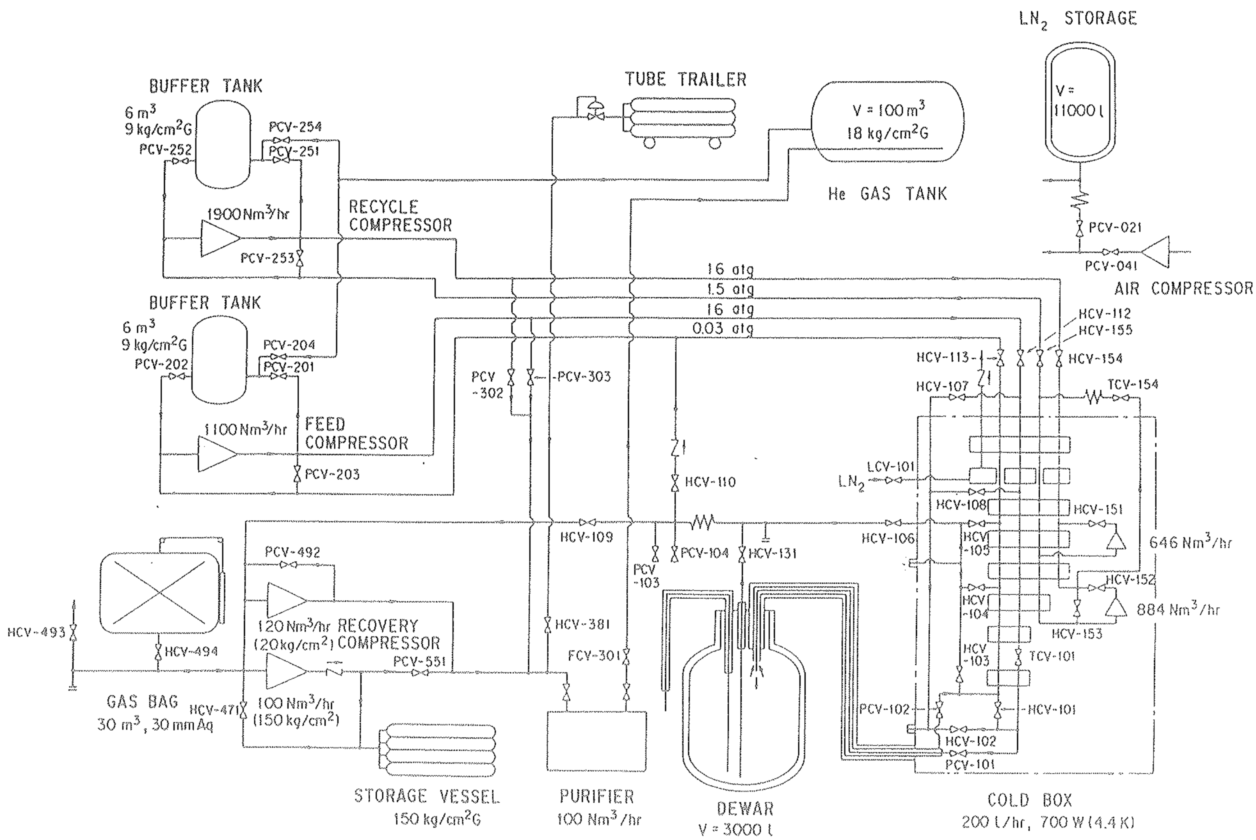
Program pause conditions

DN724=ABS (TCC724-TPC702) >40K (LN₂-outer-shield & Coil)
DN733=ABS (TCC733-TPC702) >40K (LN₂-inner-shield & Coil)
DT702=ABS (TPC702-TPC703) >30K (Coil-middle & Coil-in)
DT703=ABS (TPC703-TPC709) >60K (Coil-in & He-gas-in)
DT724=ABS (TCC724-TCC718) >40K (LN₂-outer-shield in & out)
DT733=ABS (TCC733-TCC727) >40K (LN₂-inner-shield in & out)
DT718=ABS (TCC718-TCC745) >60K (LN₂-shield in & N₂-gas-in)
ABS (TIC003PV-TOC003SV) >5K (TIC003 ±DV)



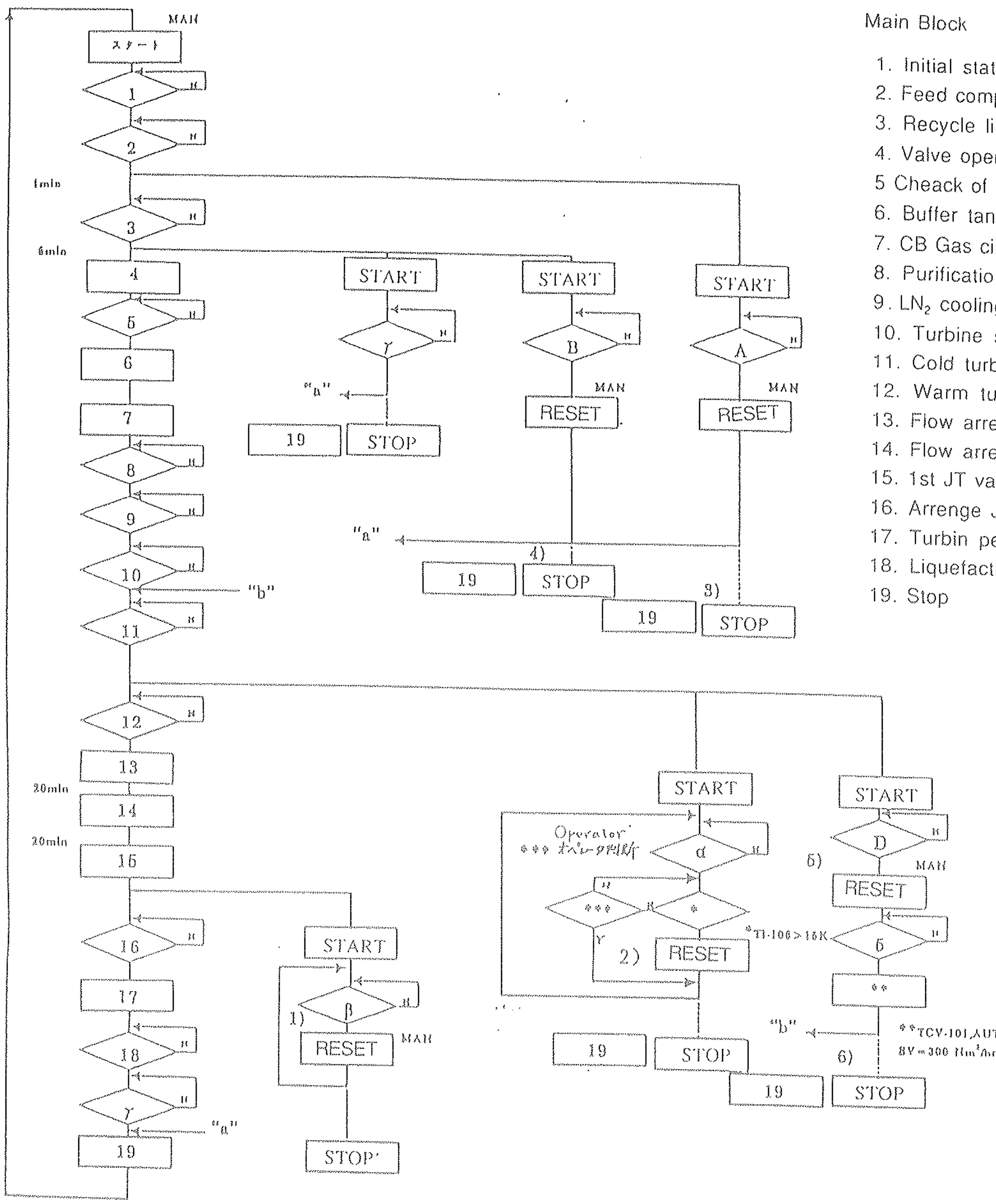
2nd step --- Liquefaction System in the East Counter Experimental Hall

- Full-automatic control software for the liquefying operation has been completed.



He Liquefaction System in the Counter Experimental Hall

Flowchart of the full automatic operation of He liquefation System



Main Block

1. Initial states setting
2. Feed compressor start
3. Recycle line vo,pressor dtart
4. Valve operation
5 Cheack of recycle line
6. Buffer tank setting
7. CB Gas circulation
8. Purification of system
9. LN_2 cooling
10. Turbine start ready
11. Cold turbine start
12. Warm turbine start
13. Flow arrenge in feed line (1)
14. Flow arrenge in feed line (2)
15. 1st JT valve hold
16. Arrenge JT flow
17. Turbin performance up
18. Liquefaction
19. Stop

Supplemental function

α. Protect of lower temeprature at turbine
β. Protect of high round speed of turbine
γ. Necessary condition to stop

Annotations

1) Control by round speed is resetted.
2) Automatic control is resetted and MV is kept.
3),4)When (1 9) starts, both A and B stop.
5)The inter-lock of turbine is restted at the local panel.
6)When (1 9) starts, the subroutine stops.

Emergent stop mode

A. Emergent stop of the compressor in the feed line
B. Emergent stop of the compressor in the recycle line
D. Turbine trip

3rd Step -- Cryogenic System for SKS Spectrometer

- Based on the software developed in 1stand 2nd steps, full-automatic cnotrol software for the cryogenic system for the superconducting magnet has been completed.
- Magnet data which are not directly reffered in control loops are gathered by an engineering work station (HP9000.)

Table 1. Main specification of SKS cryogenic systems

Middle-size refrigerator:		
Type of refrigerator		Claude cycle
Cold box:	Refrigeration	300 W at 4.5 K (Using LN_2)
		180 W at 4.5 K (Without LN_2)
	liquefaction rate	100 L/hr (Using LN_2)
		40 L/hr (Without LN_2)
Compressor:	Type	Screw compressor
	Flow rate	1,400 Nm^3/hr
LN_2 Storage		10,000 L
G-M refrigerator:	Refrigeration	6 W at 20 K + 60 W at 80 K
Magnet:	Cooling method	Pool boiling
	LHe Capacity	156 L
	Cold mass	4.5 ton (SUS, Cu)
	Thermal load	5 W + 1.5 L/hr
	Cooling down time	50 hours
	Central field	3 T
	Current	498 A

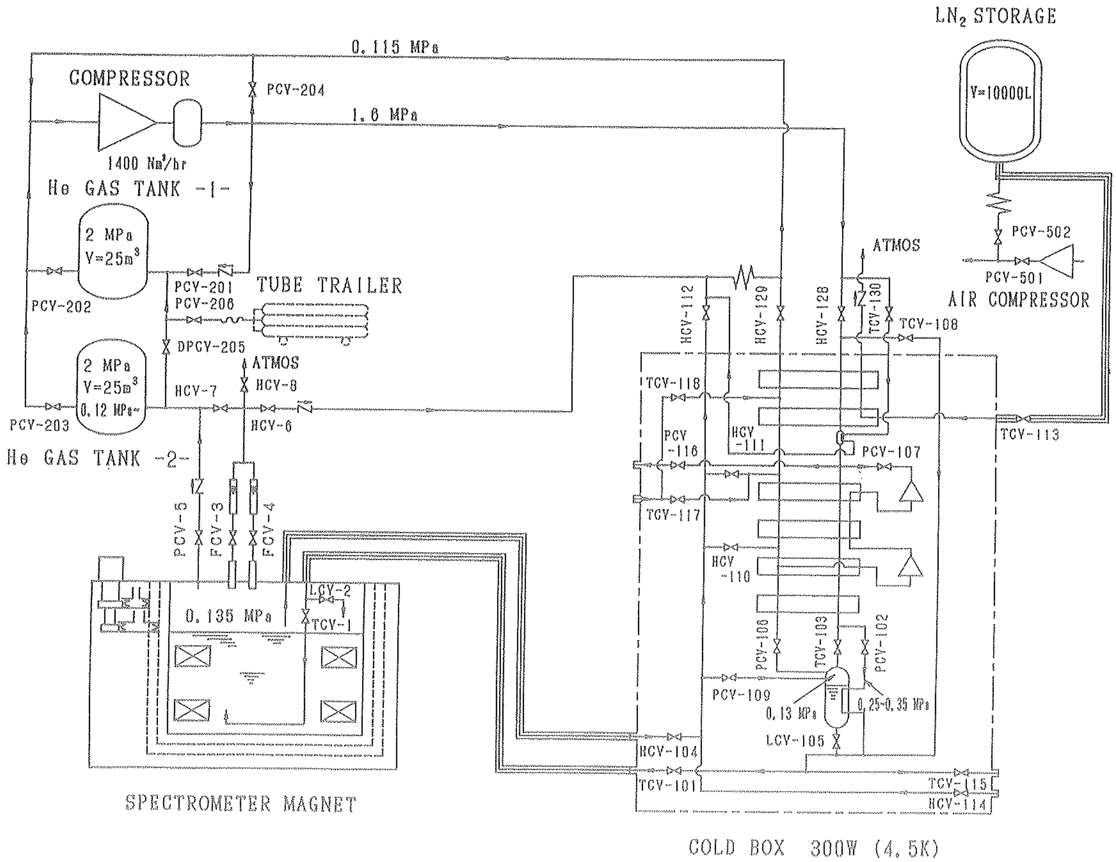
Special features for the SKS cryogenic systems

1) To measure angular distributions of reaction particles, the magnet was requested to be **rotatable around a target**. For this request, the helium transfer lines have **the rotatable mechanism.**

2) To diminish the number of transfer lines having rotatable mechanism, the magnet adopted small size **G-M refrigerator on the yoke** to cool the thermal radiation shields and thermal anchor instead of liquid nitrogen.

