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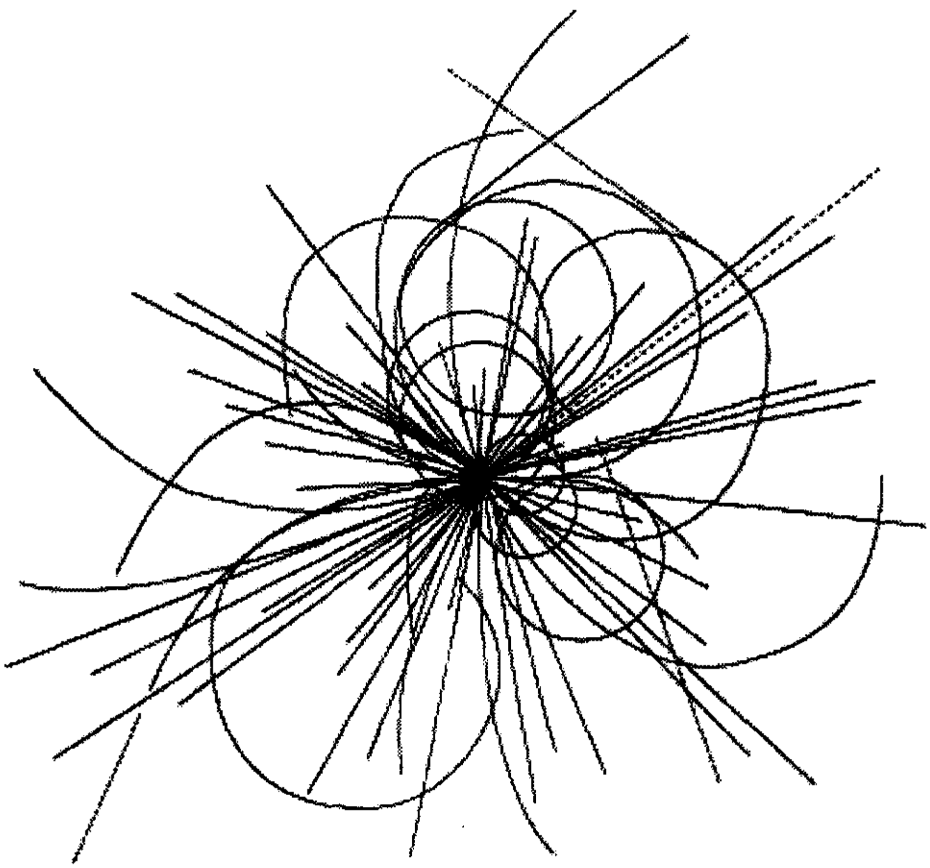

Superconducting Super Collider Laboratory

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The SSC Cryogenic System Design and Operating Modes

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1. INTRODUCTION

The SSC is an application of superconductivity on a scale vastly larger than any before. An extensive cryogenic system is required, capable of providing for the normal operation of the superconducting magnets while handling transient conditions such as quenches, beam activation and ring filling, and beam ramping (acceleration). The cryogenic system must also be able to perform services such as cleanup, cooldown, and warmup to allow for maintenance and repair of the superconducting components throughout the ring.

The magnets in the collider rings and in the HEB (high energy booster) ring will be refrigerated by single-phase helium flow controlled at a temperature of 4 K to maintain the magnet windings in a superconductive state. To minimize the heat load into the 4 K loop, the magnet cryostats are designed to provide high quality thermal insulation at nominal temperatures of 84 K and 20 K, using thermal shields contained in a high vacuum chamber with multilayer insulating materials (MLI).

The two collider beam tubes are encased in parallel rings of superconducting magnets, each ring 87,120 m in circumference; the magnet rings are installed one above the other, 90 cm apart, in a tunnel 25 to 74 m below ground. The HEB single ring, 10,800 m in circumference, is constructed in a separate tunnel parallel to and 14 m above the collider tunnel.

This immense system, if it is to be brought into operation within a reasonable period of time, requires parallel plans for tunnel construction and for installation and commissioning of the magnets. Thus, a highly centralized cryogenic system would not be adequate. Instead, there will be a series of units, each capable of independent operation but interconnected for redundancy. The number of independently operating units is determined in a trade-off between economies of scale in the refrigeration plants and the cost of transporting heat from the magnets. The design of the SSC calls for ten sectors, each over 8 km in length with a helium refrigeration plant installed at midpoint. The cryogenic heat load for the HEB results primarily from ramping losses in the superconducting magnets and is about ten times greater than the synchrotron radiation, the largest dynamic heat load in the collider. Two helium refrigeration plants each with a capacity similar to a collider plant are required for the HEB.

Figure 1-1 is a schematic view of the SSC and the relative locations of the refrigeration plants.

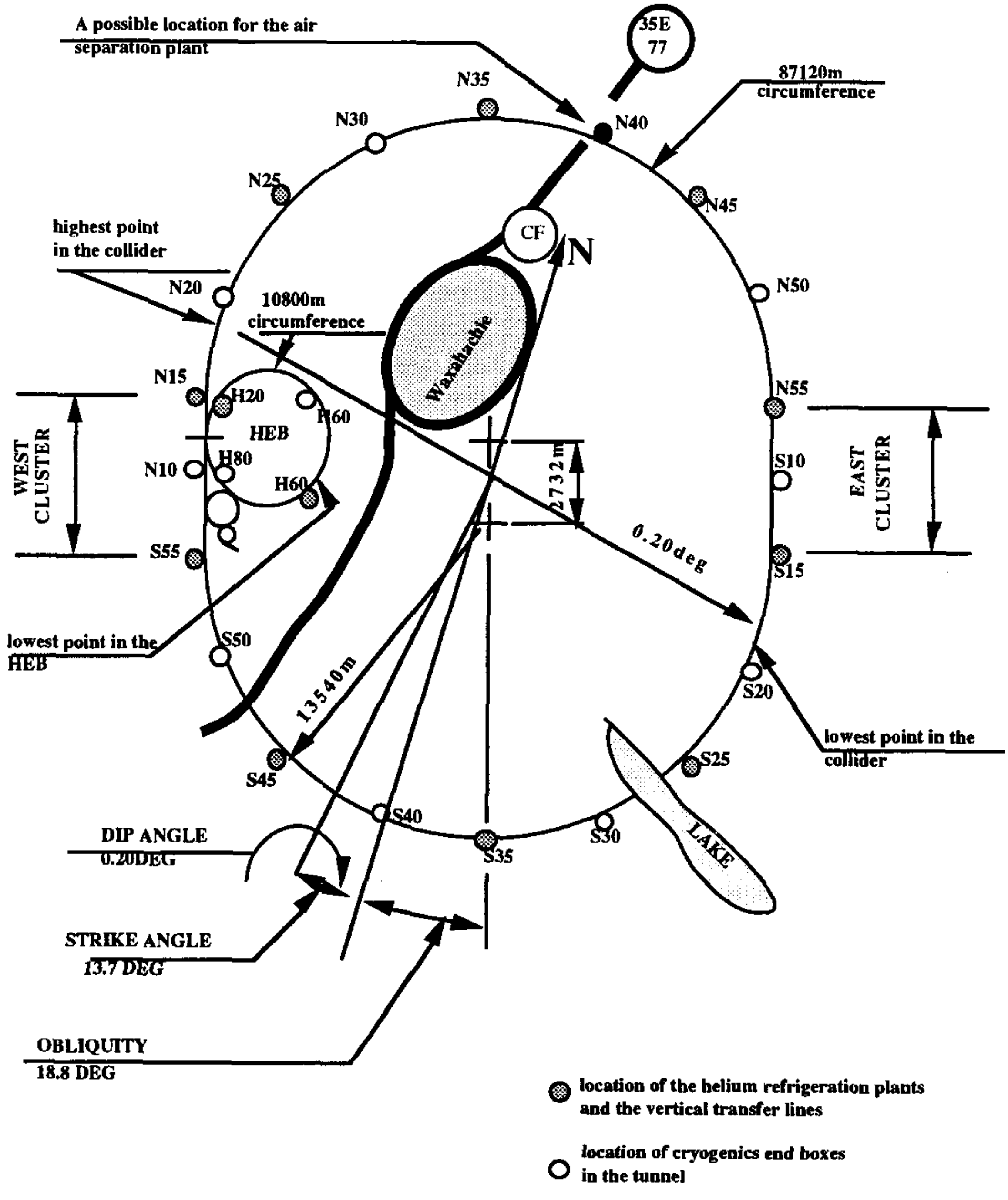


Figure 1-1. Geometry of the collider and the HEB rings and the location of the helium refrigeration plants.

2. THE SYSTEM GEOMETRY

2.1 THE COLLIDER RINGS

The main tunnel of the collider is on a plane with an inclination of 0.2 degrees. It is configured in two arcs, north and south, connected on the east and west by almost straight sections (see Fig. 1-1). The highest point in the tunnel is in the vicinity of N15, and the lowest point is close to S15.

A helium refrigeration plant located on the surface serves a sector in the tunnel extending approximately 4.3 km to each side of the plant. The locations of the helium refrigeration plants for the collider are designated N15, N25, N35, S15, S25, etc.

Cryogens are supplied from the plants to the tunnel through transfer lines in vertical utility shafts near the plants. Additional service shafts are located near the sector boundaries.

A schematic cross section of the collider tunnel is shown in Figure 2.1-2

Between N15 and N55 and between S15 and S55 the collider arcs contain almost continuous strings of superconducting magnets, for which they require a continuous stream of coolants. The cryostats in these regions are designed to enable the handling—including circulation, distribution, and recooling—of the different cryogens.

The remaining sections of the collider ring contain the utility regions (beam injection, beam acceleration, beam dump, and tune-up) and the interaction regions (for the main detectors of the SSC). In these fairly straight segments, superconducting magnets are separated from each other by warm equipment. To close the cryogenic loops, special transfer lines bypass these warm regions.

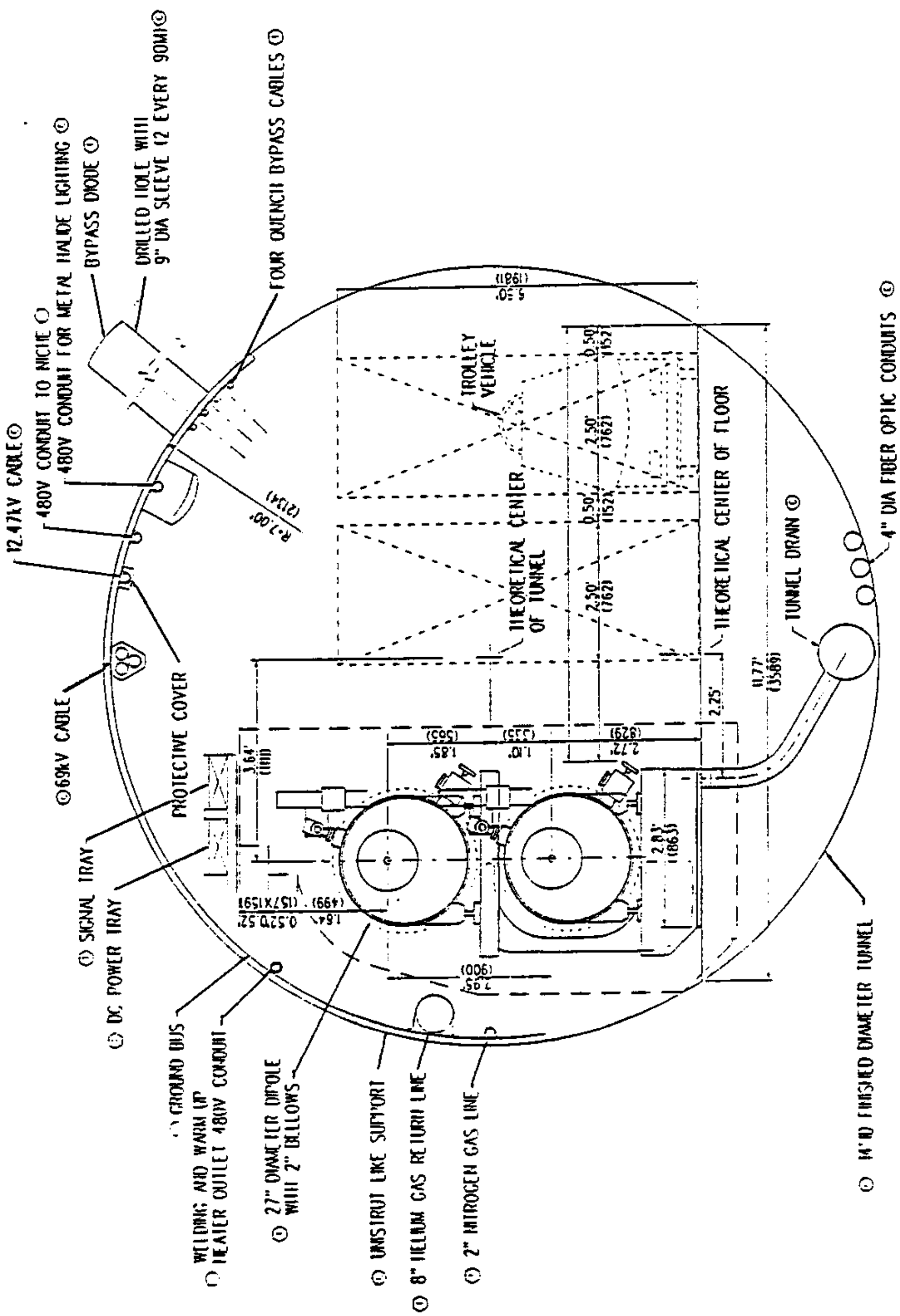


Figure 2.1-1. Tunnel cross section

Variations in terrain and in tunnel inclination cause shaft depths and tunnel locations to vary from site to site. Surface and tunnel elevations and the depth of the shafts for the collider are shown in Table 2.1-1 and in Figure 2.1-2.

Table 2.1-1. Surface and beam altitudes, in meters

Location	Surface altitude	Depth to beamline (shaft depth)	Beamline altitude	Beamline ref. altitude
N15 (E1)	233.17	74.06	159.11	75.96
N20 (F1)	217.17	53.13	164.04	80.89
N25 (E2)	197.97	33.87	164.10	80.95
N30 (F2)	207.26	48.00	159.26	76.11
N35 (E3)	208.03	57.92	150.11	66.96
N40 (F3)	161.54	23.70	137.83	54.68
N45 (E4)	161.54	37.50	124.04	40.89
N50 (F4)	151.64	41.21	110.43	27.28
N55 (E5)	140.21	41.45	98.76	15.61
S10*	TBD			
S15 (E6)	150.88	66.48	84.40	1.25
S20 (F6)	140.21	57.06	83.15	0.00
S25 (E7)	139.45	53.40	86.05	2.90
S30 (F7)	145.54	52.76	92.78	9.63
S35 (E8)	129.54	27.04	102.50	19.35
S40 (F8)	155.45	41.49	113.96	30.81
S45 (E9)	156.21	30.51	125.70	42.55
S50 (F9)	163.83	27.61	136.22	53.07
S55 (E10)	169.16	24.99	144.17	61.02
N10*	TBD			

** S10 in the east cluster and N10 in the west cluster are located between the utility straights and the interaction regions.*

An arrangement of magnets in series, starting with the feed connection at the refrigeration plant and ending with a return box at the cryogenic sector boundary, is termed a "string." A nominal string is 4.3 km long. The strings are segmented into "sections" connected to each other by U tubes that enable the isolation of parts of the system for maintenance.

For practical reasons, the lengths of the magnet strings and the lengths of the sections vary, as shown in Table 2.1-2.

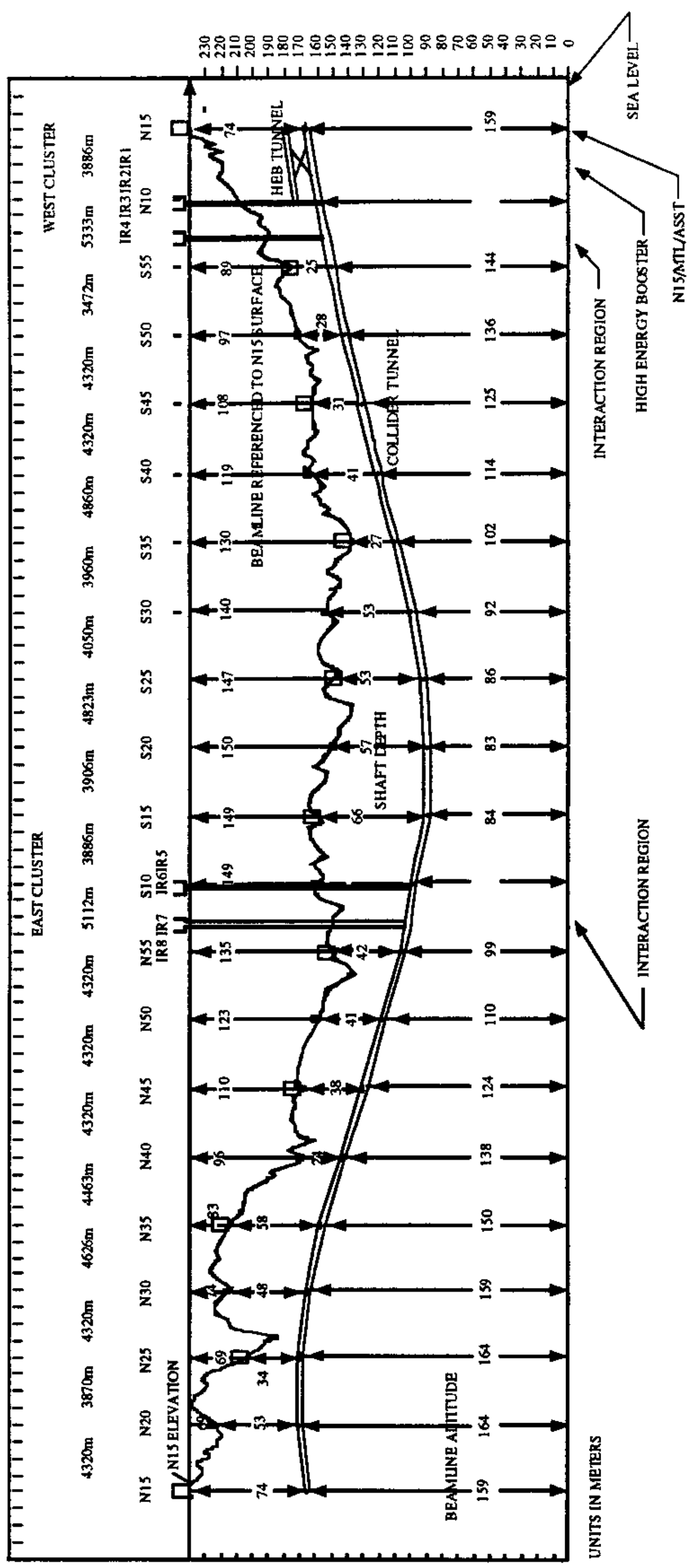


Figure 2.1-2. Collider tunnel and surface elevation

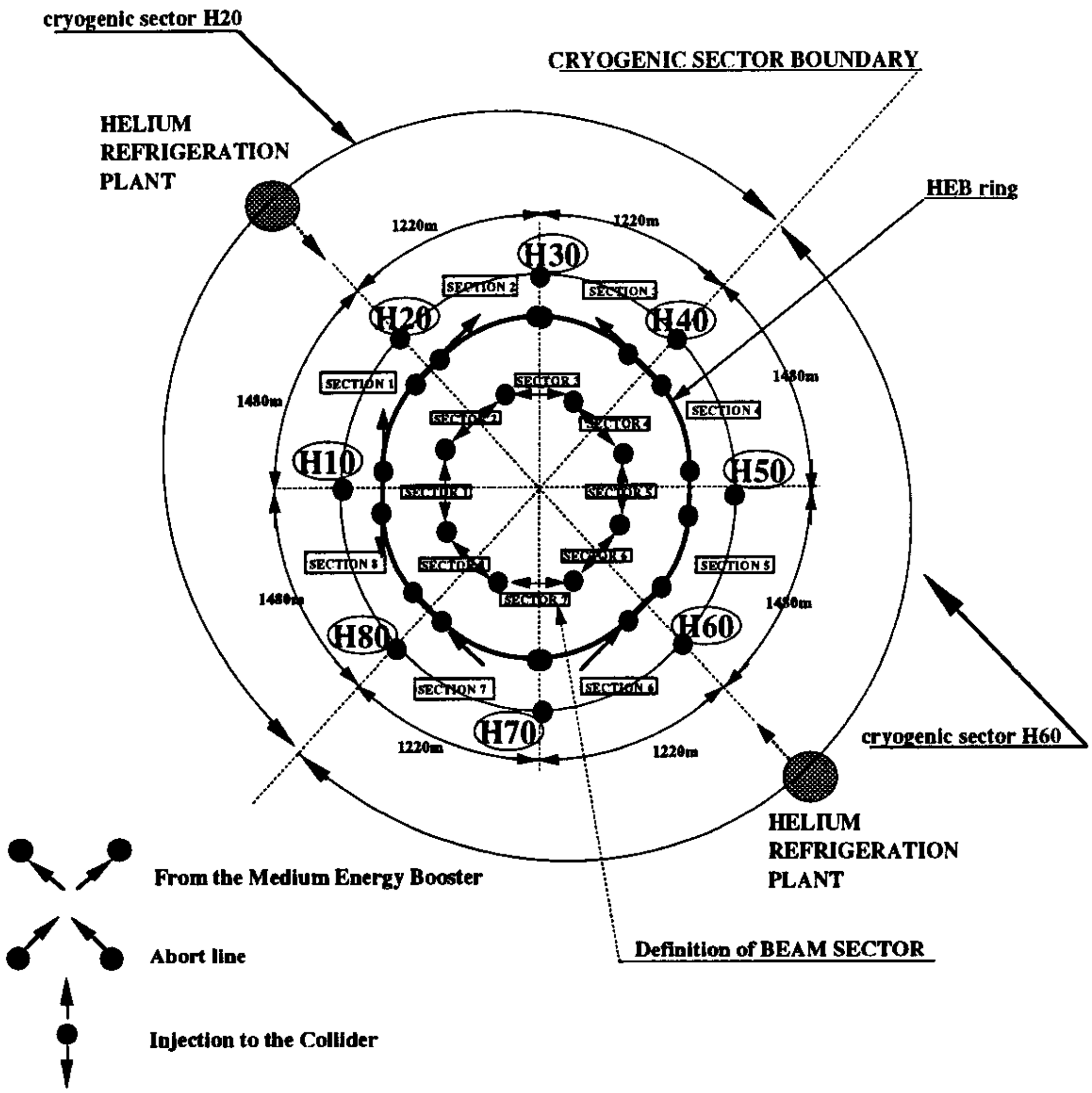
Table 2.1-2. Length of collider strings and sections, in meters