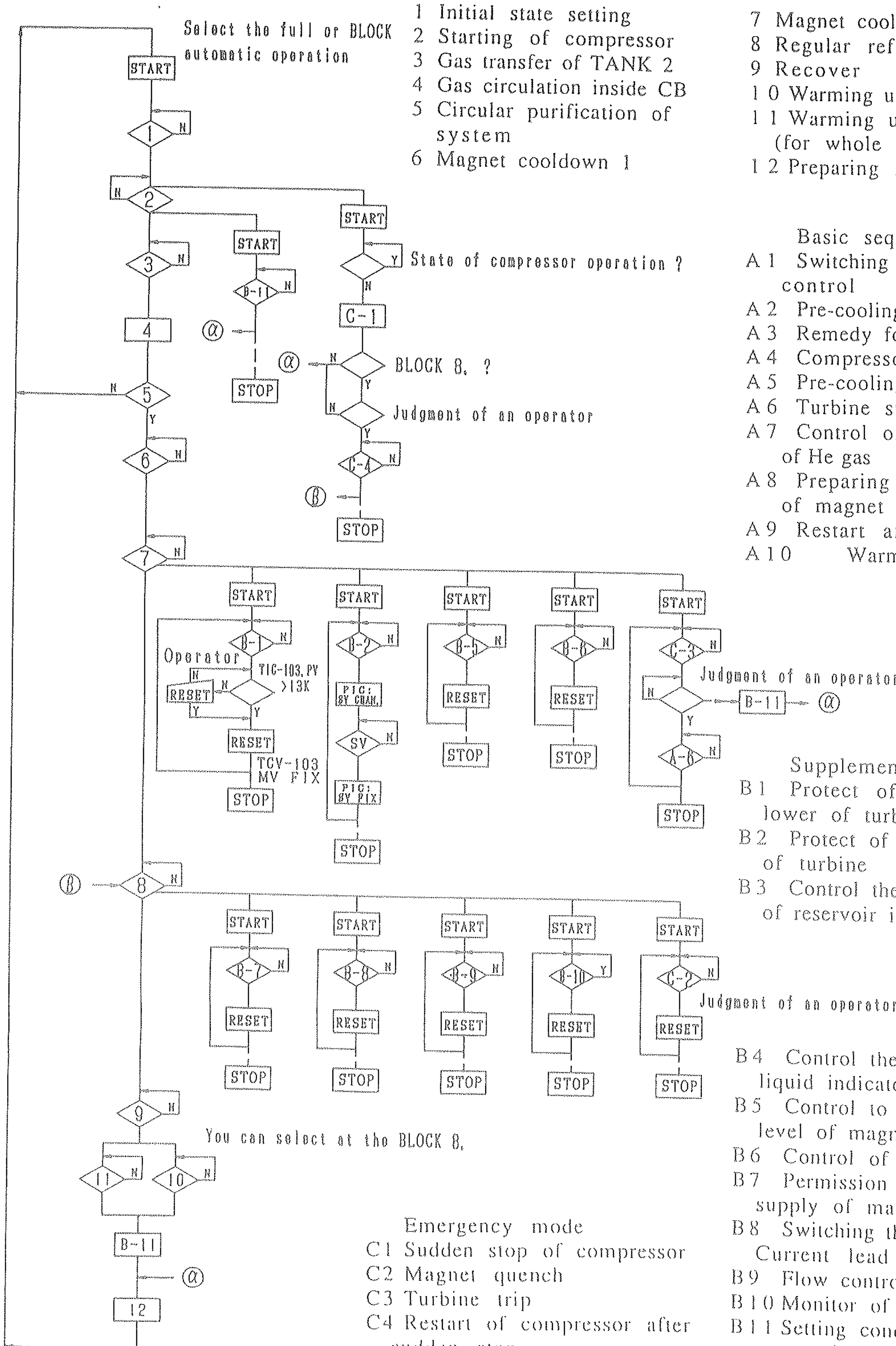
3) The small size G-M refrigerator is effective also to **suppress the raise of magnet temperature** during the rest period of experiment without the cooling by the middle-size refrigerator.

4) All cryogenic systems are **controlled and operated full automatically** from beginning of cooling down to the end of warming up, easily and safely.



Cryogenic System of the SKS Magnet

Flowchart of the full automatic operation



Main Block

1 Initial state setting
2 Starting of compressor
3 Gas transfer of TANK 2
4 Gas circulation inside CB
5 Circular purification of system
6 Magnet cooldown 1
7 Magnet cooldown 2
8 Regular refrigeration made
9 Recover
10 Warming up 1 (for CB only)
11 Warming up 2 (for whole systems)
12 Preparing for stop

Basic sequence

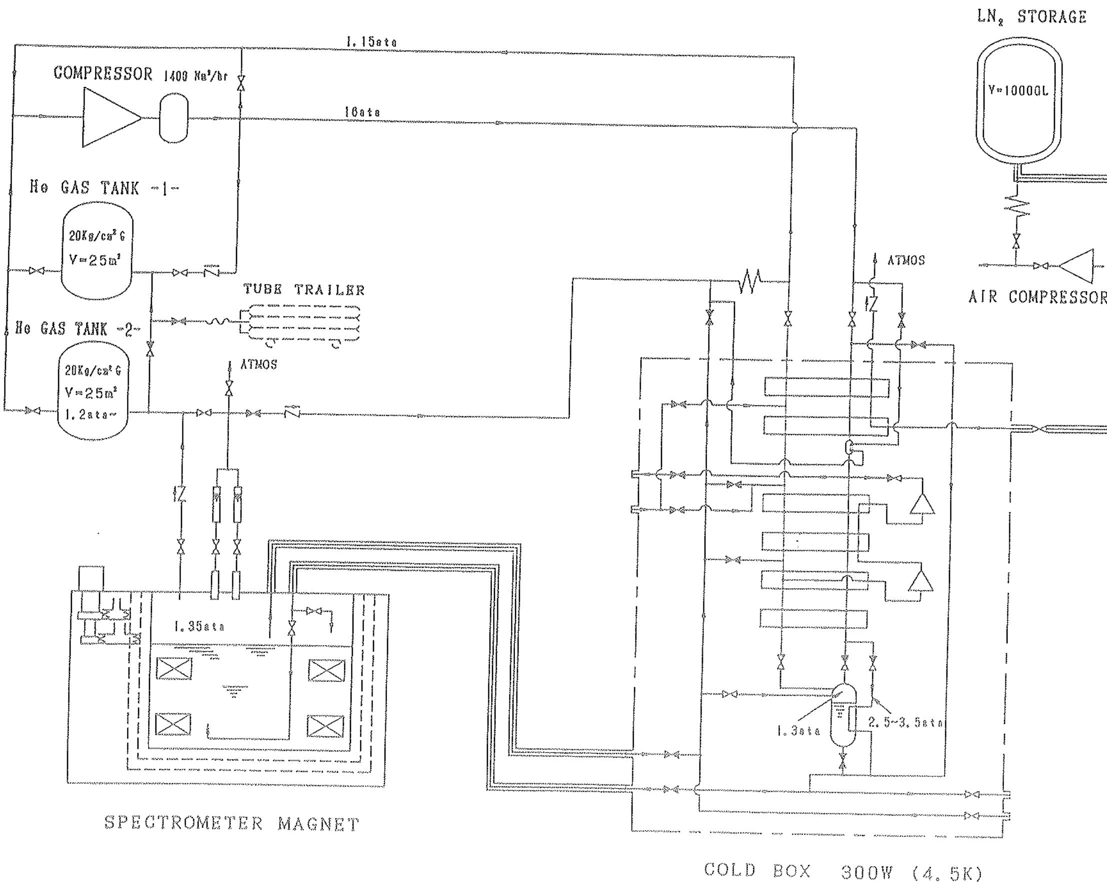
A1 Switching air and GN for control
A2 Pre-cooling by LN
A3 Remedy for non fine gas
A4 Compressor stop
A5 Pre-cooling of magnet
A6 Turbine start and atop
A7 Control of returning rote of He gas
A8 Preparing for movement of magnet
A9 Restart after movement
A10 Warming up of magnet

Supplemental function

B1 Protect of temperature lower of turbine
B2 Protect of round speed high of turbine
B3 Control the liquid level of reservoir inside CB
B4 Control the power supply of liquid indicator of magnet
B5 Control to maintain liquid level of magnet
B6 Control of turbine power
B7 Permission for power supply of magnet
B8 Switching the flow of Current lead
B9 Flow control of current lead
B10 Monitor of G-M refrigerator
B11 Setting condition to finish operating

Emergency mode

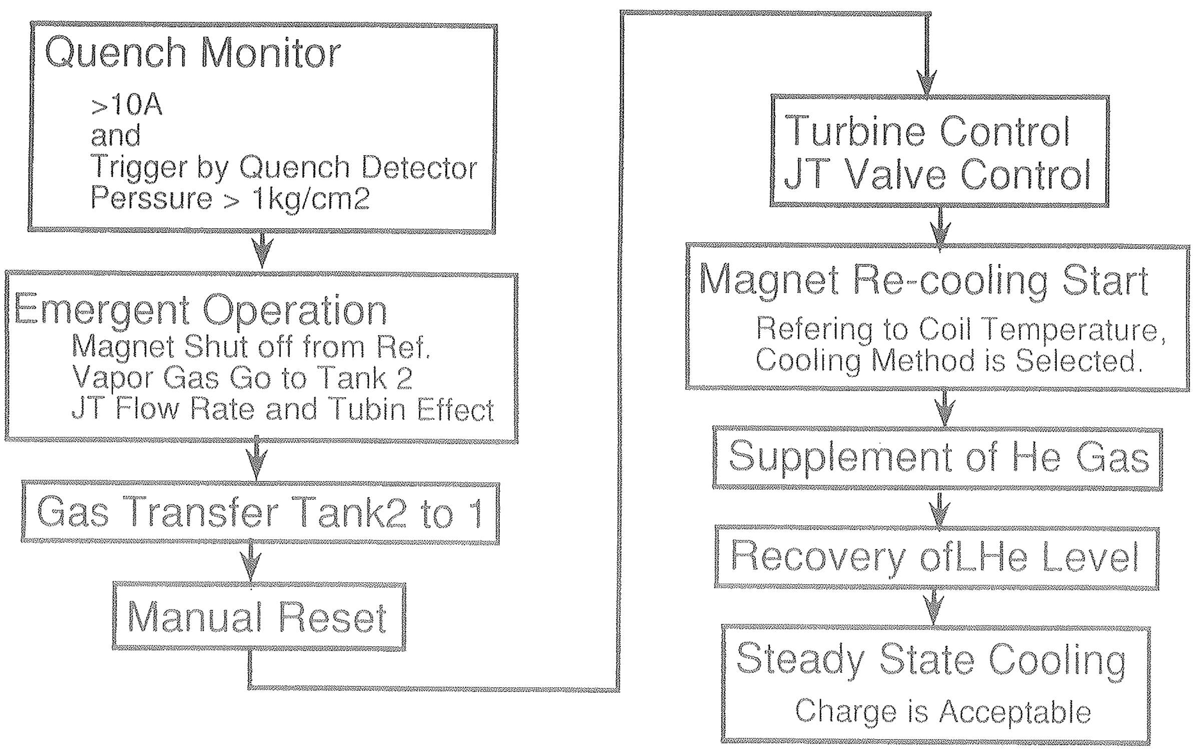
C1 Sudden stop of compressor
C2 Magnet quench
C3 Turbine trip
C4 Restart of compressor after sudden stop

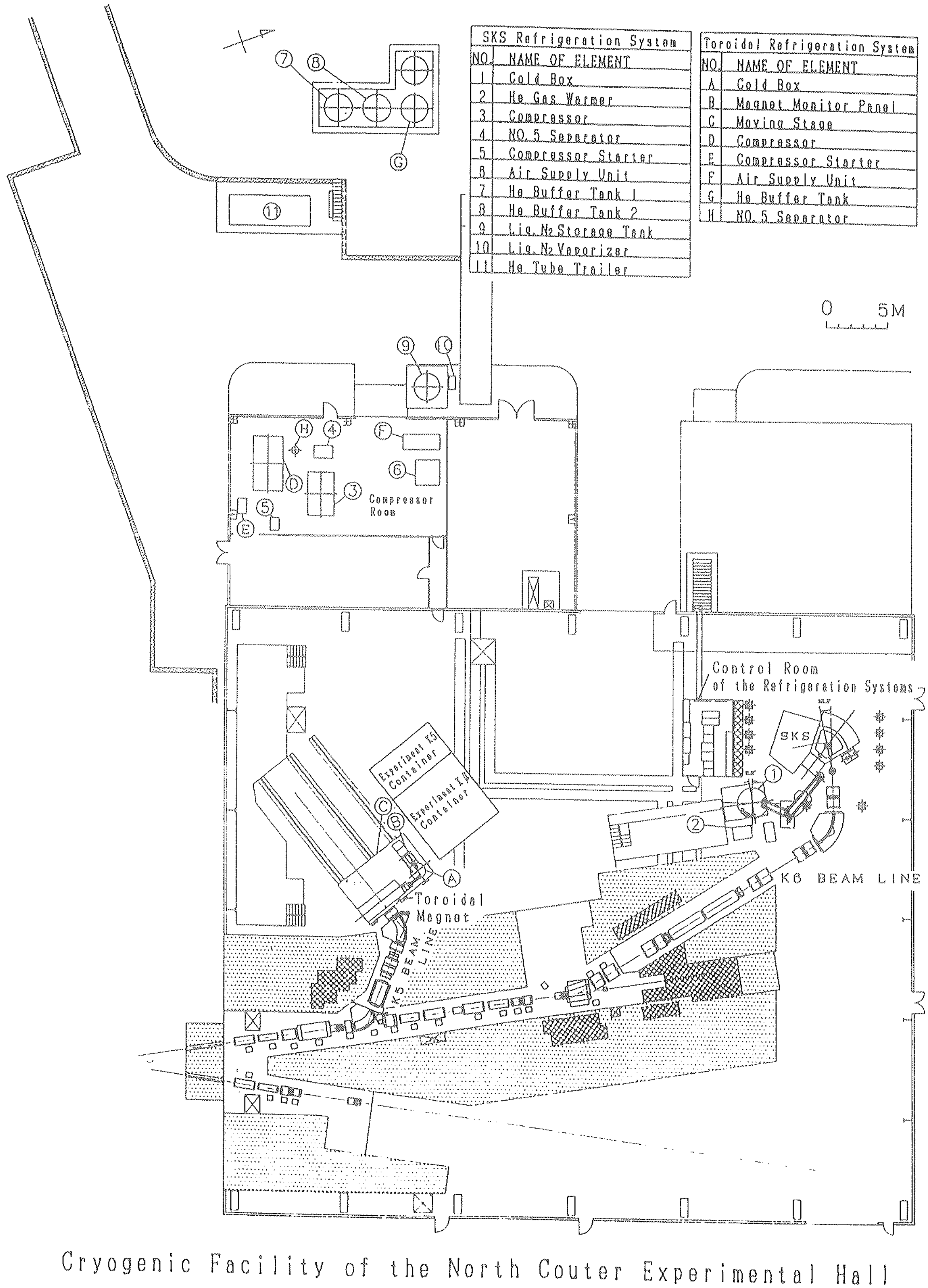


Cryogenic System of the SKS Magnet

Example of Sequence (2)

Magnet Quench Sequence





SKS Refrigeration System	
NO.	NAME OF ELEMENT
1	Cold Box
2	He Gas Warmer
3	Compressor
4	NO. 5 Separator
5	Compressor Starter
6	Air Supply Unit
7	He Buffer Tank 1
8	He Buffer Tank 2
9	Liq. N_2 Storage Tank
10	Liq. N_2 Vaporizer
11	He Tube Trailer

Toroidal Refrigeration System	
NO.	NAME OF ELEMENT
A	Cold Box
B	Magnet Monitor Panel
C	Moving Stage
D	Compressor
E	Compressor Starter
F	Air Supply Unit
G	He Buffer Tank
H	NO. 5 Separator

Cryogenic Facility of the North Couter Experimental Hall

Main specifications of the SKS refrigeration system

Type of refrigerator		Claude cycle
Cold box :	Refrigeration	300 W at 4.5 K (Using LN_2)
		180 W at 4.5 K (Without LN_2)
	Liquefaction rate	100 L/hr (Using LN_2)
		40 L/hr (Without LN_2)
Compressor :	Type	Screw compressor
	Flow rate	1,400 Nm^3/hr
G-M refrigerator :		
	Refrigeration	6 W at 20 K + 60 W at 80 K
LN_2 Storage		10,000 L
Magnet :		
	Cooling method	Pool boiling
	LHe Capacity	156 L
	Cold mass	4.5 ton (SUS,Cu)
	Thermal load	5 W + 1.5 L/hr
	Cool down time	50 hours

PERFORMANCES OF CRYOGENIC SYSTEMS FOR A LARGE SUPERCONDUCTING SPECTROMETER MAGNET - SKS

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ABSTRACT

Cryogenic systems for large superconducting spectrometer magnet SKS was designed and constructed at KEK for nuclear physics experiments. These systems are composed of two helium gas tanks, a middle-size refrigerator, transfer lines with the rotatable mechanism according to the magnet rotation, and from -10 degrees to +40 degrees rotatable superconducting magnet combined with a small-size G-M refrigerator cooling thermal shields. For the magnet, pool boiling method was taken. The middle-size refrigerator send single phase helium gas in supercritical state through transfer line to the magnet and after J-T valve of the magnet side helium changes the state to two phase of liquid and gas at 4.5 K. All cryogenic systems are controlled and operated full automatically according to the programed steps from the beginning of cooling down to the end of warming up. The most recent cooling test proved the middle-size refrigerator had refrigeration capability of 350 W with liquid nitrogen pre-cooling at 4.5 K, the rotatable mechanism of transfer lines could rotate smoothly according to the rotation of the magnet and automatic control system worked safely enough, and at last the magnet attained 2.9 T at central field.