String	Length	Length of Sections						
S15 to S20	3906	1080	1080	667	1080			
S20 to S25	4823	773	1080	1080	990	900		
S25 to S30	4050	1080	810	1080	1080			
S30 to S35	3960	810	540	1080	450	1080		
S35 to S40	4860	765	945	630	1080	1080	360	
S40 to S45	4320	1350	1080	810	1080			
S45 to S50	4320	1170	720	1080	1350			
S50 to S55	3472	396	1088	1125	1350			
S55 TO N10 *(I.R.)*	5333	450	1116	1087	676	756	1087	298
N10 to N15 *(West Utility)*	3886	917	990	1350	629			
N15 to N20	4320	1080	1080	667	1080	413		
N20 to N25	3870	360	1080	1080	990	360		
N25 to N30	4320	540	1080	810	1080	810		
N30 to N35	4626	1080	540	1080	450	1080	396	
N35 to N40	4463	953	990	1080	1080	360		
N40 to N45	4320	1350	1080	810	1080			
N45 to N50	4320	1170	720	1080	1350			
N50 to N55	4320	405	1080	765	1080	990		
N55 TO S10 *(I.R.)*	5112	1206	1087	676	756	1087	298	
S10 to S15 *(East Utility)*	3886	917	990	1350	629			

2.2 THE HEB RING

The HEB is a bipolar machine with one ring of superconducting magnets. It is constructed in a tunnel 10,800 m in circumference, located in a parallel plane to the collider, 14 m above the collider tunnel. The general layout of the HEB ring is shown in Figure 2.2-1. Two helium refrigeration plants located on the surface at H20 and H60 supply the cryogens to the HEB. The boundaries between the two cryogenic sectors are at H80 and H40. Each of the four strings of the HEB is divided into two sections. Altitudes and depths to the beamline are given in Table 2.2-1. Lengths of the sections are shown in Table 2.2-2.

As in the collider, there are straight regions along the ring where cryogen flows bypass warm equipment through special cryogenic transfer lines.



Straight segments and warm beam equipment are located at H10, H20, H40, H50, H60, and H80

Figure 2.2-1. The HEB ring.

Table 2.2-1. Surface and beam altitudes for the HEB, in meters

Location	Surface altitude	Depth to beamline	Beamline altitude	Beamline ref. altitude
H10	229.3	39.4	189.9	16.3
H20	247.4	57.7	189.7	16.1
H30	248.6	63	185.6	12
H40	233.6	55	178.6	5
H50	226.2	52.5	173.7	0.1
H60	226.6	53	173.6	0
H70	221.6	43.3	178.3	4.7
H80	215.0	30.2	184.8	11.2

Table 2.2-2: Length of HEB strings and sections, in meters

String	Length	Length of Sections	
H80 to H20	2960	1480	1480
H20 to H40	2440	1220	1220
H40 to H60	2960	1480	1480
H60 to H80	2440	1220	1220

The nitrogen is supplied directly from delivery trucks to the HEB's nitrogen dewars located at H20 and H60. From the dewars the nitrogen is supplied to the tunnel for the 80 K shield refrigeration, and to the helium plants for precooling. A more sophisticated scheme would supply the nitrogen through the collider shield lines and is given in detail elsewhere,.

3. THE SYSTEM CONFIGURATION

3.1 THE CRYOSTAT

The cold components (cryostat with superconducting magnets, spool pieces, empty cryostats, etc.) of the collider and the HEB are designed for six different streams, described as follows:

Line 1 – Single-phase feed

For normal operation, a nominal helium flow of 100 g/s at 4 K, 0.4 MPa flows through the magnets to maintain the coils in the superconductive state. This flow enters the string at one end and exits at the other end, while being recooled every 180 m in recoolers located in the spool pieces. The cross section of this flow is defined by the sum of the different flow areas within the magnet. A small amount of this feed stream is tapped off at different locations along the string for the refrigeration of the high current leads, the bypass leads, and the current leads for the corrector magnets.

Line 2 – Single-phase return

This line, which has an inside diameter (ID) of 45.2 mm, is mounted in the vacuum envelope alongside the magnet winding case. It carries the single-phase flow from the end of the string back to the refrigerator. A sizable portion of this return stream is injected into the recoolers. Under nominal conditions and for a nominal string length in the collider, the balance of the flow returning at the end of the line is approximately 25 g/s per string. The heat load of the HEB strings is higher than that of the collider and the high boil-off rate in the recoolers may require supply of single-phase flow from both ends.

Line 3 – 4 K helium vapor return

This line, sized at 86.5 mm ID for the collider and 110 mm ID for the HEB, returns the boil-off helium from the recoolers to the cold compressor, which discharges it to the refrigerator.

Line 4 – 20 K feed/return

For the 20 K shield loop, 82.5 mm ID pipe is used. The design flow rate is 100 g/s at 0.3 MPa with a design load of 2500 W per string (or a total of 5000 W per loop). According to a given scheme, the flow is supplied to the top ring and returned to the plant through the bottom ring. A different scheme calls for a clockwise flow in one ring and counterclockwise in the second ring; this may allow for sharing loads between sectors and balancing mass inventory.

In the HEB the flow is routed from one refrigerator through the two connecting strings to the second refrigerator (from H20 through H30, H40, and H50 to H60; and from H60 through H70, H80, and H10 to H20).

Line 5 – 80 K LN_2 shield line

This 57.2 mm ID line is used to distribute the liquid nitrogen in the tunnel for the refrigeration of the 80 K shield and to supply liquid nitrogen to the refrigeration plants for precooling. A detailed description of the nitrogen system is presented in "Nitrogen System for the SSC."[1]

Line 6 – 80 K GN_2 shield line

A second 57.2 mm ID line is used to return the vapor nitrogen produced in the nitrogen recoolers to the helium refrigerator for precooling purposes. The vapor is subsequently vented to atmosphere at 300 K.

Warm helium return header

A warm return header, sized at 213 mm ID, is installed in the tunnel to return the warm helium flow from the current leads. This header is also used to return warm helium during cleaning, cooldown, and maintenance processes.

The insulating spaces around the cryogenic components (magnets, spool pieces, and transfer lines) are evacuated to 1.3×10^{-2} Pa by mechanical pumps and to 1.3×10^{-5} Pa by cryo pumping. This vacuum is required to minimize the heat load on the cold mass. The insulating space is bounded radially by the outer walls of the cryostat and axially by the vacuum barriers located in the spool pieces. In the collider, the insulating vacuum volume between two vacuum barriers (half-cell) is approximately 22 m^3.

Cross sections of different cryostats are shown in Figure 3.1-1 (collider dipole), Figure 3.1-2 (collider and HEB bypasses), and Figure 3.1-3 (vertical transfer line connecting the surface helium refrigeration plants to the rings in the tunnel).

Besides the standard cryostats and bypasses used in the collider, there are more complicated cryostats, such as those containing two cold masses (Fig. 3.1-4) and those which require complex connections to the cryogenic bypasses. These will be discussed elsewhere.

[1]McAshan, M., M. Thirumaleshwar, S. Abramovich and V. Ganni. SSC Laboratory Report No. SSCL-592, September 1992.

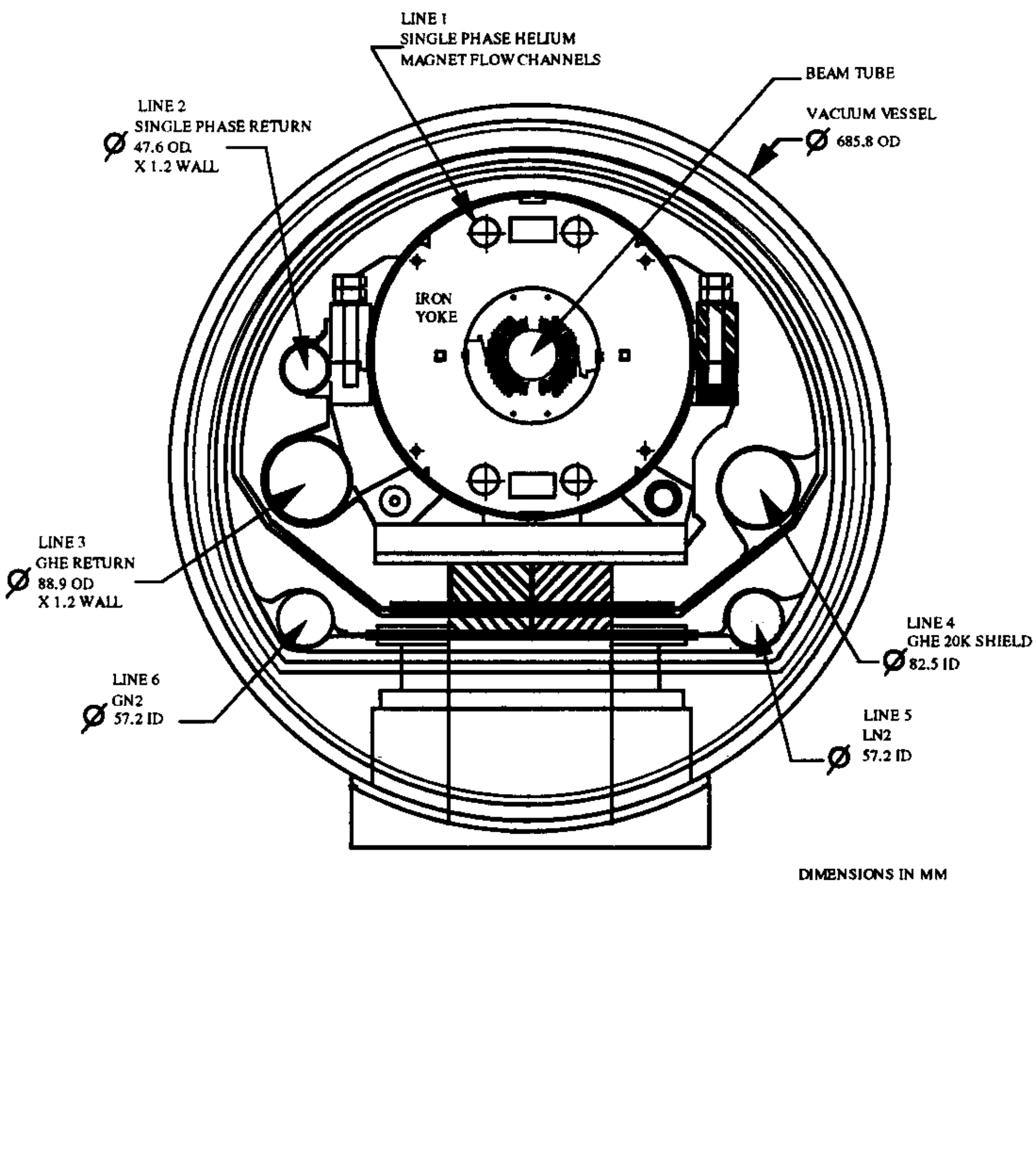
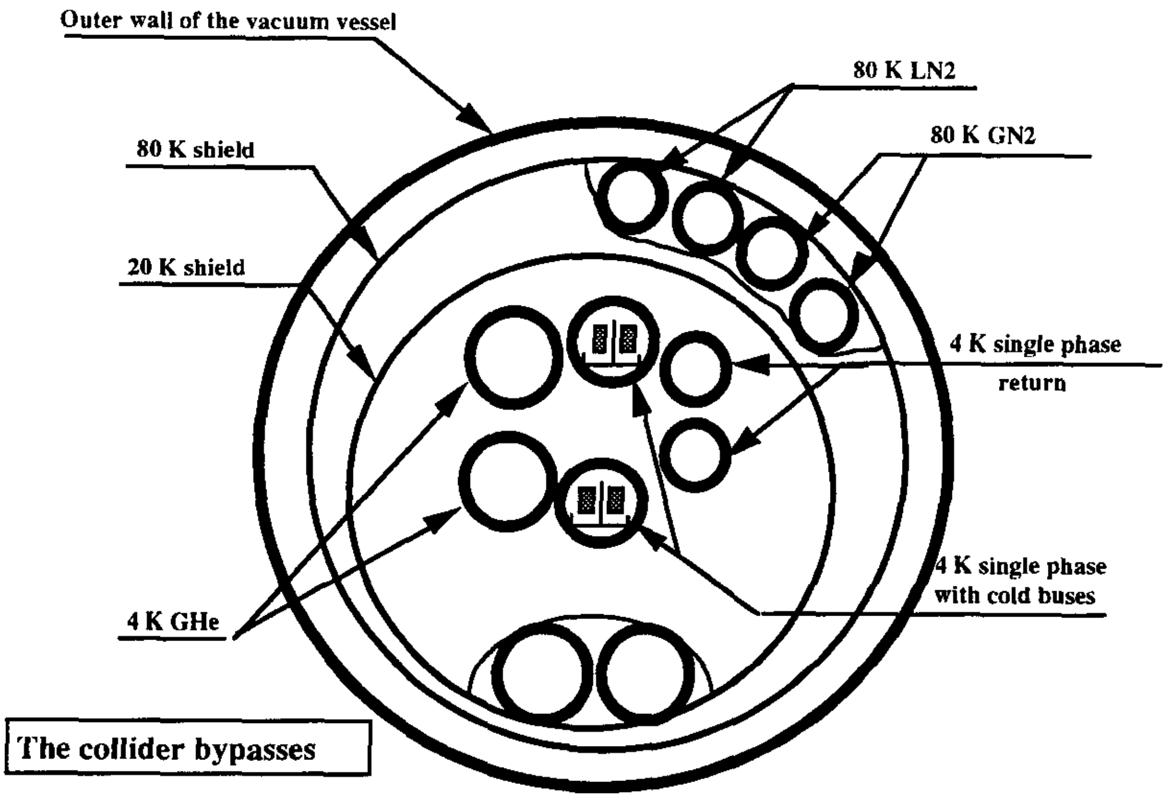