INTRODUCTION

For the study of π, K and other meson reactions at 1 GeV/c region, new spectrometer with high momentum resolution and large solid angle is required. A superconducting kaon spectrometer SKS was designed and constructed for these purposes and was set at K6 secondary beam line of 12 GeV proton synchrotron in KEK. All cryogenic systems for SKS were designed and constructed to cool down and warm up the magnet smoothly and maintain safely during cooling period including magnet excitation.

In designing the systems, the following points were taken into account and devised.

1) To measure angular distributions of reaction particles, the magnet was requested to be rotatable around a target. For this request, the helium transfer lines have the rotatable mechanism.
2) To diminish the number of transfer lines having rotatable mechanism, the magnet adopted small size G-M refrigerator on the yoke to cool the thermal radiation shields and thermal anchor instead of liquid nitrogen.
3) The small size G-M refrigerator is effective also to suppress the raise of magnet temperature during the rest period of experiment without the cooling by the middle-size refrigerator.
4) All cryogenic systems are controlled and operated full automatically from beginning of cooling down to the end of warming up, easily and safely.

CRYOGENIC SYSTEMS OVERVIEW

Figure 1 is a flow diagram of the cryogenic systems. The systems consist of two helium gas tanks, a helium compressor, a cold box, transfer lines with the rotatable mechanism, liquid nitrogen storage tank, which compose the middle-size refrigerator, and spectrometer magnet with a small G-M refrigerator. Helium gas, compressed to 1.6 MPa, flows into the cold box and the temperature becomes 6 K before J-T valve inside the cold box. After J-T valve, the pressure of expanded helium gas becomes 0.3 MPa. Passing through the flow line inside the liquid reservoir of cold box, the temperature of the single phase helium gas becomes lower. In this point, the state of helium is supercritical. After flowing through transfer line, at the inlet of superconducting magnet, second J-T valve makes helium into two phase state of 0.135 MPa at 4.5 K to cool the magnet. The returning two phase helium from the magnet flows through an another transfer line and enters into the liquid reservoir inside the cold box to help to cool the input single phase helium as previously described. The boil off helium from the liquid reservoir returns to the compressor. Other flows from the magnet are used to cool current leads. The returning flow route after cooling of current leads can take a route from three candidates. One route is an usual returning route to the compressor and other two routes, to the atmosphere and to the helium gas tank 2, are selected when the emergency occurred as the magnet quench. These operations of valves are selected properly and controlled automatically from computers.

The G-M refrigerator on the magnet yoke cools the thermal radiation shield of 80 K and the thermal anchors of 20 K and 80 K at the magnet separately from the control of the middle-size refrigerator.

The main specifications of SKS cryogenic systems are listed in Table 1.

HELIUM GAS TANKS, COMPRESSOR AND COLD BOX

The middle-size refrigerator has two helium gas tanks. Both have a volume of 25 m^3 and the specification of pressure inside tank is 1.96 MPa. Each tank is called as tank 1 or tank 2. The tank 1 is used as a buffer tank of the compressor and the tank 2 is used to recover a large amount of gas from the magnet when the quench occurred.

The compressor is an oil lubricated two-stage screw type and has five oil separators. Especially the fifth oil separator was newly set to remove the moisture from the system, which contains 300 kg molecular sieve 13X.

The cold box is a vertical-type vessel and houses the inner adsorber, six stages of the heat exchangers, valves, two gas-bearing turbo-expanders

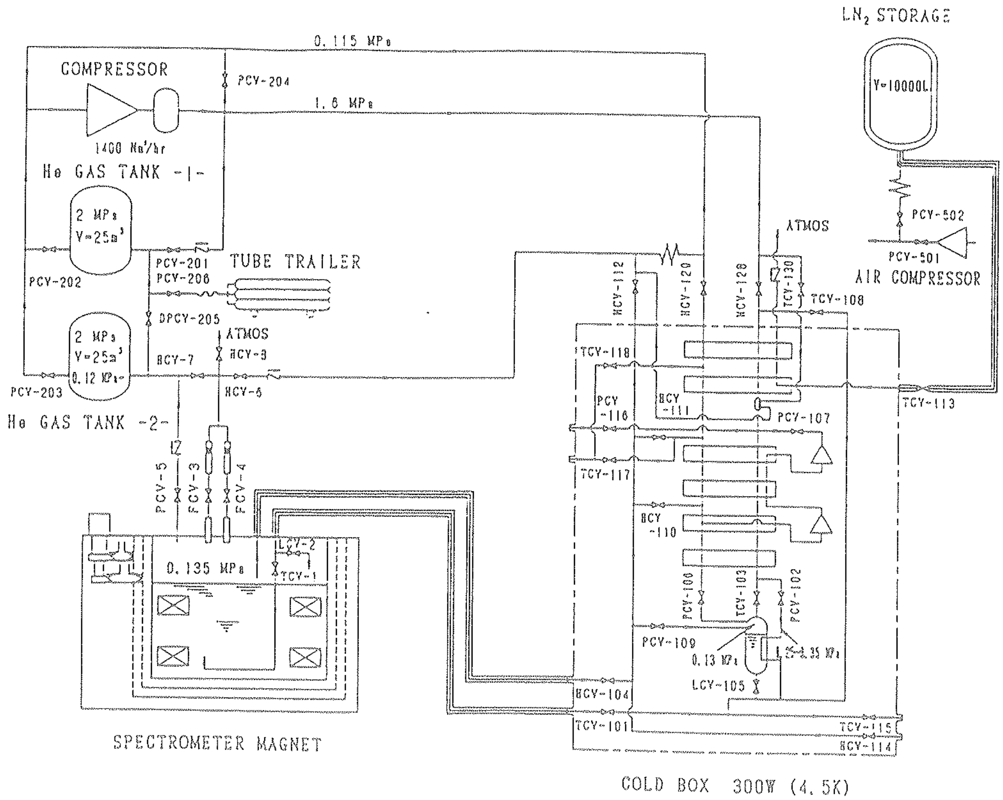

Figure 1. Cryogenic Systems of the SKS Magnet

Table 1. Main specification of SKS cryogenic systems

Middle-size refrigerator:		
Type of refrigerator		Claude cycle
Cold box:	Refrigeration	300 W at 4.5 K (Using LN_2)
		180 W at 4.5 K (Without LN_2)
	liquefaction rate	100 L/hr (Using LN_2)
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	Flow rate	1,400Nm^3/hr
LN_2 Storage		10,000L
G-M refrigerator:		
	Refrigeration	6 W at 20 K + 60 W at 80 K
Magnet:		
	Cooling method	Pool boiling
	LHe Capacity	156 L
	Cold mass	4.5 ton (SUS, Cu)
	Thermal load	5 W + 1.5 L/hr
	Cooling down time	50 hours
	Central field	3 T
	Current	498 A

arranged in series and liquid helium reservoir [illegible] exchanger inside. The inner adsorber was adopted [illegible] refine helium gas. Liquid nitrogen from storage [illegible] circular purification of systems, which can promote [illegible] adsorber, and used in succession during cooling down of the magnet. After liquefaction in the cryostat of the magnet, supply of liquid nitrogen to the cold box stops. The subsequent regular refrigeration mode doesn't use liquid nitrogen.

TRANSFER LINES

Since the magnet is requested to be rotatable around the target, the helium transfer lines must have the rotatable mechanism too. Figure 2 shows the cross section of rotary coupling of transfer line. By two ball bearings, bayonet joint of an inner transfer pipe can rotate smoothly according to the rotation of the magnet. This mechanism was set in the middle of transfer lines. Figure 3 shows the transfer lines with rotary coupling and the supporting stage.

MAGNET AND G/M REFRIGERATOR

The SKS superconducting magnet is a sector type magnet with an iron yoke. The total weight of magnet and yoke amounts to almost 300 ton. The magnet has transpositioner systems by the air at the four corners of the bottom of yoke and can float within 1 cm height from the floor level to rotate smoothly around the target from -10 degrees to +40 degrees. The magnet took pool boiling method and has liquid helium capacity of 156 L. The pressure of specification for the liquid reservoir of the cryostat is 0.69 MPa. If the quench occurs and all liquid helium of the magnet is recovered to the helium gas tank 2 via phase transition, assuming that the initial state of tank 2 has 0.04 MPa at 15 C, the raise of pressure in the tank 2 is only 0.45 MPa and the total pressure is still under the specification of the liquid reservoir of the cryostat.

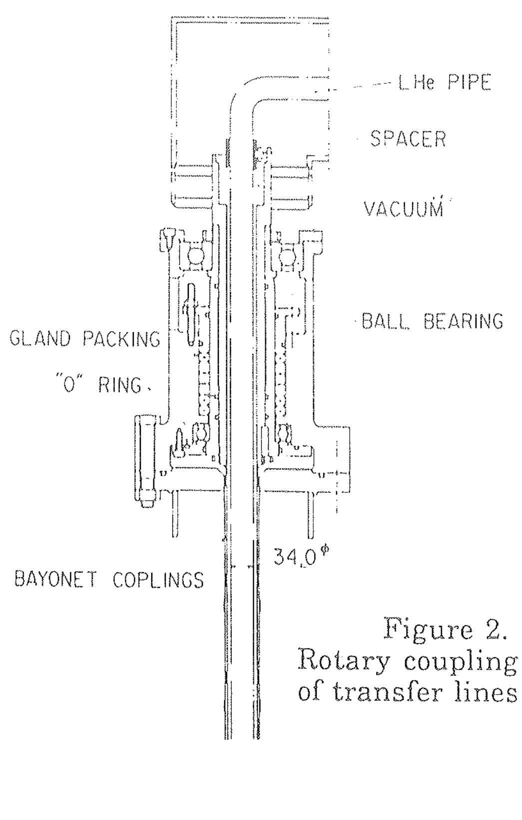


Figure 2.
Rotary coupling
of transfer lines

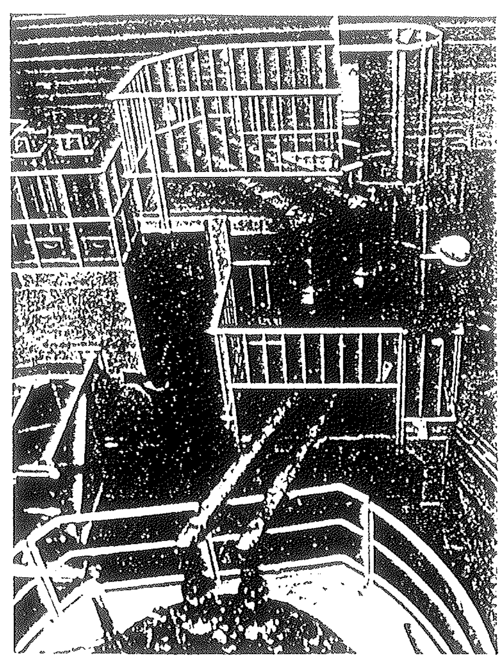


Figure 3 Transfer Lines

The G-M refrigerator on the iron yoke involves compressor by itself and uses helium gas without the frequent supply. The use of G-M refrigerator is favorable to diminish the number of transfer lines having the rotatable mechanism which would be necessary if liquid nitrogen were used for cooling, and to suppress the raise of magnet temperature to minimum by using it when the middle-size refrigerator is separated from the magnet by valves and stops cooling during the rest period between the experiment and next experiment. As the result, the cooling time of the magnet down to 4.5 K can be reduced. This operation mode is convenient for the beam schedules of the accelerator.

CONTROL SYSTEM

For the control of cryogenic systems, by the request that any operator who is not necessarily an expert of cryogenic systems can control and operate easily and safely, the full automatic control system was developed.

The systems are composed of two parts. One is a large process control system, YOKOGAWA CENTUM-XL, consists of an operator station with two operator consoles, an engineering work station to develop the program, a printer, a color hard-copy unit, I/O control stations and a gate way unit. CENTUM-XL monitors almost all data from cryogenic systems other than some data from the magnet and controls whole systems during cooling down, warming up and emergency mode. The operator station has MC68020 for main processor, 8 Mbytes memory, 80 Mbytes harddisk and 3.5 inch floppy disk drive. The system has 105 DDC loops, 18 graphic pages, 48 historical trend pages (sampling interval: 60 sec) and 16 realtime trend pages (sampling interval: 10 sec) for the control of SKS. The number of process input/output signal are listed in Table 2. The other is SKS magnet monitor system which consists of HP9000 360CH$^+$ work station, 323 Mbytes harddisk, 133 Mbytes cartridge tape drive, a printer and HP3852S data logger. This system monitors the residual data from the magnet which are unnecessary to control by CENTUM-XL and communicates with CENTUM-XL through the gate way unit. By this communication, SKS magnet monitor system sends data to CENTUM-XL to be referred on the operator console and get important data from CENTUM-XL to print out regularly and to record data in 323 Mbytes harddisk. The purposes of development of SKS magnet monitor system are to help CENTUM-XL by independent sampling of data which is unnecessary for control and to analyze data flexibly.

In the development of software program, simple and safety were most important points. The program is composed of four groups of sequences.

1) Main blocks: constituting main part of the control flow.
2) Basic sequences: having continuous actions and being called from main blocks.
3) Supplemental functions: being called from main blocks and monitored in parallel through several blocks.
4) Emergency modes: being monitored in parallel with main blocks. But once the emergency is occurred, the control flow is moved completely to this mode.

A schematic flow diagram of control is showed in Figure 4. The movement of the magnet is chosen at the block 8, an regular refrigeration mode. If once the movement is chosen, the magnet is separated from the cold box by closing the valve PCV-102 until the rotation of magnet finished. (See Figure 1) Operator can choose the warming up method alternatively from block 10, warming up 1, and block 11, warming up 2. Block 10 is a warming up of the

Table 2. Input/output signals of the systems

CENTUM-XL		
Analog input:	72 points	(pressure:20, temperature:34, others:18)
Analog output:	39 points	(control valves:36, heater:1, others:2)
Digital input:	63 points	(status:26, alarms:37)
Digital output:	25 points	(on/off valves:3, others:22)
SKS magnet monitor system		
Analog input:	67 points	(temperature:20, strain:36, others:11)

only cold box, keeping the magnet temperature low. This mode is used for the rest time between the experiment and next experiment keeping cooling the magnet shield by G-M refrigerator. Block 11 is a warming up of whole systems involving the magnet.

From the point of view of safe operation, program has alternative operation modes, full automatic operation and a block operation. A block operation can operate only a block automatically. Operator can choose full automatic operation mode only once at the beginning of programs. To move from full automatic operation mode to a block operation mode can be selected freely at the end of each block. But the contrary is not allowed.

Four accidents were assumed for the emergency mode and the remedies were prepared.
1) Sudden stop of main compressor
2) Magnet quench
3) Turbine trip
4) Restart of main compressor after sudden stop, which is combined with 1).

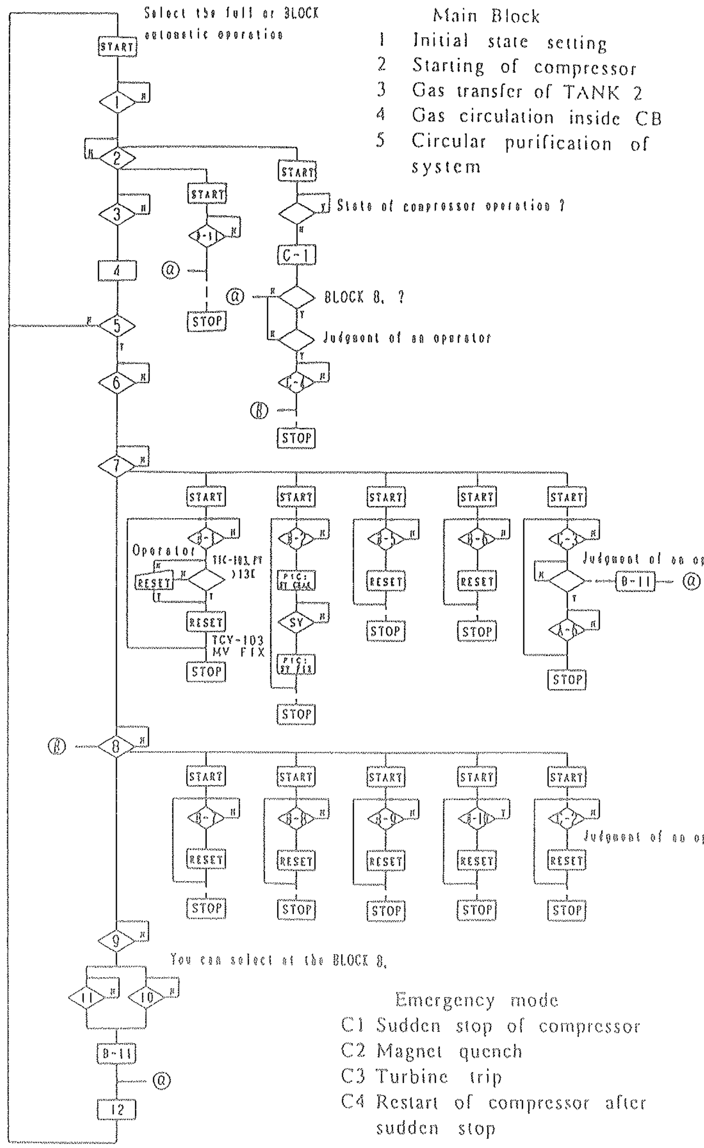
TEST RESULTS

In the most recent cooling test, some good features are obtained. These are listed in Table 3.

In the regular refrigeration mode, cold box sends helium in the two phase state to the magnet by 10 grams per second. By the performed minimum necessity of flow rate, It was realized that helium of 5.5 grams per second returns to the liquid reservoir inside the cold box. Figure 5 shows cooldown curve with using G-M refrigerator for shield cooling and Figure 6 shows temperature raise of the magnet using G-M refrigerator without the middle-size refrigerator.

In the rotation test of magnet from -10 degrees to +40 degrees, both mechanism of transpositioner of magnet and the rotary coupling of transfer lines were proved to work smoothly and safely enough.

The operation by the full automatic control was checked and examined in derail. Finally the system was confirmed to work safely enough through cooling down, regular refrigeration, warming up and emergency modes. For the emergency modes, following recovery times were needed.



Main Block
1 Initial state setting
2 Starting of compressor
3 Gas transfer of TANK 2
4 Gas circulation inside CB
5 Circular purification of system
6 Magnet cooldown 1
7 Magnet cooldown 2
8 Regular refrigeration made
9 Recover
10 Warming up 1 (for CB only)
11 Warming up 2 (for whole systems)
12 Preparing for stop

Basic sequence
A1 Switching air and GN for control
A2 Pre-cooling by LN
A3 Remedy for non fine gas
A4 Compressor stop
A5 Pre-cooling of magnet
A6 Turbine start and atop
A7 Control of returning rote of He gas
A8 Preparing for movement of magnet
A9 Restart after movement
A10 Warming up of magnet

Supplemental function
B1 Protect of temperature lower of turbine
B2 Protect of round speed high of turbine
B3 Control the liquid level of reservoir inside CB
B4 Control the power supply of liquid indicator of magnet
B5 Control to maintain liquid level of magnet
B6 Control of turbine power
B7 Permission for power supply of magnet
B8 Switching the flow of Current lead
B9 Flow control of current lead
B10 Monitor of G-M refrigerator
B11 Setting condition to finish operating

Emergency mode
C1 Sudden stop of compressor
C2 Magnet quench
C3 Turbine trip
C4 Restart of compressor after sudden stop

Figure 4. Flowchart of the full automatic controll

Table 3. Performances of SKS cryogenic systems at the cooling test

Cold box of middle-size refrigerator:	
Refrigeration	350 W at 4.5 K (Using LN_2)
	265 W at 4.5 K (Without LN_2)
Refrigeration and liquefaction	150 W + 39 L/hr at 4.5 K (Without LN_2)
Liquefaction	78.5L/hr (Without LN_2)
Magnet:	
Thermal load	5 W
minimum necessity of flow rate	4.5 g /sec

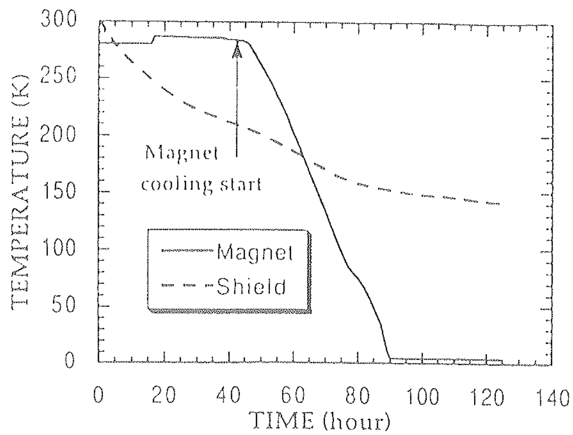


Figure 5. Cooldown curve with using the G-M refrigerator

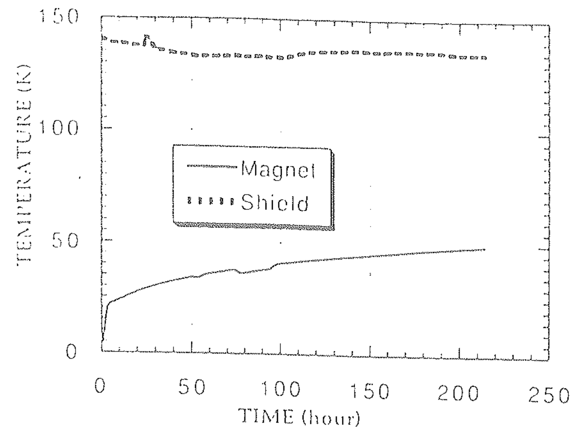


Figure 6. Tenperature raise of magnet using the G-M refrigerator

1) Sudden stop of main compressor and restart after that	6 hr and 25 min
2) Magnet quench	7 hr and 45 min
3) Turbine trip	13 hr and 20 min

In the excitation test of magnet, central magnetic field attained 2.9 T with 460 A before last quench.

SUMMARY

Cryogenic systems for large superconducting spectrometer magnet SKS was designed, constructed and tested. By the test, the refrigeration capability of the middle-size refrigerator was proved to be 350 W with liquid nitrogen pre-cooling at 4.5 K. This figure is pretty good over the specification value. Through the test, the use of G-M refrigerator was proved to be very useful for SKS magnet. In the rotation test of the magnet from -10 degrees to + 40 degrees with the rotary coupling of transfer lines, it was confirmed that there was no trouble and the magnet and transfer lines could rotate smoothly. Through the whole test, full automatic control system was confirmed to be work well and be safe. At last, in the excitation test, the magnet succeed in excitation of magnetic field up to 2.9 T at central field with 460 A. Though the field didn't reach the specification of 3 T at 498 A, it mainly depended on the suppress of time schedule.

ACKNOWLEDGEMENT

The authors would like to express our gratitude to Professors K.Nakai and J.Imazato for their continuous support and encouragement.

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Operation modes for the SDC magnet

1. Normal operation modes.
   ① Initial state setting.
   ② Compressor start.
   ③ Cold box gas circulation.
   ④ Circulating purification of the system.
   ⑤ Magnet cool down. -1-
   ⑥ Magnet cool down. -2-
   ⑦ Steady state operation.
   ⑧ LHe recovery.
   ⑨ Magnet warm up.
   ⑩ Operation stop.

2. Emergency modes.
   C-1.(1) Magnet quench.
   (2) Magnet quench recovery.
   C-2. Compressor emergency stop.
   C-3. Turbine trip - Case 1.
   Turbine trip - Case 2.
   C-4. Flow down of the current leads.

Cryogenic System of the SDC Magnet -1-

(He storage dewar sits on a ground level.)

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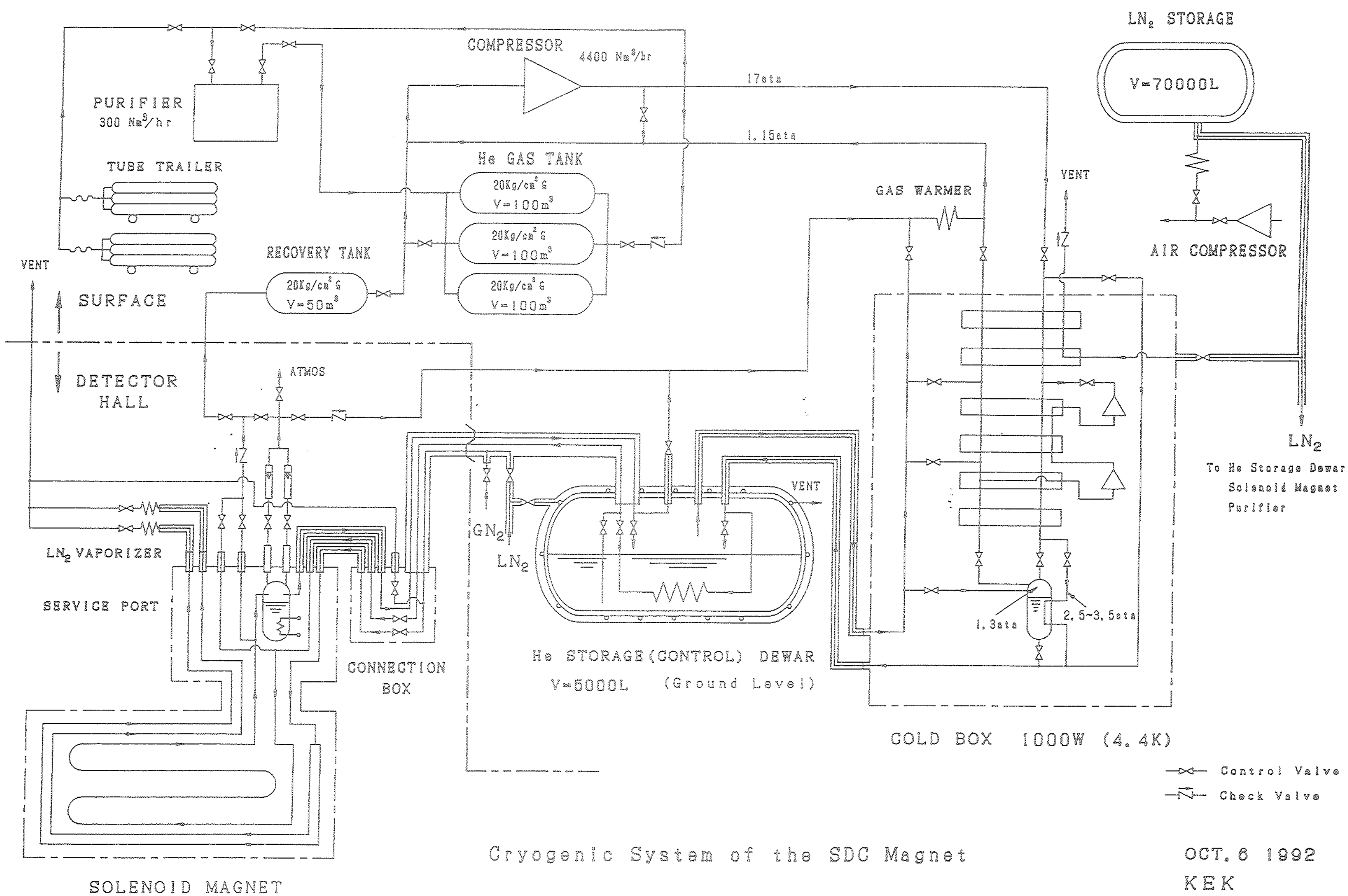

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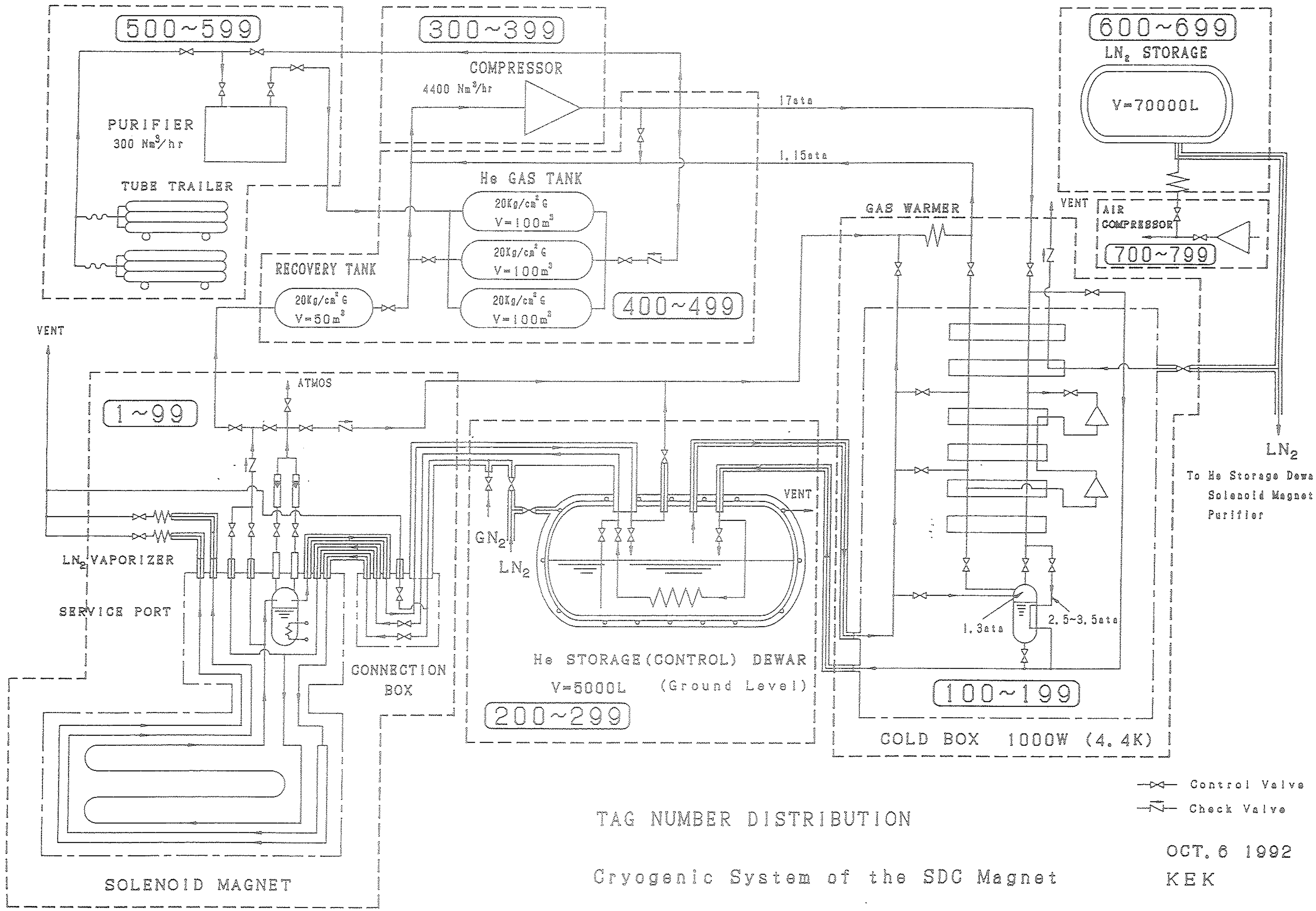