Figure 3.1-1. Typical collider dipole cryostat cross section.



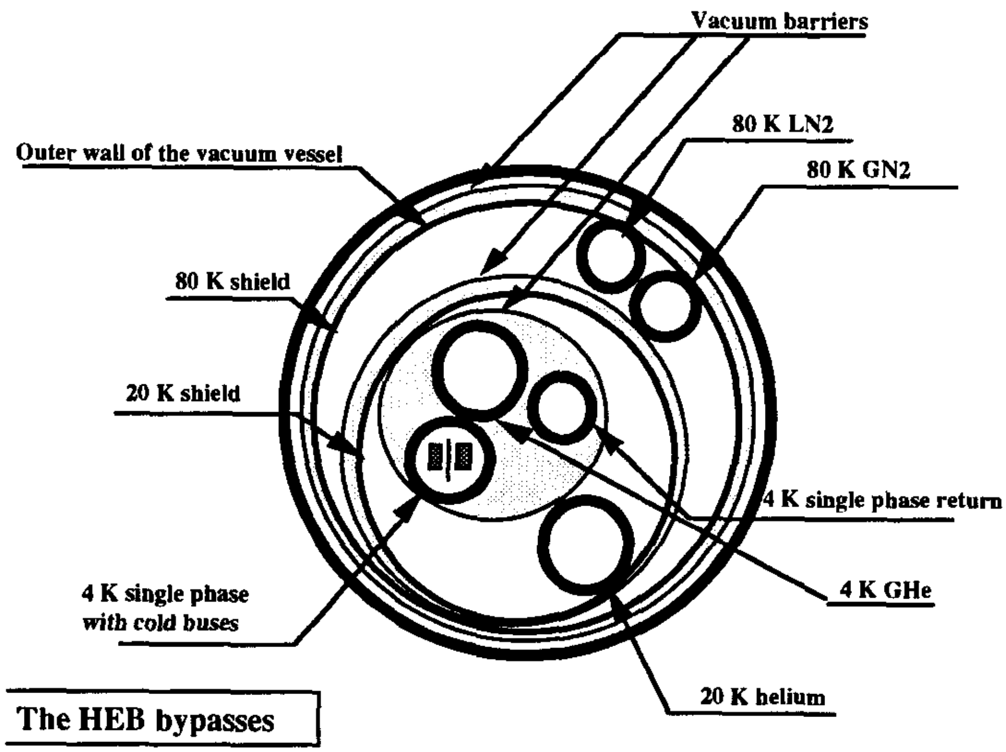


Figure 3.1-2. Bypass cryostat cross sections

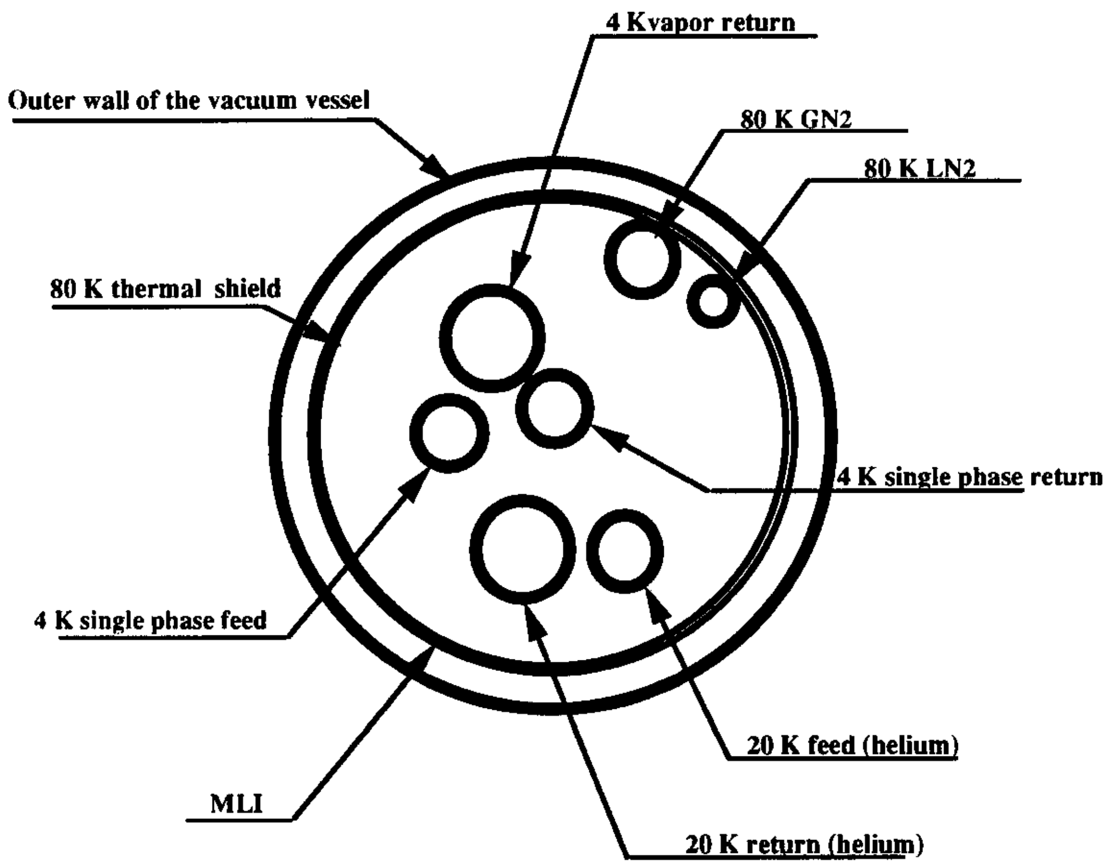


Figure 3.1-3. Cross section of a vertical transfer line from the surface to the tunnel

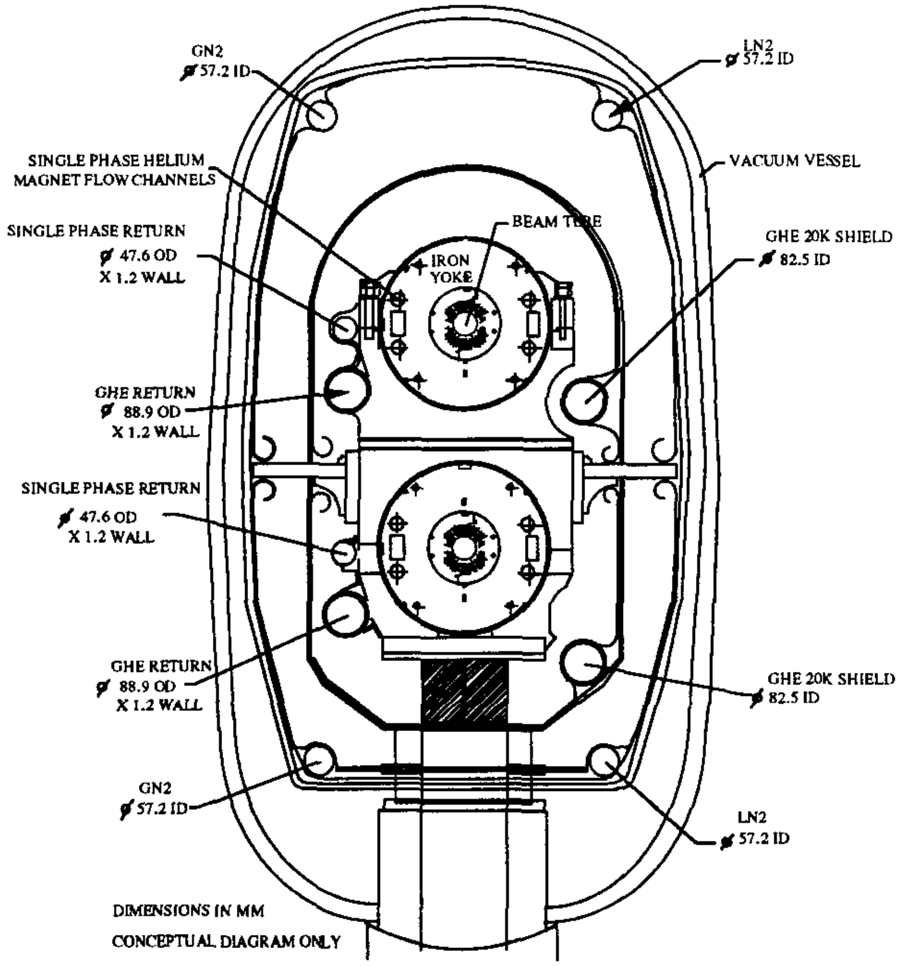
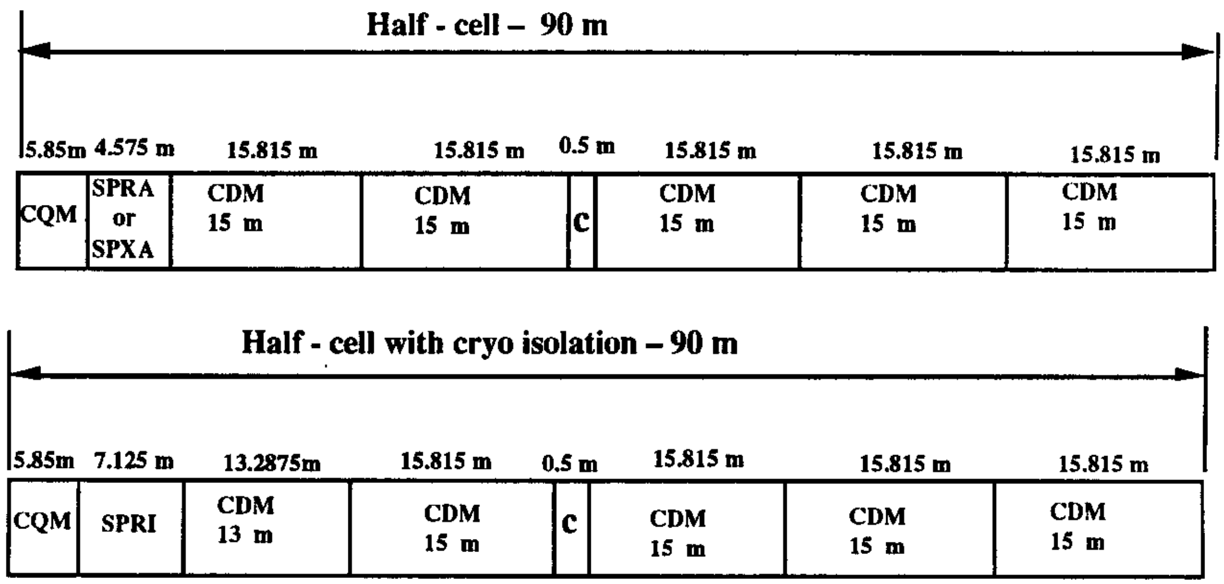