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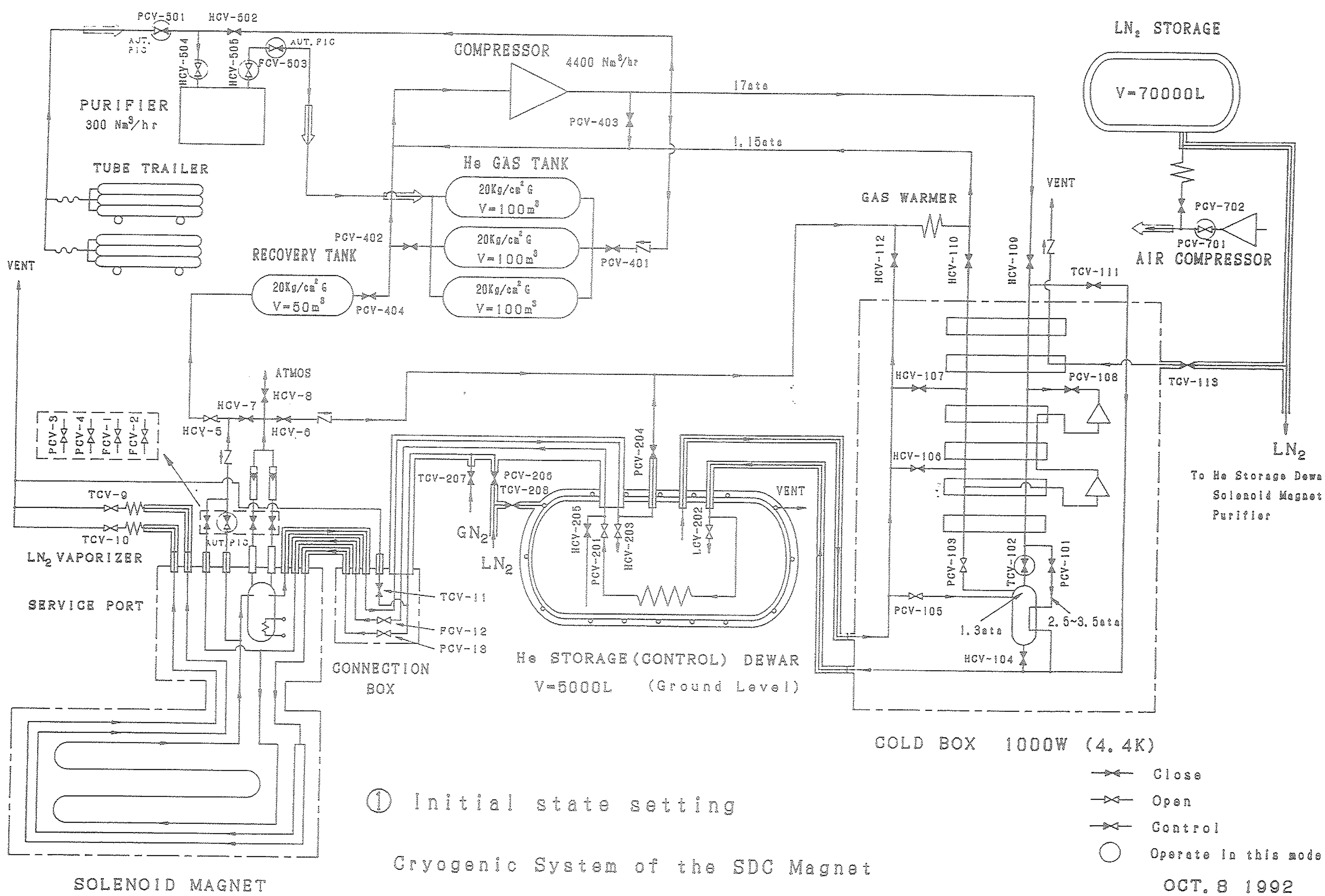

① Initial state setting

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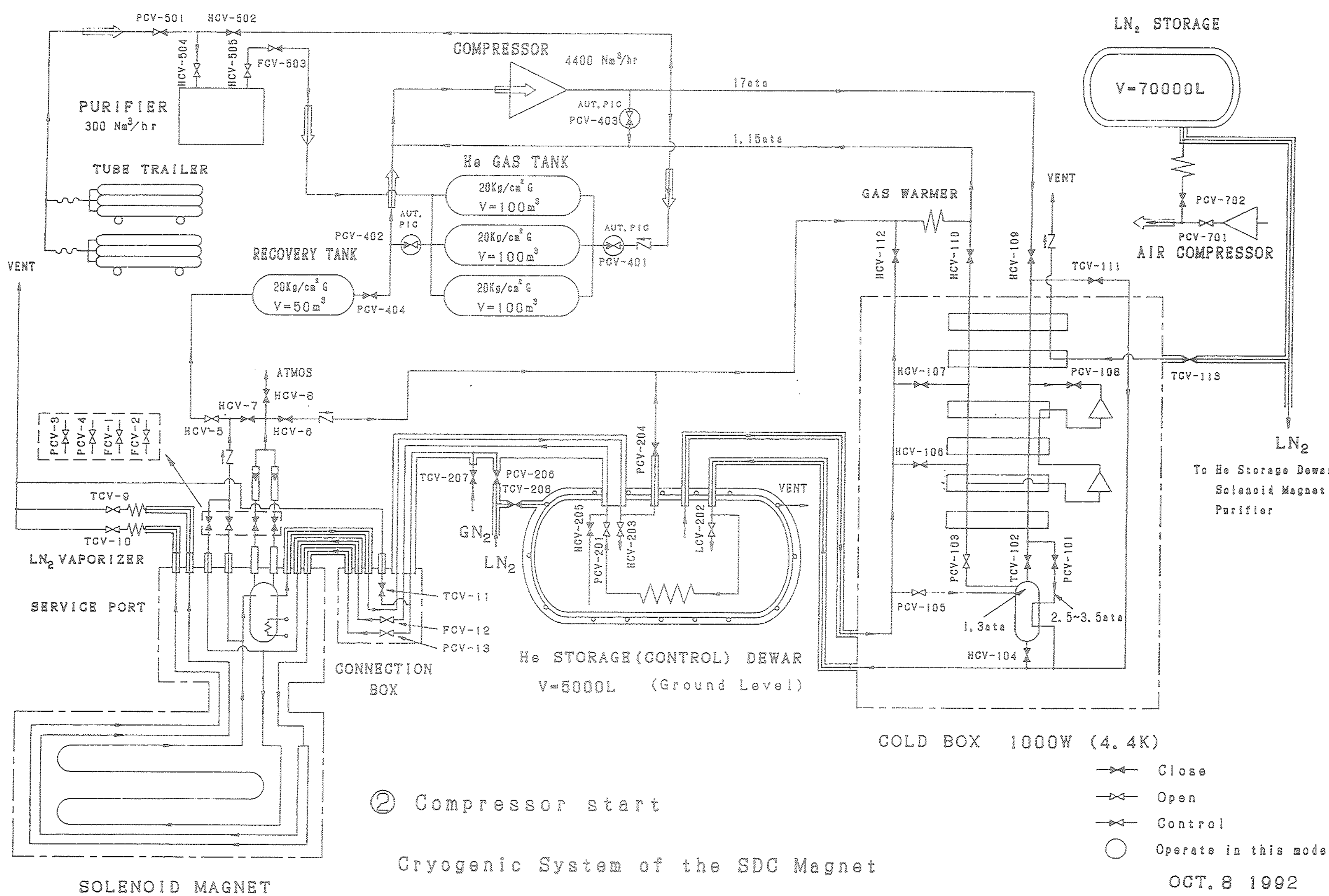

② Compressor start

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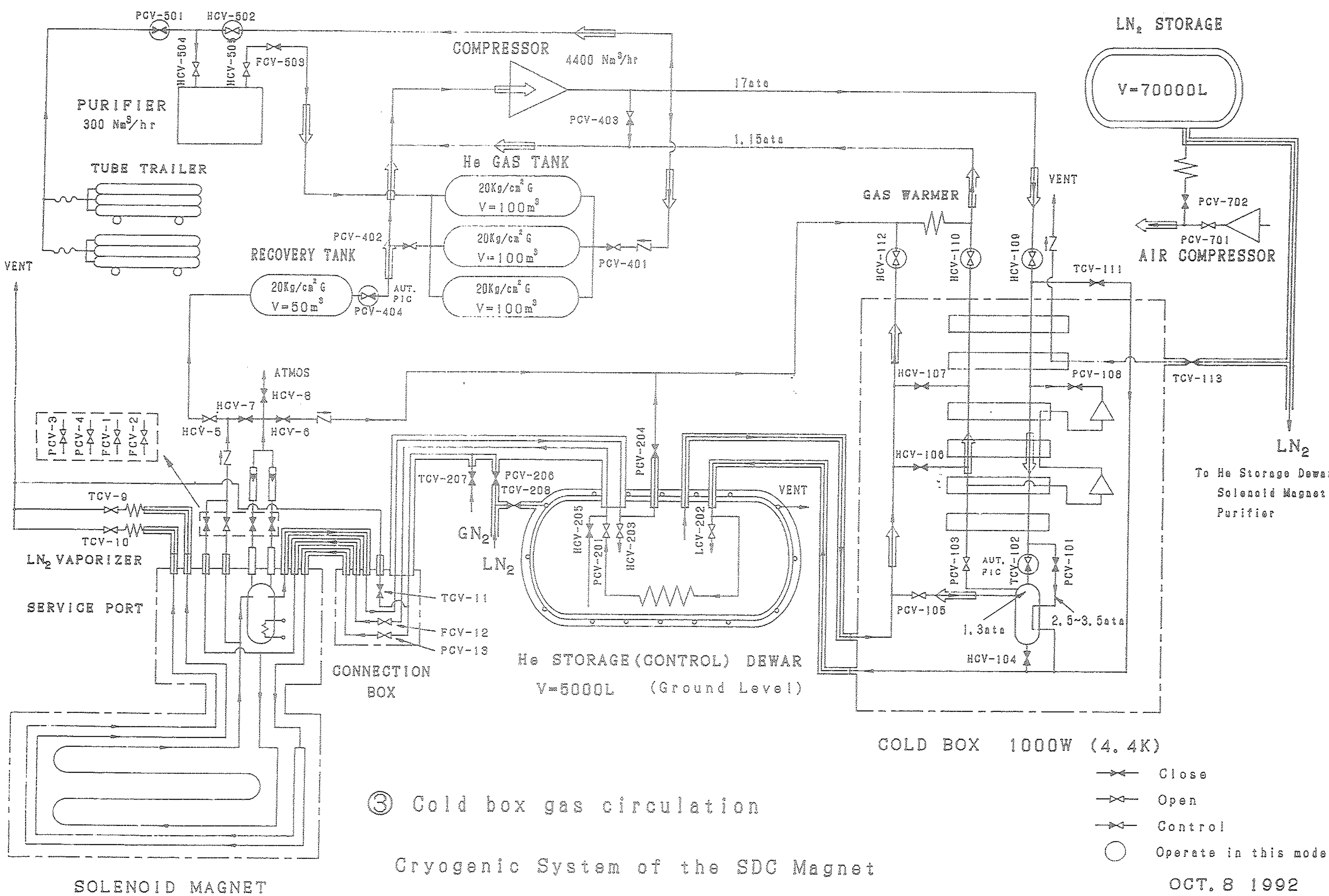

③ Cold box gas circulation

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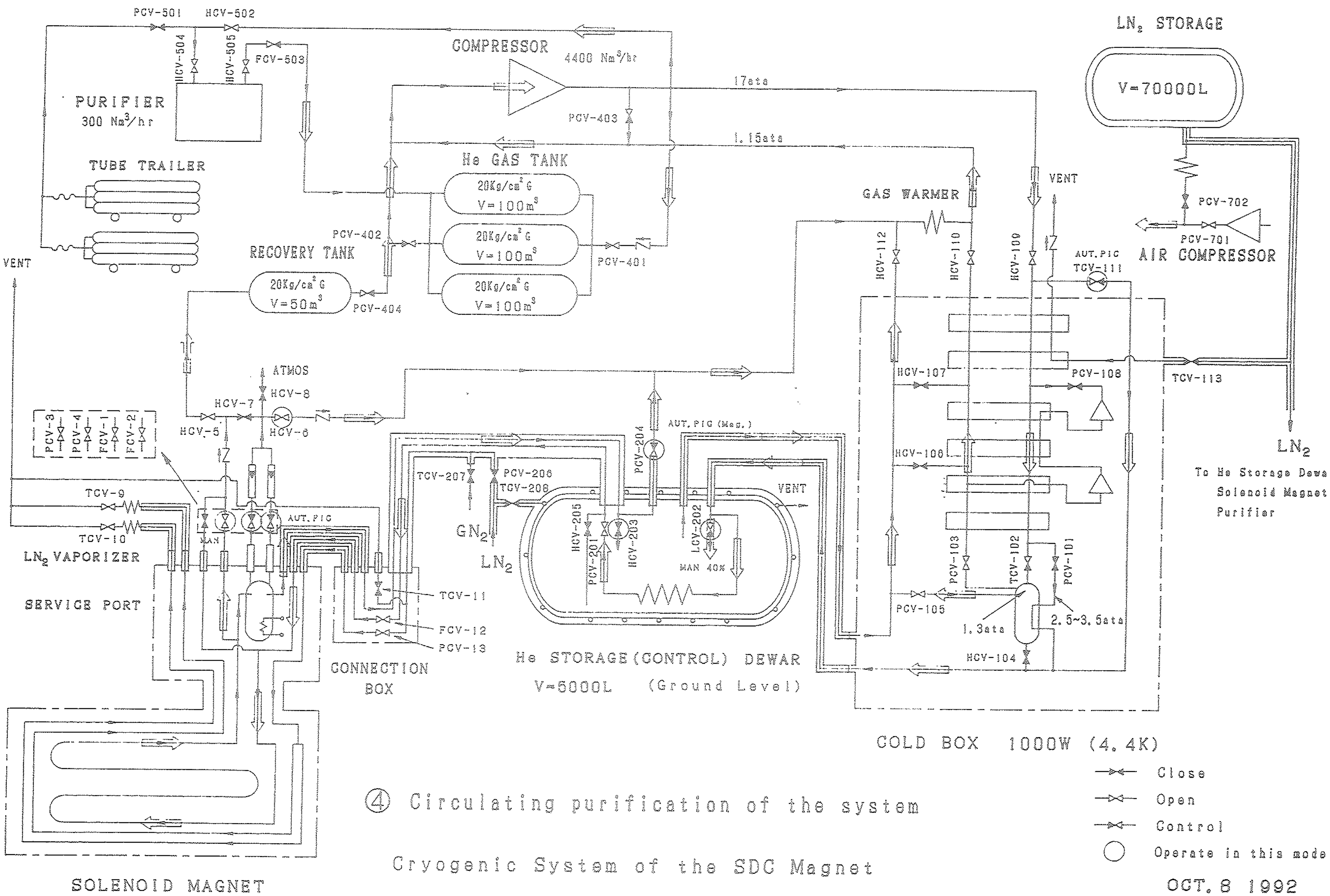
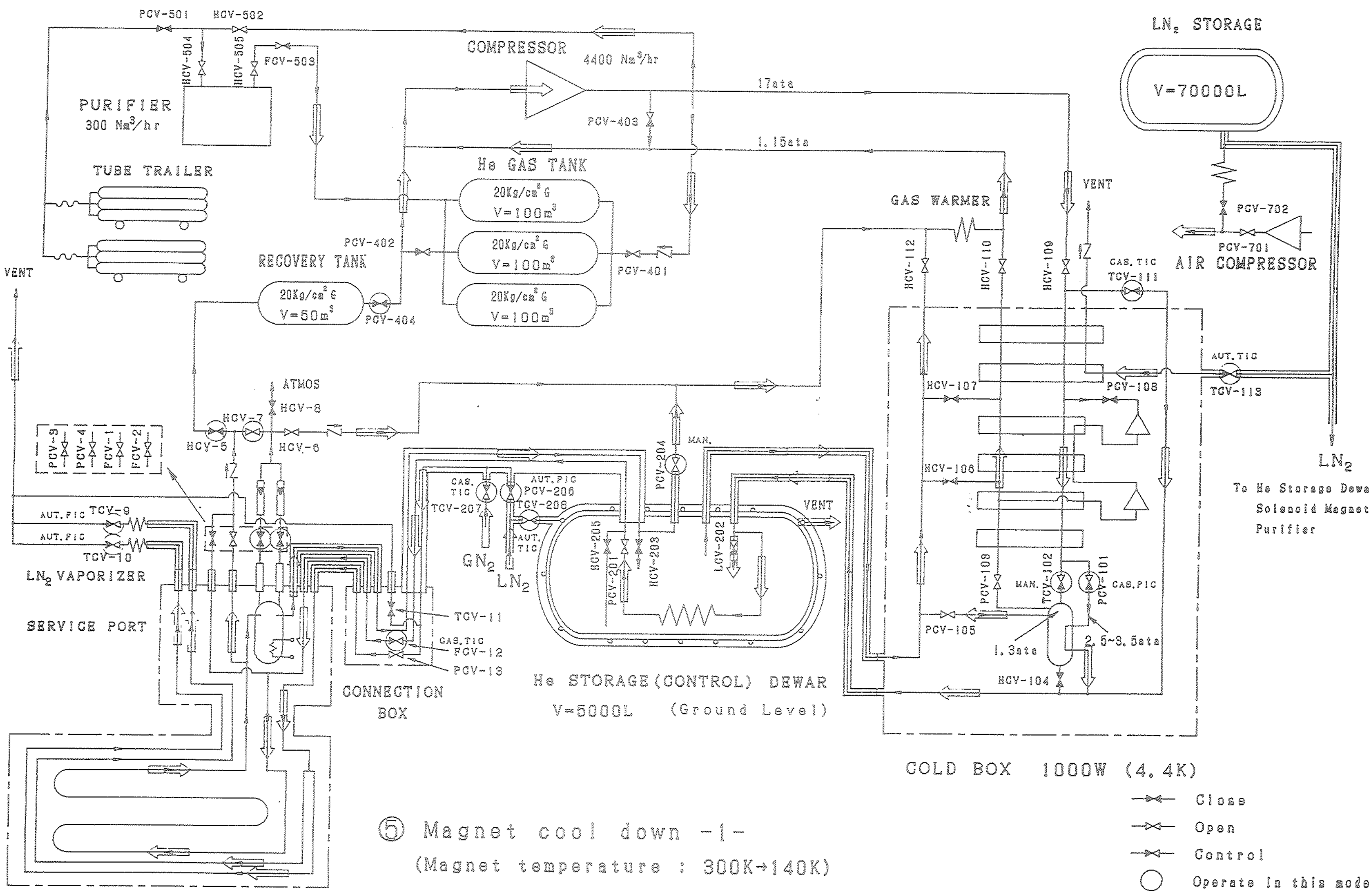


④ Circulating purification of the system

Cryogenic System of the SDC Magnet



⑤ Magnet cool down -1-

(Magnet temperature : 300K→140K)

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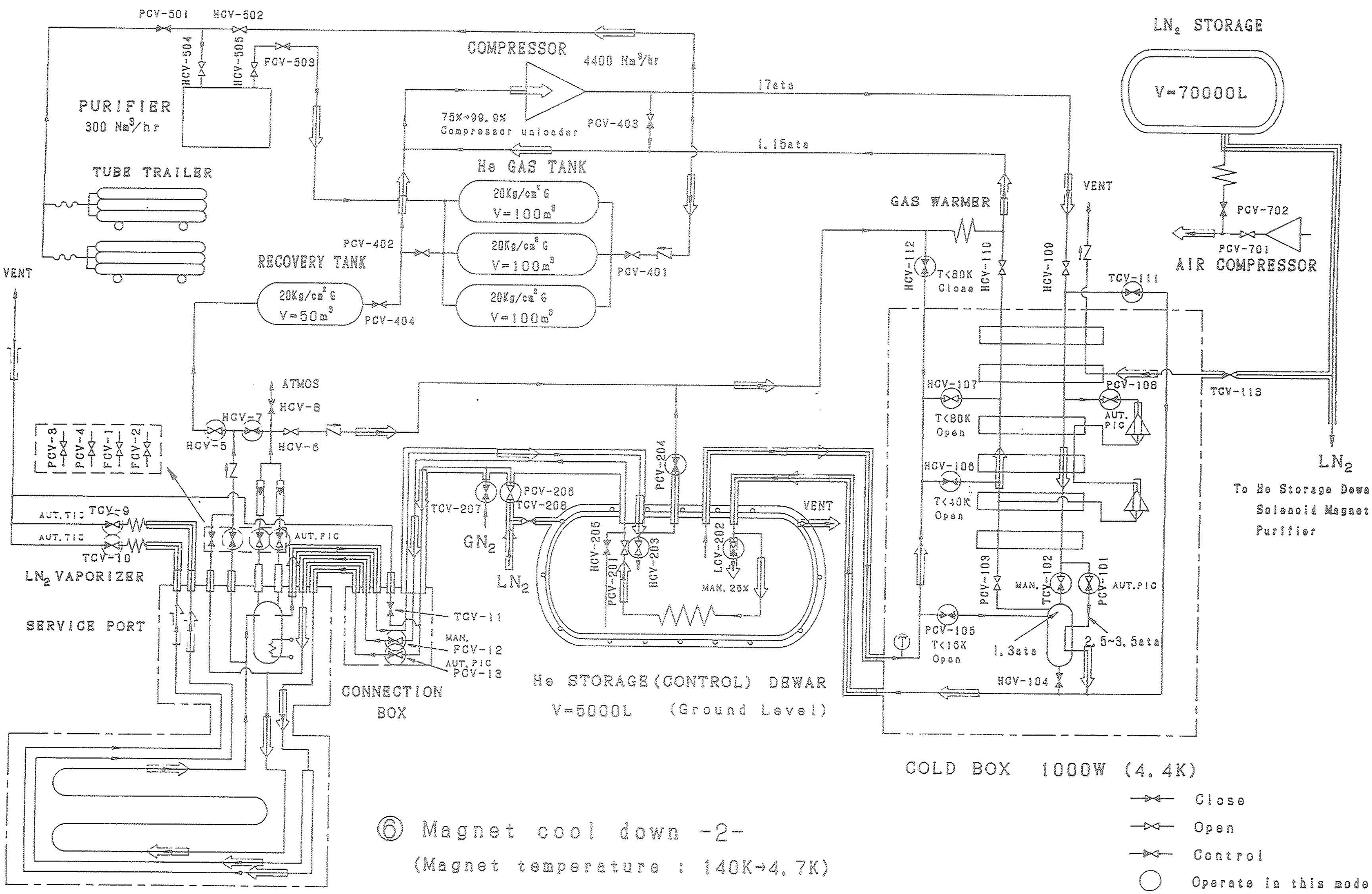

⑥ Magnet cool down -2-

(Magnet temperature : 140K→4.7K)

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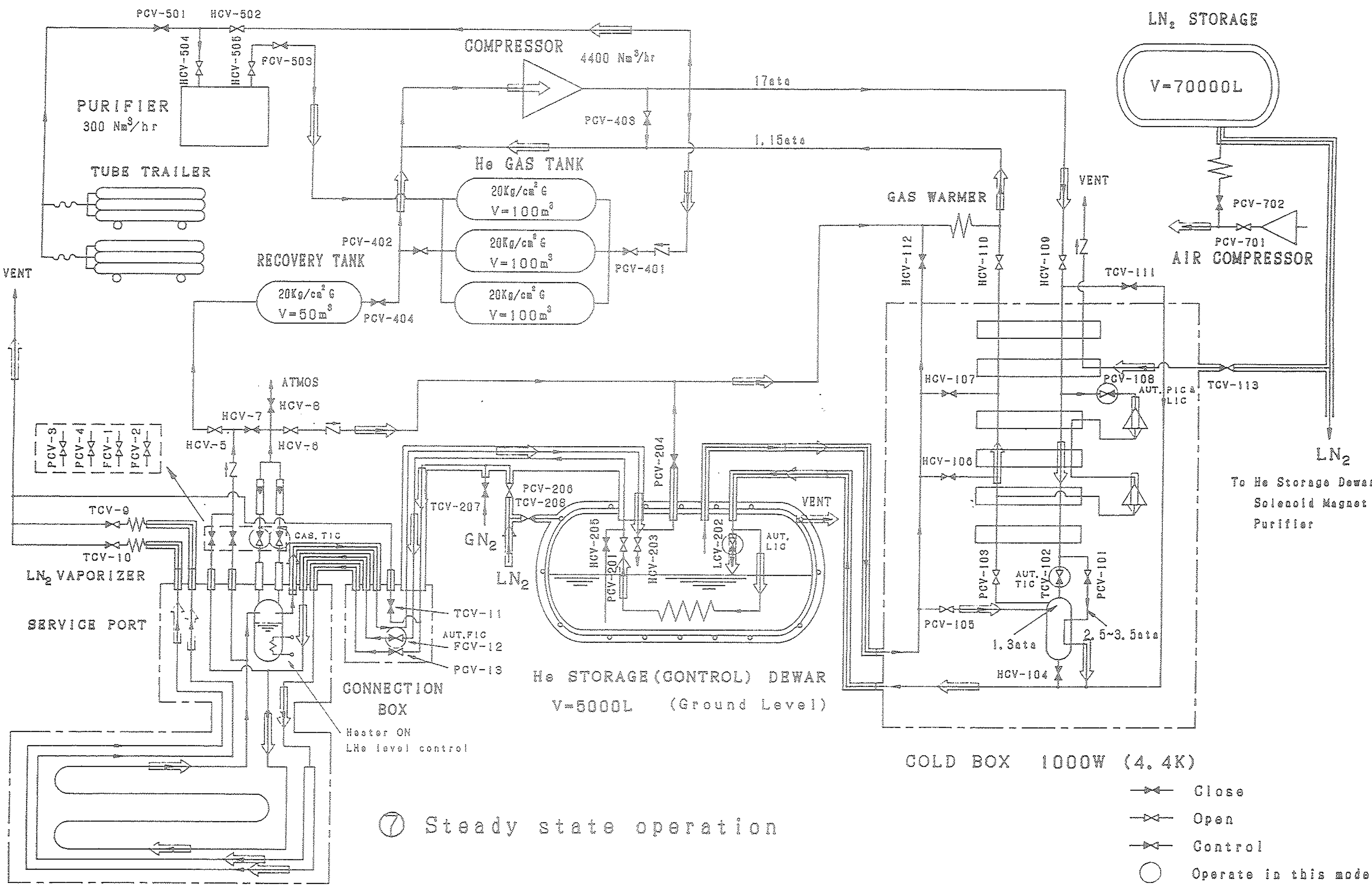

⑦ Steady state operation

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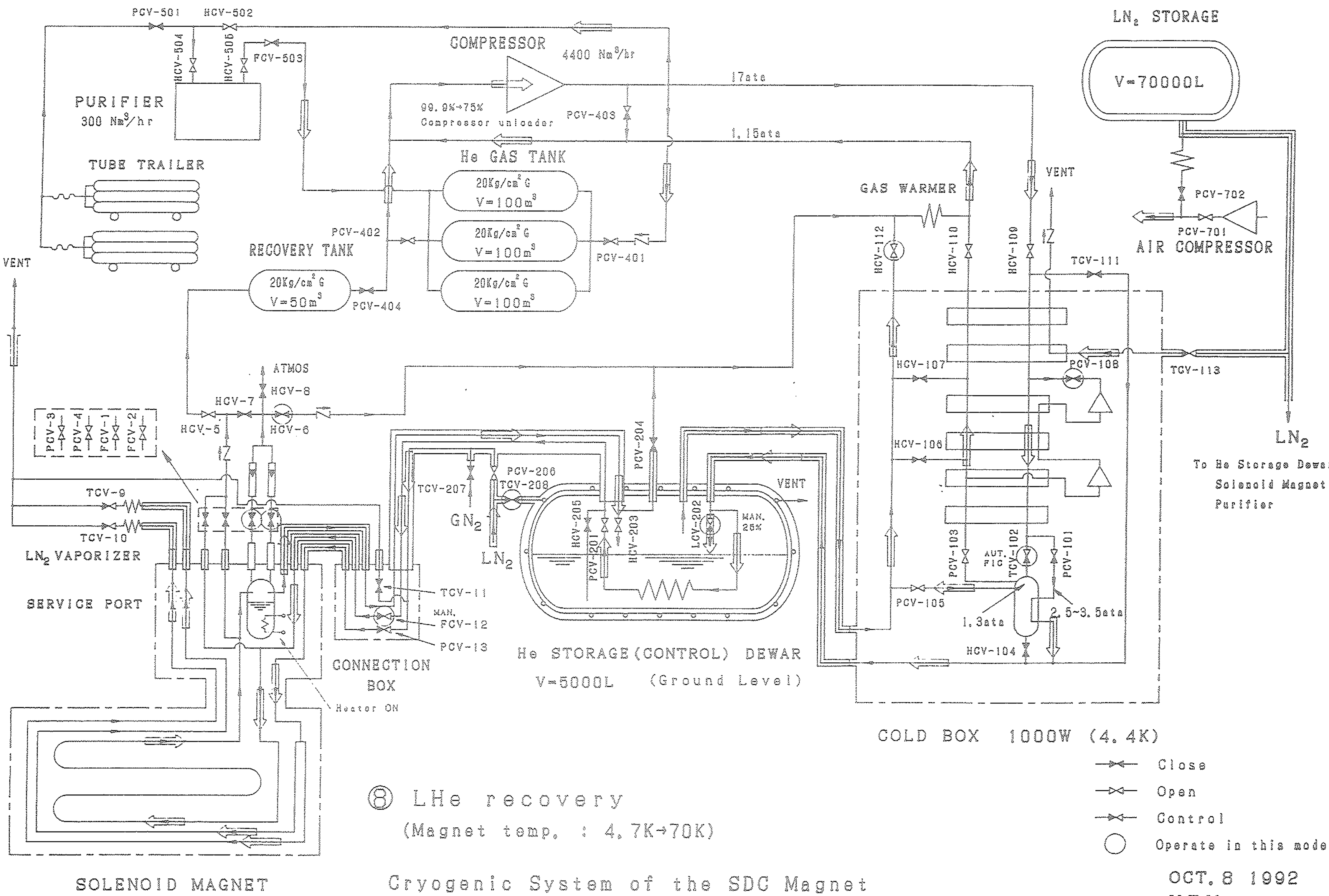