Figure 3.1-4. Cross section of cryostat containing two vertical bending dipoles

3.2 THE CELL AND THE HALF-CELL

The collider half-cell

The smallest repetitive group of magnets (dipoles and quadrupoles) in an accelerator is the half-cell. A regular collider arc half-cell contains five dipoles, a quadrupole, and a spool piece, and its length is 90 m. Figure 3.2-1 shows the configuration of a regular arc half-cell and that of an isolation half-cell. The spool pieces contain correction magnets, recoolers (every other spool), cryogenic instrumentation, a vacuum barrier, and quench protection bypasses. This design enables the system to contain vacuum problems and magnet quenching problems within the half-cell.

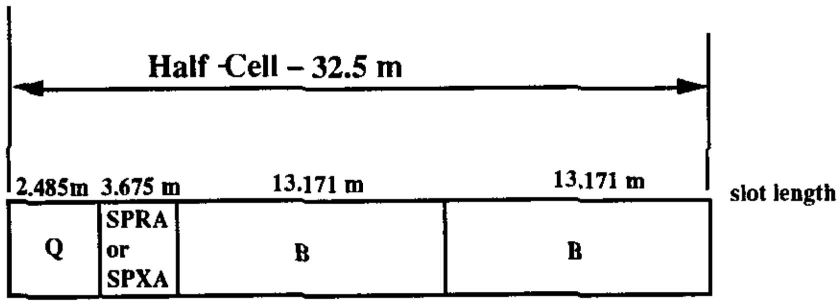


CDM15 – Regular arc dipole 15.8150 m long
CDM13 – Regular arc dipole 13.2875 m long
CQM – Regular arc quadrupole
SPXA – Arc spool without recooler
SPRA – Arc spool with recooler
SPRI – Isolationspool with recooler
C – Correction elements

Figure 3.2-1. The collider half-cell

The HEB half-cell

In the HEB a regular arc half-cell contains two HEB dipoles, one HEB quadrupole, and a spool piece. The length of a half-cell is 32.5 m. Figure 3.2-2 shows the configuration of a regular arc half-cell of the HEB. A vacuum barrier is located in every other spool (~65m). The alternate spool contains the recooler. The recoolers and vacuum barriers are located in alternate spools because of space limitations.



B – Regular arc dipole 13.171 m long
Q – Regular arc dipole
SPXA – Arc spool without recooler with vacuum barrier
SPRA – Arc spool with recooler without vacuum barrier

Figure 3.2-2. The HEB half-cell.

3.3 SECTIONS AND STRINGS

A cryogenic section is a series of cells with an isolation can at each end. The cryogenic connection between two sections is made through U-tubes.

A cryogenic string is a series of sections with a cryogenic feed can on one end and an end can (return can) at the other end.

The length of a nominal section in the collider is 1080 m and the nominal length of a string is 4320 m. The actual lengths vary as shown in Table 2.1-2, above.

In the HEB there are two standard sections, 1220 m long and 1480 m long respectively. Each string in the HEB contains two sections of the same length; thus, there are strings 2440 m long and strings 2960 m long (see Figure 2.2-1, above).

3.4 THE CRYOGENIC SECTOR

The collider cryogenic sector

Figure 3.4-1 depicts a specific cryogenic sector in the collider. It includes regular arc strings N15 to N20 and the west utility straight with the bypass transfer line. There is a series of isolated cryostats connected to the bypass but not shown in the diagram. A typical cryogenic sector structure is given in Table 3.4-1.

The HEB cryogenic sector

There are two cryogenic sectors in the HEB, each 5400m long, with their refrigeration plants located at H20 and H60. The H20 area contains the injection into the collider and the HEB beam dump. The H60 area contains the beam injection from the MEB to the HEB and future beam test equipment. These differences cause some differences in the heat loads for the two sectors. The flow direction (uphill in H60 and downhill in H20), cause some differences in the pressures in the lines due to static head effects.

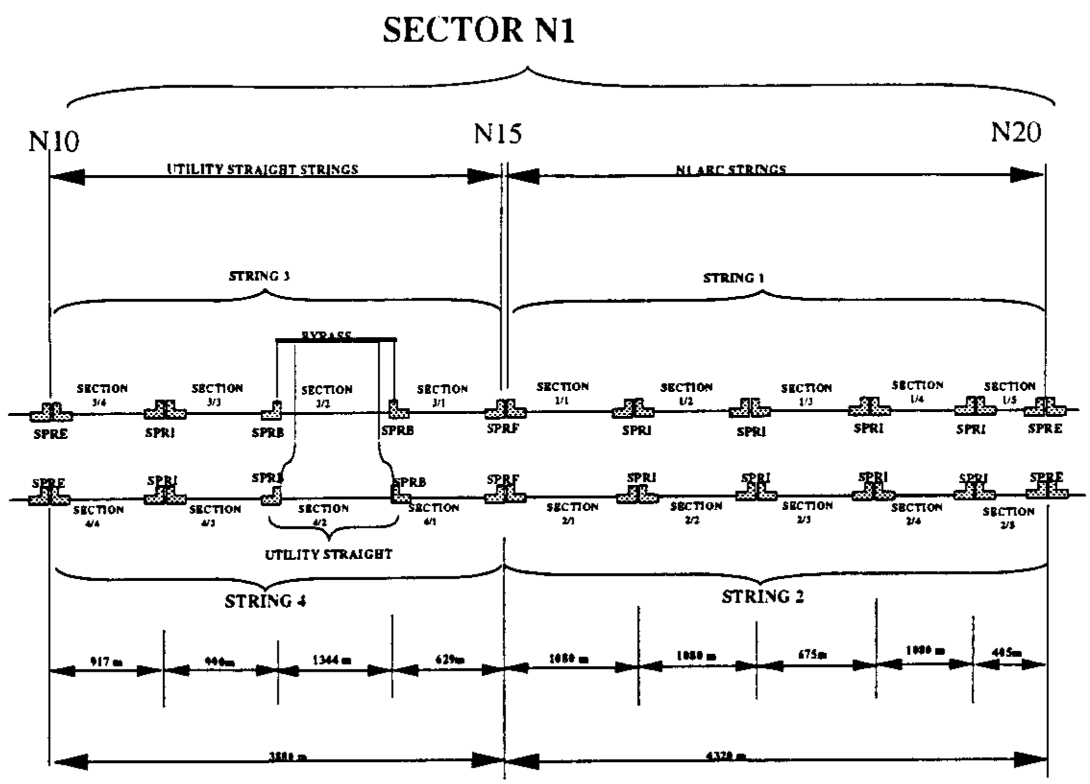


Figure 3.4-1. Definitions of a cryogenic sector for the collider.

Table 3.4-1. Typical structure of a cryogenic sector in the collider.

IN EACH RING	
Half-cell Five dipoles with interconnections Quadrupole with interconnections SPXA spool with: correction coils, bypass leads with quench stopper, beam-line pump-out, quench vent valve,vacuum barrier, and instrumentation	90 m long
Cell: Two half-cells including SPRA spool.**	180 m long
Section: Six cells including SPRI spool at each end.**	1080 m long
String: 24 cells; 4 sections including an SPRE spool at one end and an SPRF spool at the other end. SPRE and SPRF spools with end boxes with 7 kA lead pair, U-tubes, connection to refrigerator, and instrumentation Refrigeration connection box with transfer line Auxiliary end box connecting with adjacent sector	4.320 km long
Including both rings: Cryogenic sector: four strings in pairs Refrigeration plant with compressors, helium management system with gas storage, liquid helium storage, liquid helium circulator and subcooler, liquid nitrogen circulator and subcooler, liquid nitrogen storage	8.640 km long

* These distances may vary and depend on the position of isolation, feed, and end spool. Numbers given are "nominal" values.

** Spool definitions are given in Section 4.1.

4. Specific Cryogenic Components

4.1 The Spool Pieces

Generic names for the different spools are listed below:

SPXA	Standard spool with no recooler (Fig. 4.1-1).
SPRA	Standard spool with recooler (Fig. 4.1-1).
SPRI	Isolation spool with a recooler on the right side (Fig 4.1-2).
SPRF	Feed spool with recoolers on both sides (Fig. 4.1-2).
SPRE	End spool with a recooler on the right half. The right half is part of one sector and the left half is part of the adjacent sector.
SPXS	Standard spool with no recooler extended 2.5 m with the addition of an empty cryostat.
SPRS	Standard spool with recooler and 2.5 m extension.
SPRT	Spool with recooler to connect an isolated magnet to a bypass (Fig. 4.1-3).
SPRB	Spool with recooler to connect a string of magnets to a bypass (Fig. 4.1-4).
SPRC	Spool with recooler to connect an isolated magnet string to a bypass (Fig. 4.1-5)
SPXR	Return box (Fig. 4.1-3).
SPXU	Standard spool with no recooler and no vacuum barrier, used in the utility straights.

Figure 4.1-1 is an isometric view of a standard spool with no recooler. In the collider the SPRA is similar to the SPXA, but contains a recooler concentric to the cold mass.

Figure 4.1-2 shows the conceptual design of the right half of an SPRF. The SPRE, with a helium recooler in one half only, is similar to the SPRF but the two halves are interconnected through an auxiliary valve box. The SPRI is the same length as the SPRF, with the two halves connected by U-tubes.

4.2 The Empty Cryostat

The regular empty cryostat (EC) for the collider and for the HEB contains six cryogenic lines (Sec. 3.1, above). Like the magnets and spool pieces, it contains the beam tube and requires precise mechanical design. The 4 K single-phase helium line (Line 1) is designed to carry the cold superconductive electric bus. The standard EC is 15.815 m for the collider and 13.171 m for the HEB. The lead and return ends of the EC have the same interconnect design as for the regular magnets. Special empty cryostats are required in the interaction region where two parallel cryostats are merged into one. These special cryostats will contain 12 cryogenic lines of the same diameters as the EC and a vacuum vessel similar to the cryostat design containing two vertical bending dipoles (Fig. 3.1-4.), above.