⑧ LHe recovery
(Magnet temp. : 4.7K→70K)

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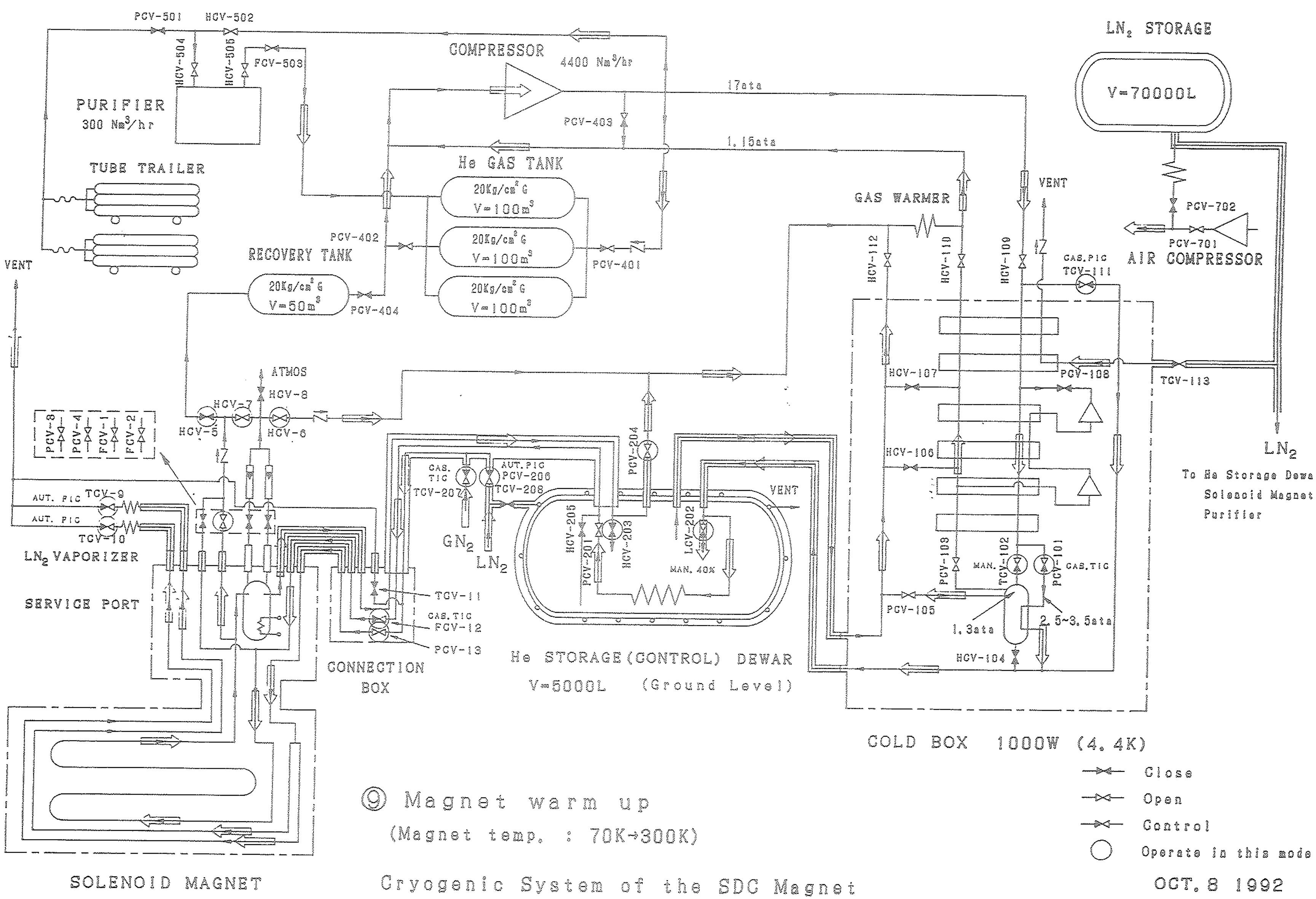

⑨ Magnet warm up

(Magnet temp. : 70K→300K)

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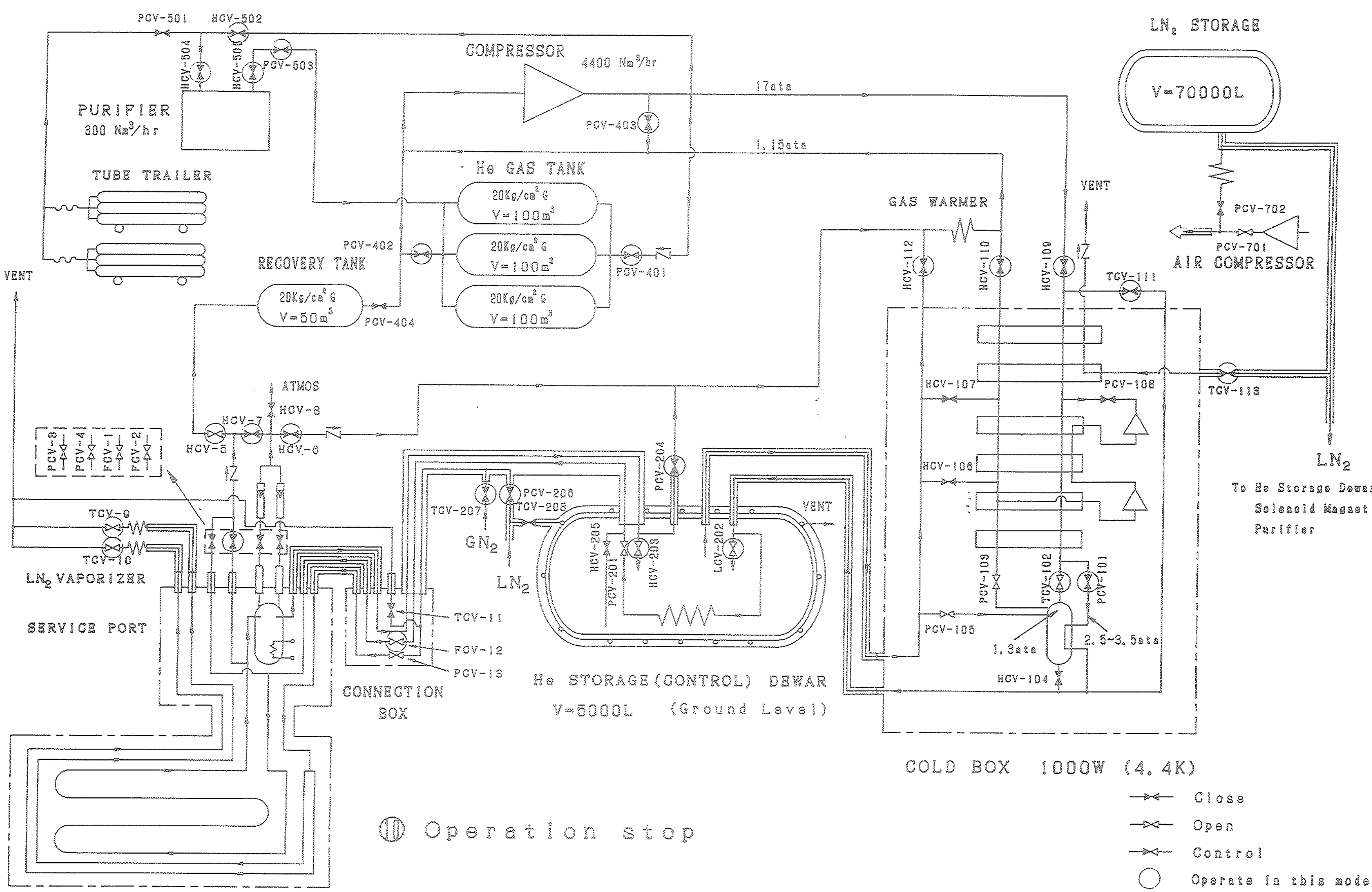

⑩ Operation stop

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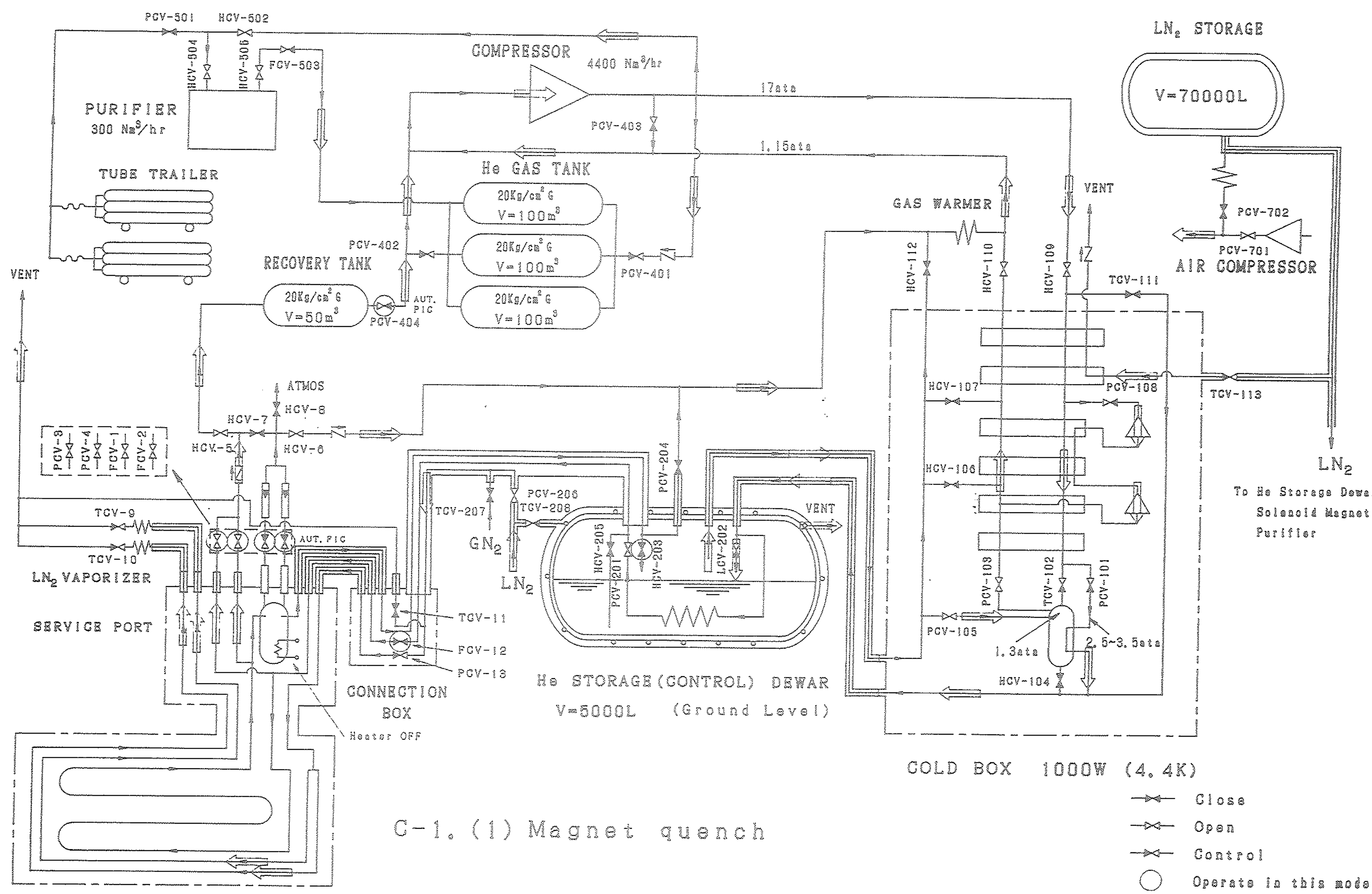

C-1. (1) Magnet quench

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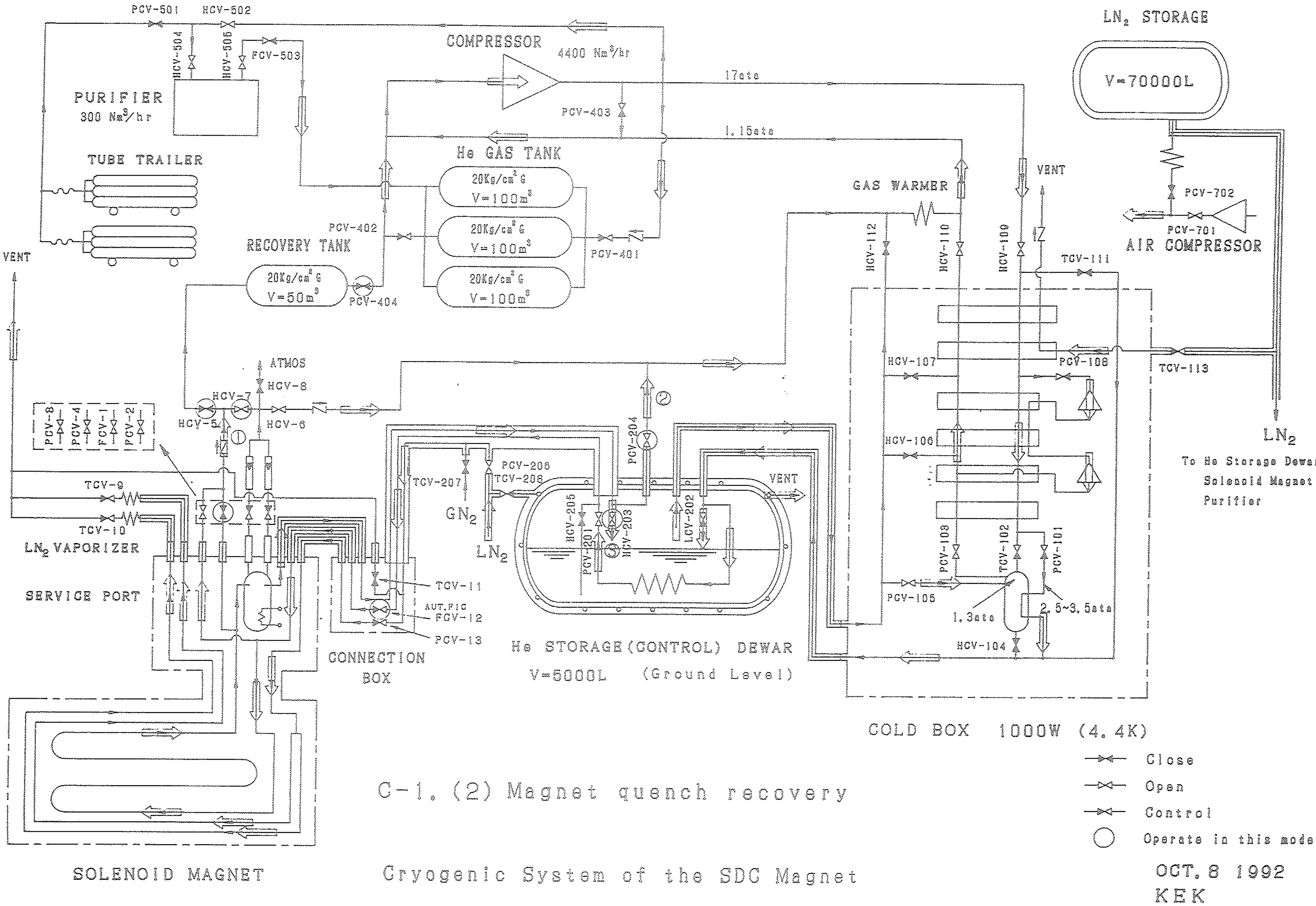