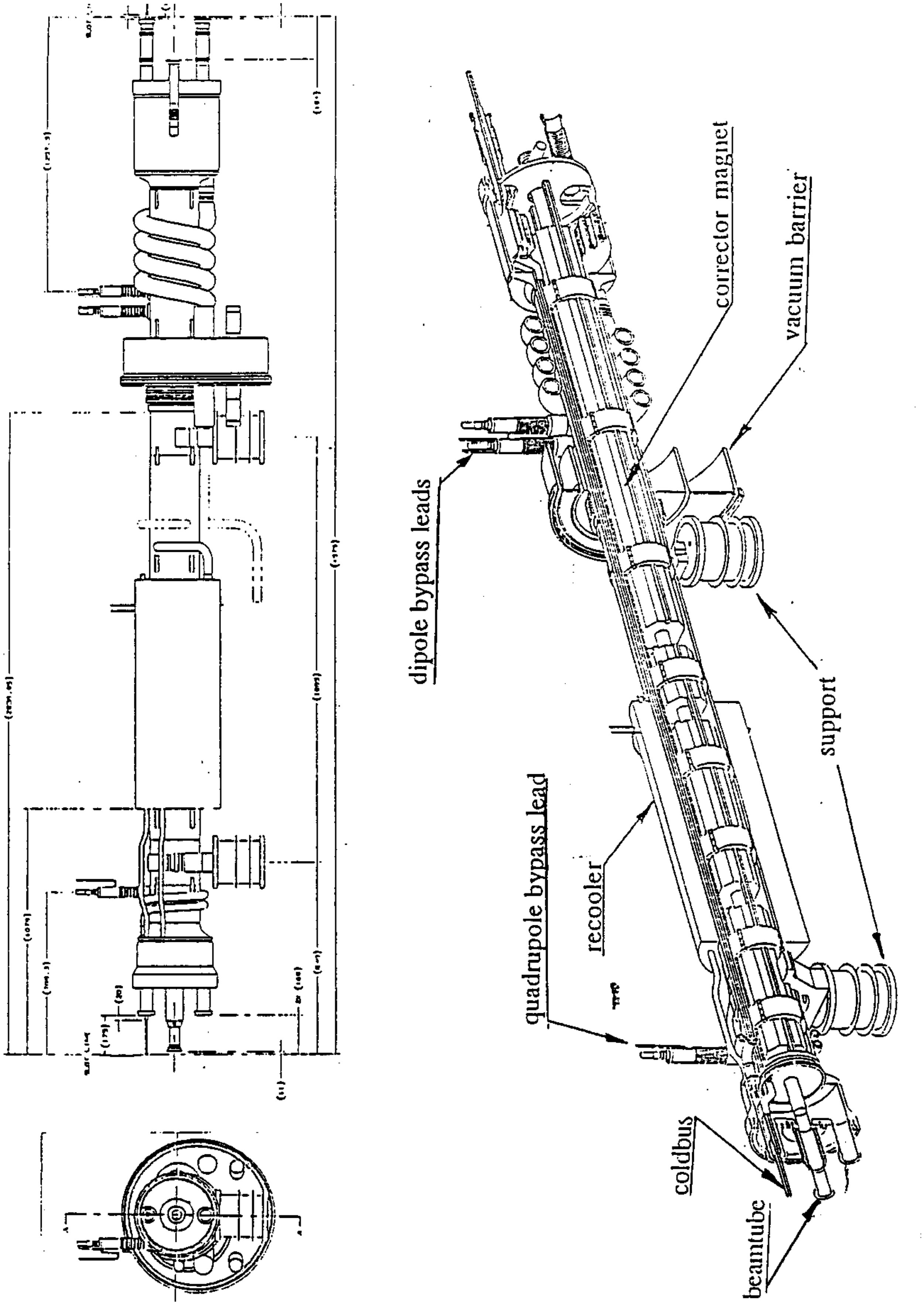


Figure 4.1-1. The cold mass of a standard spool with recooler (SPRA) with supports.

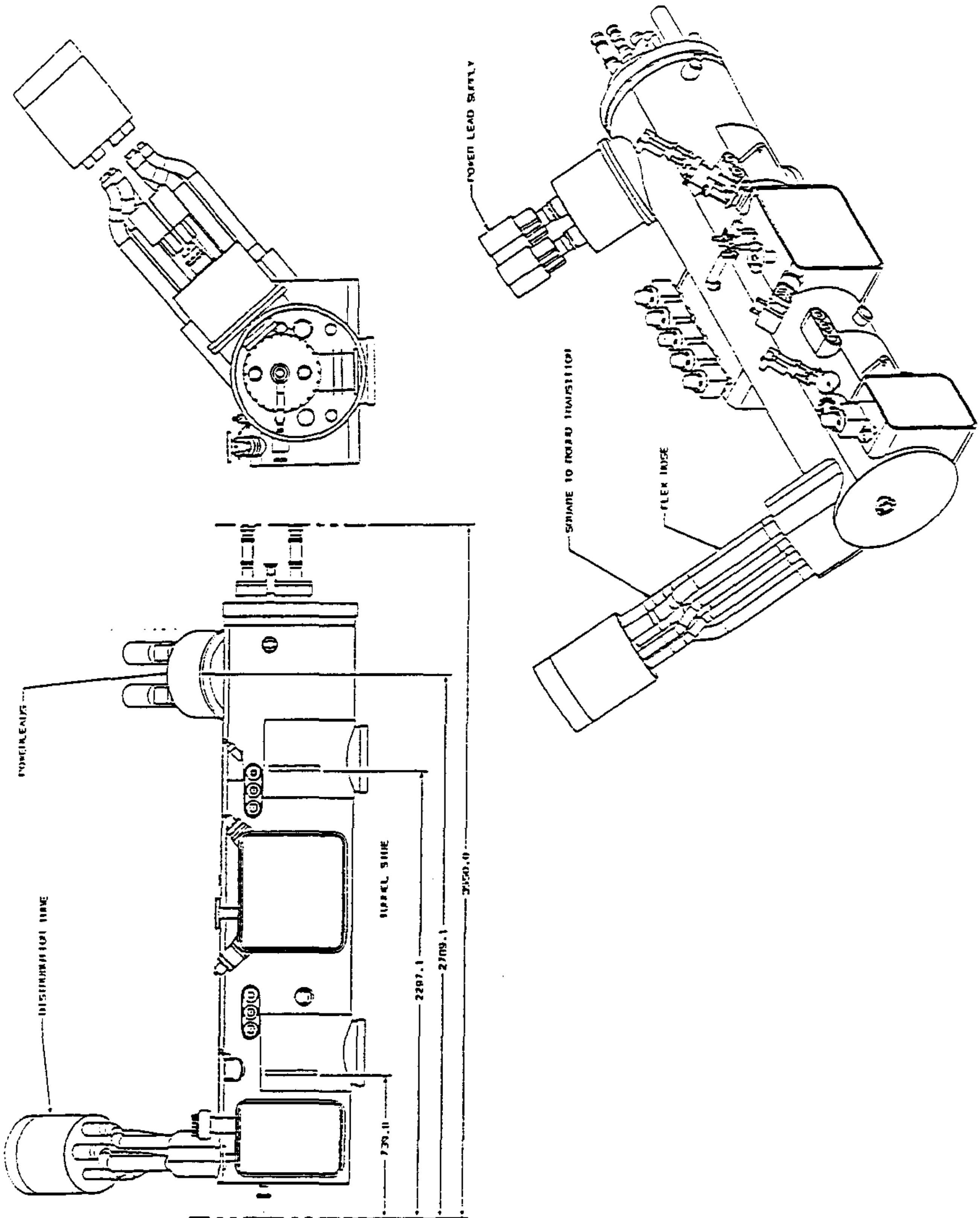


Figure 4.1-2. Right half of a feed spool with recoolers (SPRF).

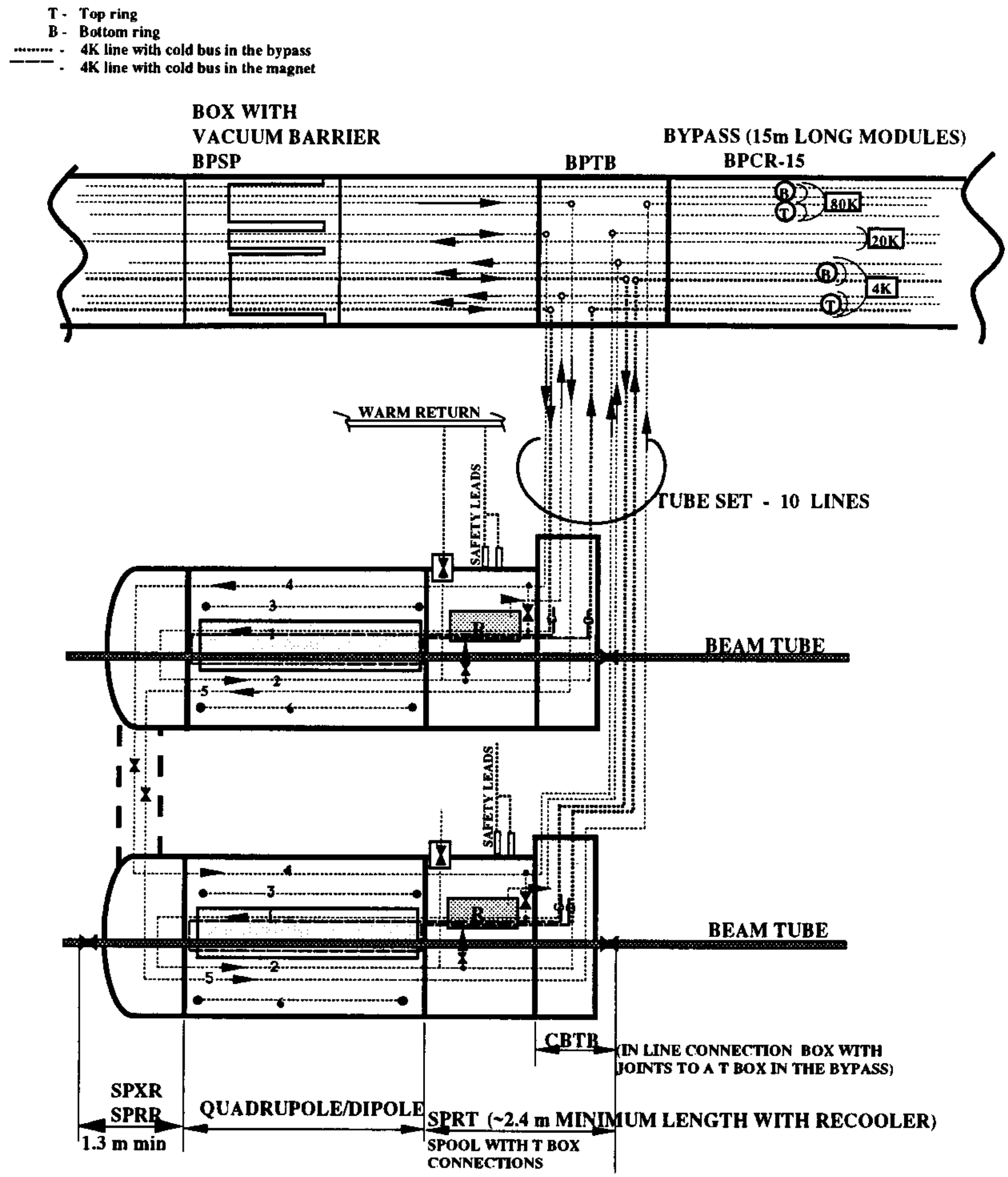


Figure 4.1-3. Isolated cryostats in the cluster regions

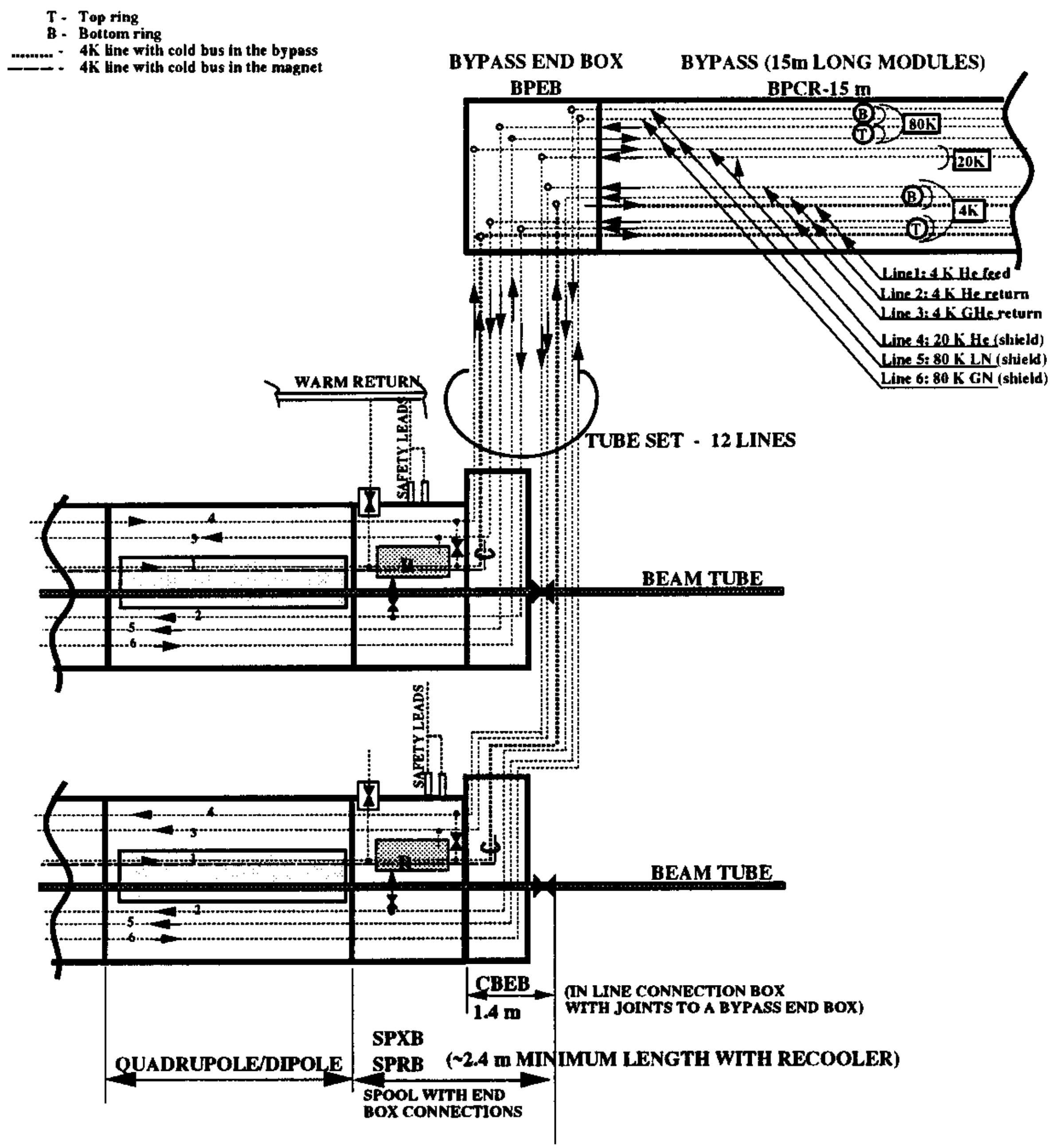


Figure 4.1-4. Connections to the cryo-bypass in the cluster regions

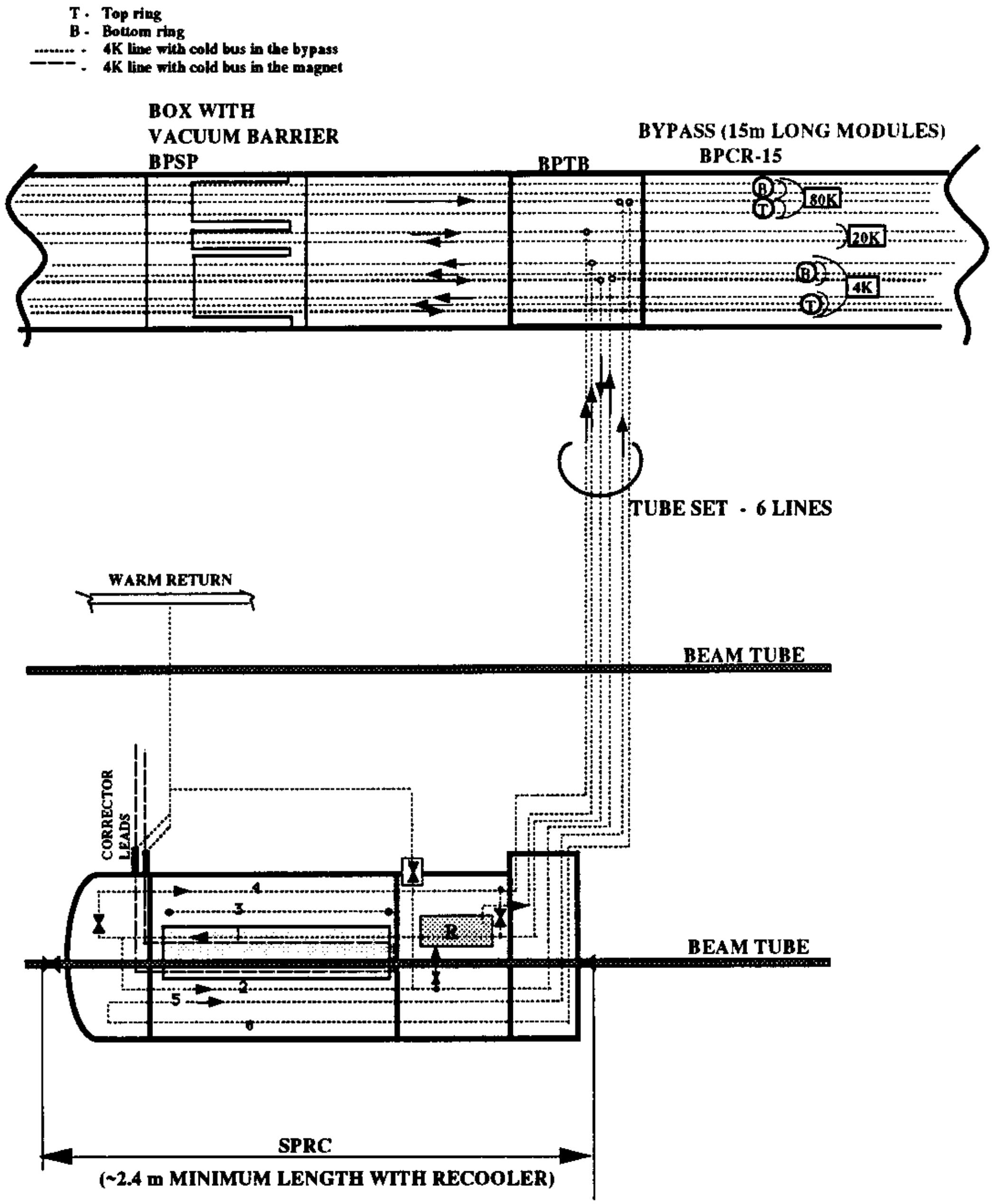


Figure 4.1-5. Isolated cryostats for the skew quadrupoles

4.3 THE CRYOGENIC BYPASS TRANSFER LINE

The cross sections of the bypass transfer lines are shown in Figure 3.1-1. For the collider the basic module of the bypass BPCR is 15.815 m long and contains 12 cryogenic lines. For the HEB the basic module is 13.171 m long and contains six cryogenic lines. The feed lines of the single-phase flow carry high current busses for the magnets.

In the bypass there are several cryogenic boxes to enable the connection of isolated magnets as well as boxes for vacuum instrumentation and helium recoolers. These are:

- BPEB To connect the magnet string to the bypass (12 connections in the collider and six in the HEB)
- BPTB To connect an isolated cryostat to the bypass (10 connections in the collider and seven in the HEB)
- BPSR A box with a recooler and/or a vacuum barrier

In the HEB the sector feed can, the sector end cans, and the isolation spools are located in the bypass.

4.4 THE TRANSFER LINES AND UNDERGROUND DISTRIBUTION BOX

The underground (tunnel) distribution box (Fig. 4.4-1, Collider and Fig. 4.4-2, HEB) distributes the cryogen streams from the surface refrigerator, via the helium cold compressor box and the liquid nitrogen subcooler box, to the four strings of the collider or to the two strings of the HEB. Transfer lines connect the underground distribution box to the helium cold compressor box and liquid nitrogen subcooler box. These lines are grouped into bundles which are packaged in superinsulated vacuum vessels.

The shaft transfer line system (STL)

The shaft transfer line connnects the surface distribution box to the tunnel's cold compressor box. It contains:

a. Single-phase feed (helium)

b. Single-phase return (helium)

c. Gaseous helium return line (helium)

d. 20 K feed (helium)

e. 20 K return (helium)

f. LN_2 line

g. GN_2 return line

Cryogenic distribution lines

The transfer line bundle from the cold compressor box to the underground distribution box contains:

a. Single-phase feed (helium)

b. Single-phase return (helium)

c. Gaseous helium return line (helium)

d. 20 K feed (helium)

e. 20 K return (helium)

f. LN_2 line

g. GN_2 return line

The transfer line bundle from the underground distribution box to the LN_2 subcooler box contains:

a. LN_2 lines (6)

b. GN_2 return line (1)

The transfer line bundles from the underground distribution box to the feed spools (four bundles in the collider, two in the HEB) each contain six lines:

a. Single-phase feed, Line 1 (helium).

b. Single-phase return, Line 2 (helium).

c. Gaseous helium return, Line 3 (helium).

d. 20 K feed/return, Line 4 (helium).

e. LN2, Line 5.

f. GN_2 return, Line 6.

The Underground Distribution Box (UDB)

The underground distribution box splits the main supply streams to the four strings. The flow through each line is regulated by a control valve and/or an ON/OFF isolation valve located in this distribution box, as follows:

a. Single-phase feed (control valve, Line 1).

b. Single-phase return (ON/OFF valve, Line 2).

c. Gaseous helium return line (ON/OFF valve, Line 3).

d. 20 K feed/return (control valve for supply, ON/OFF for return, Line 4).

e. LN_2 feed/return line (ON/OFF valve, Line 5).

f. GN_2 line (ON/OFF valve, Line 6).