C-1. (2) Magnet quench recovery

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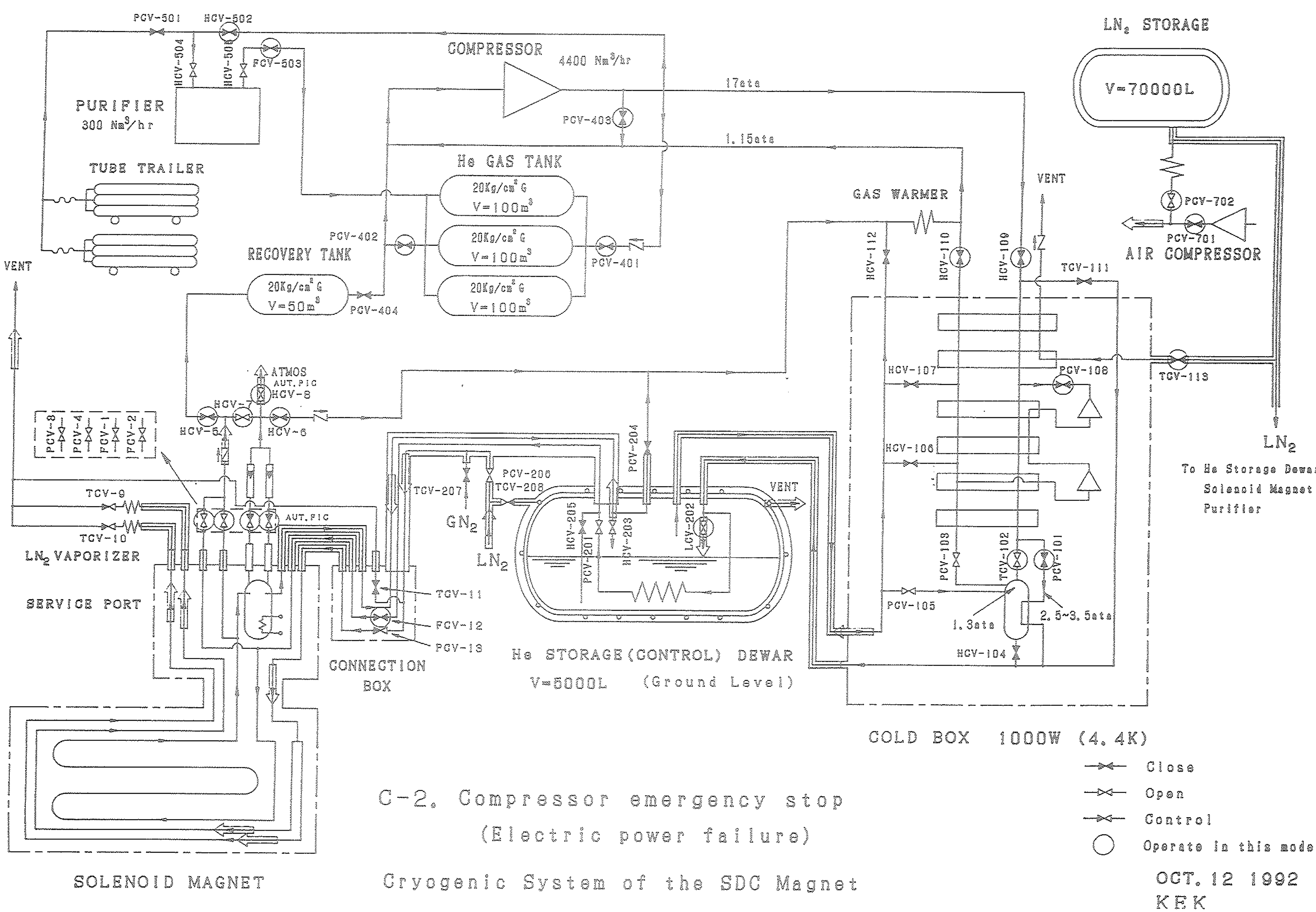

C-2. Compressor emergency stop
(Electric power failure)

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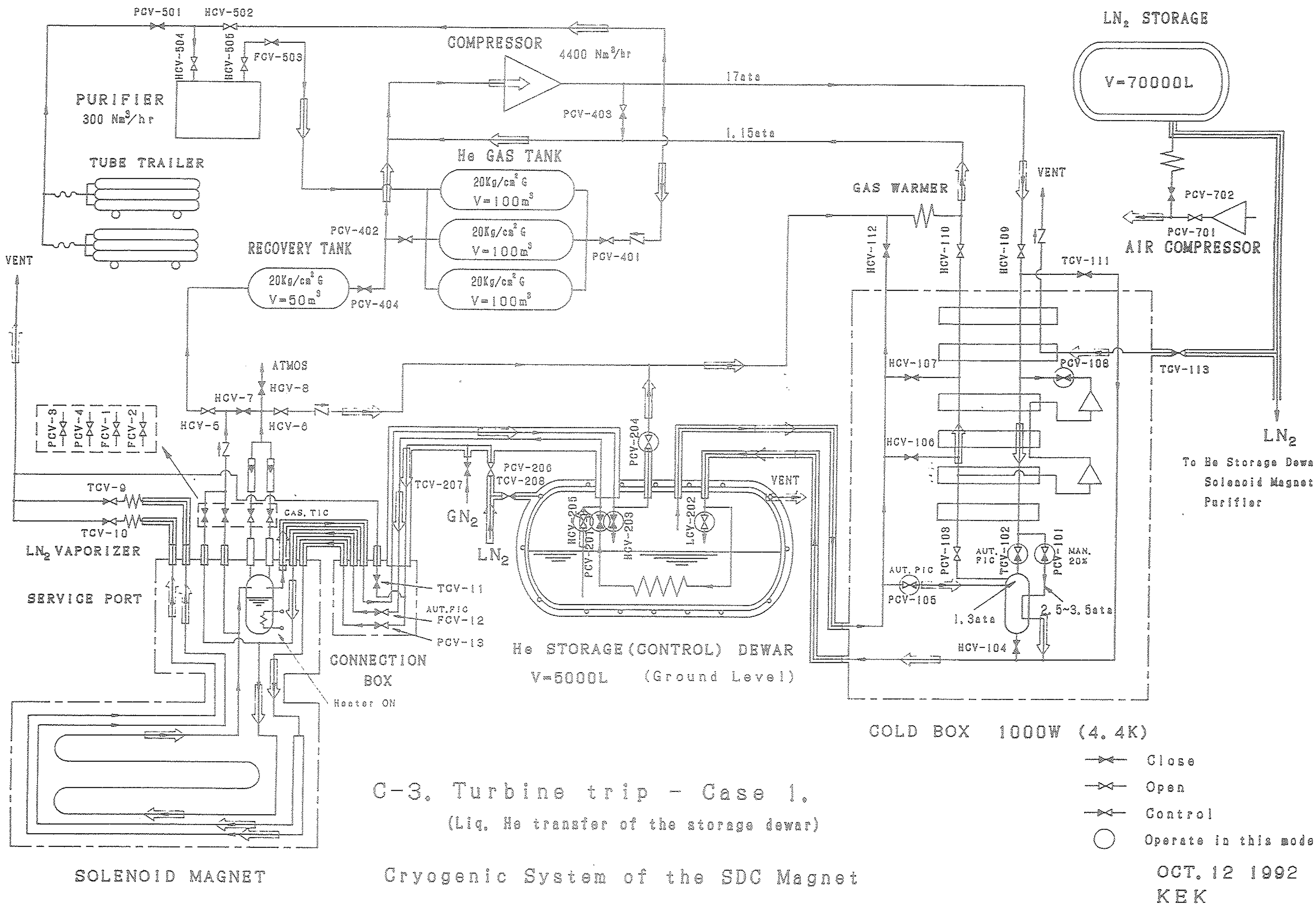
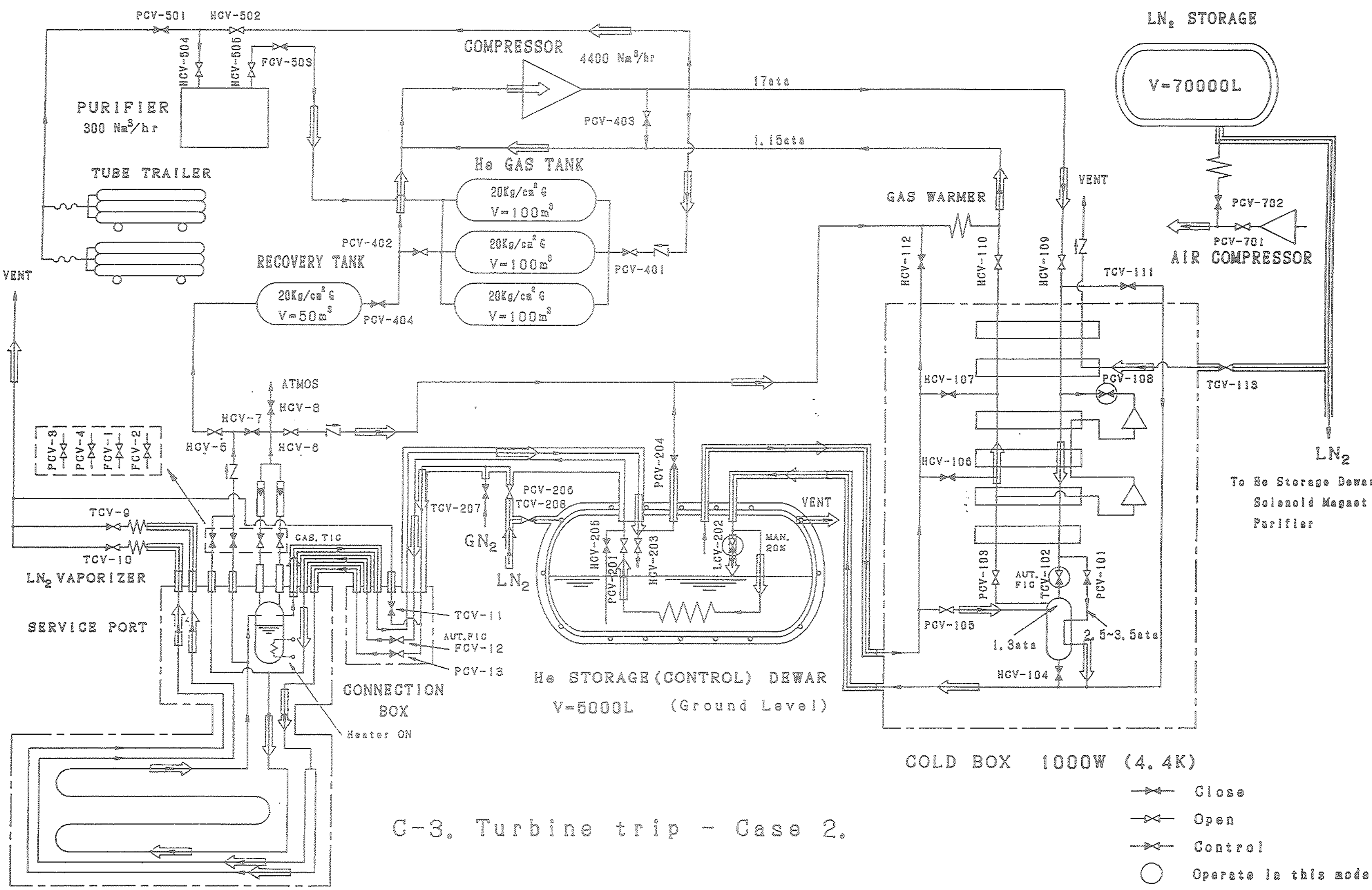


C-3. Turbine trip - Case 1.

(Liq. He transfer of the storage dewar)

Cryogenic System of the SDC Magnet



C-3. Turbine trip - Case 2.

Cryogenic System of the SDC Magnet

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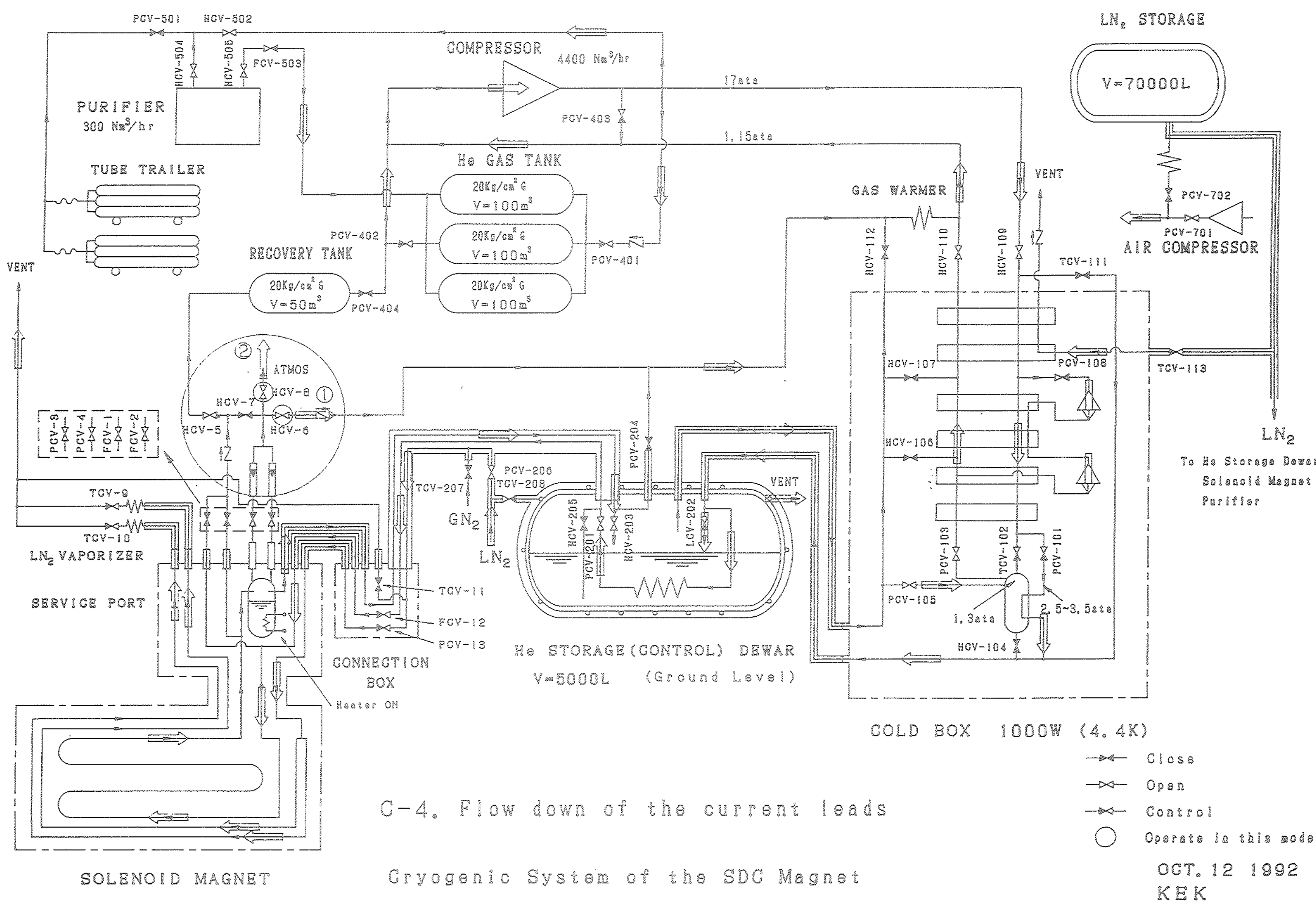

C-4. Flow down of the current leads

Cryogenic System of the SDC Magnet

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