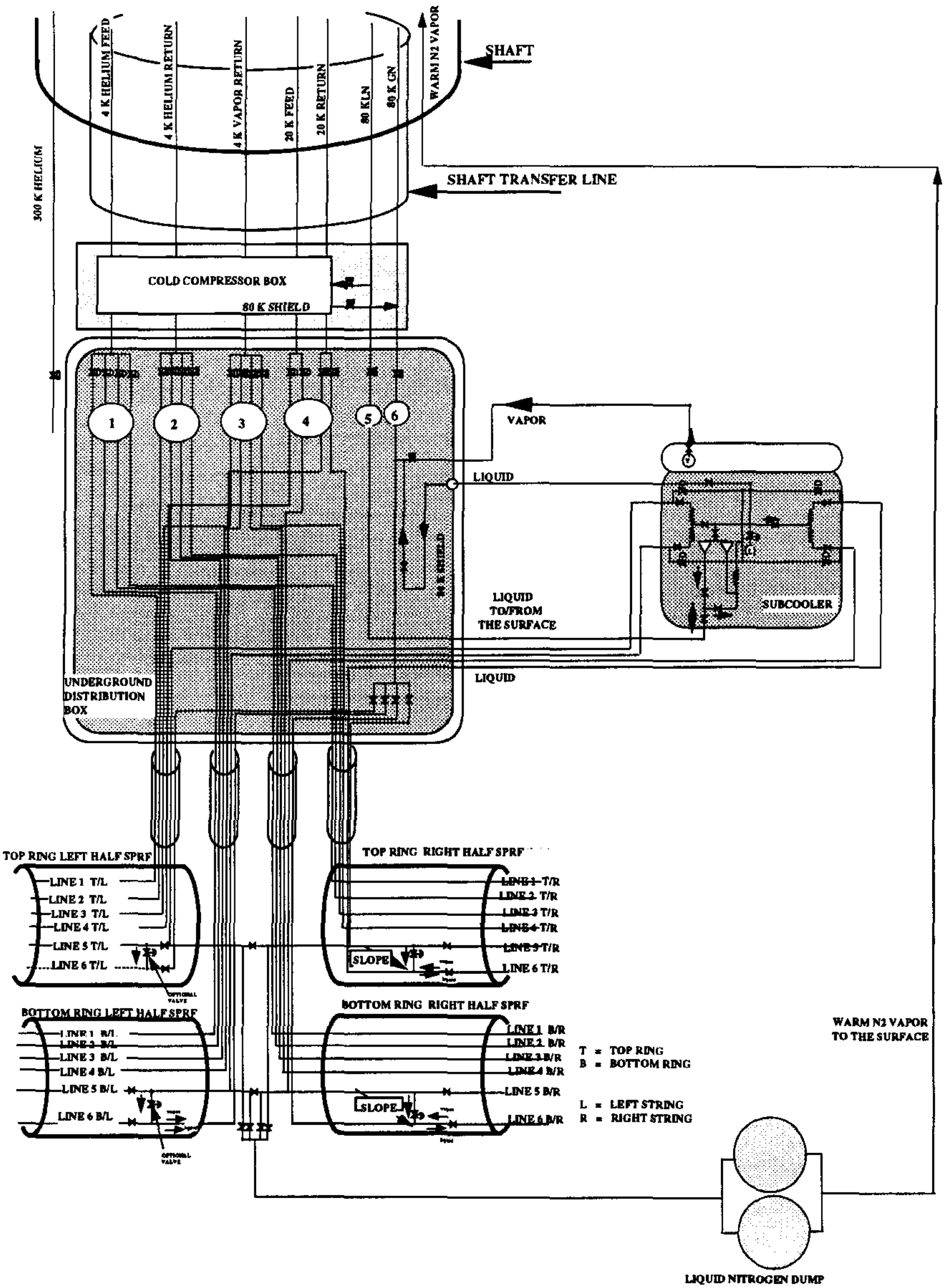


Figure 4.4-1. Collider cryogenic distribution lines, underground distribution box and LN2 coldbox

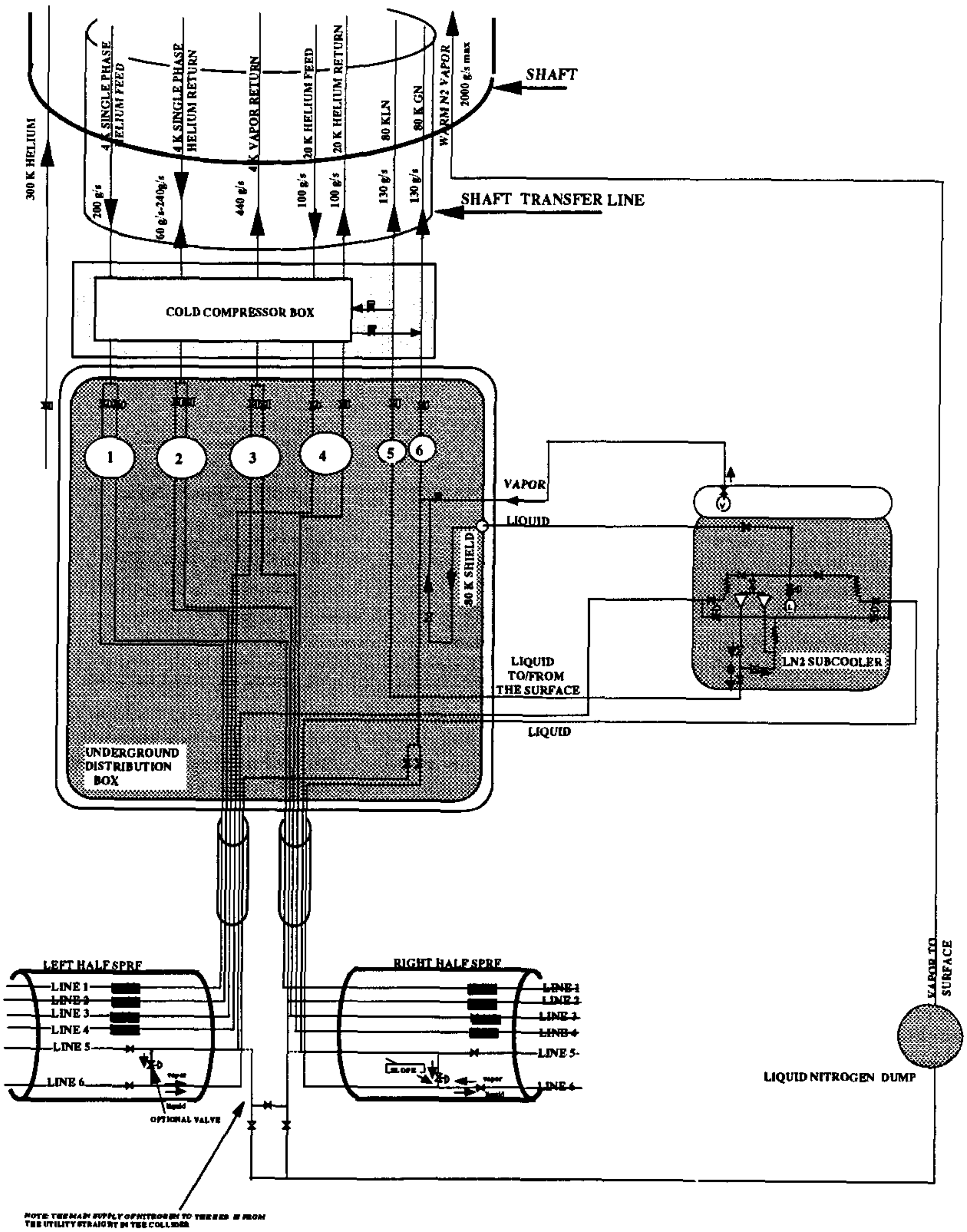


Figure 4.4-2. HEB cryogenic distribution lines, underground distribution box, and LN_2 coldbox

4.5 THE AUXILIARY END BOX

This box serves as the interface between two sectors and is located at the end of a string at the even-numbered sites. It contains isolation valves that allow cryogens to flow across sector boundaries. It also contains a nitrogen subcooler that is part of the nitrogen shield cooling system. The arrangement of the end spools and auxiliary end box can be seen in Figures 4.5-1 and 4.5-2.

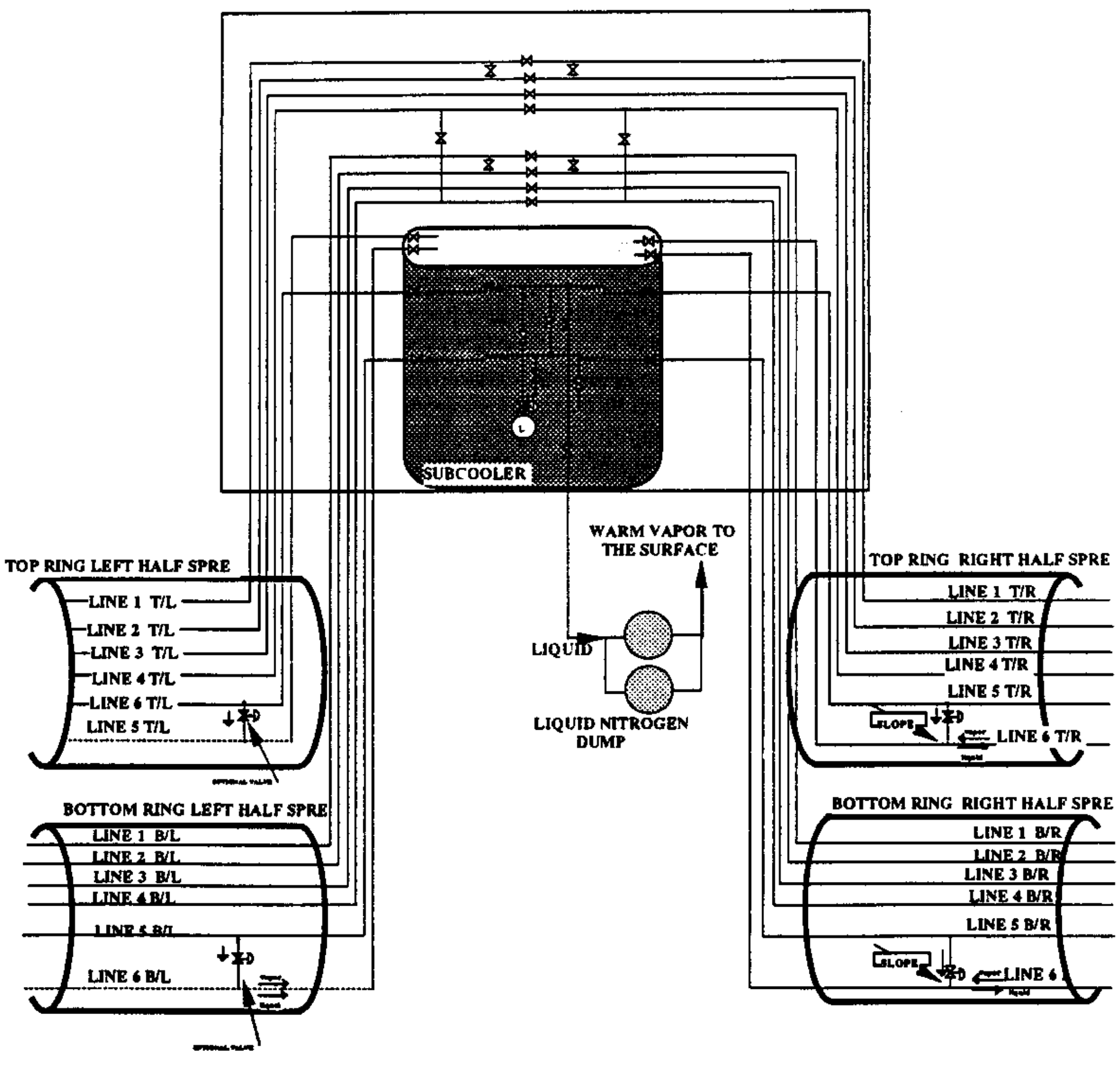


Figure 4.5-1. Collider SPRE and auxiliary end box

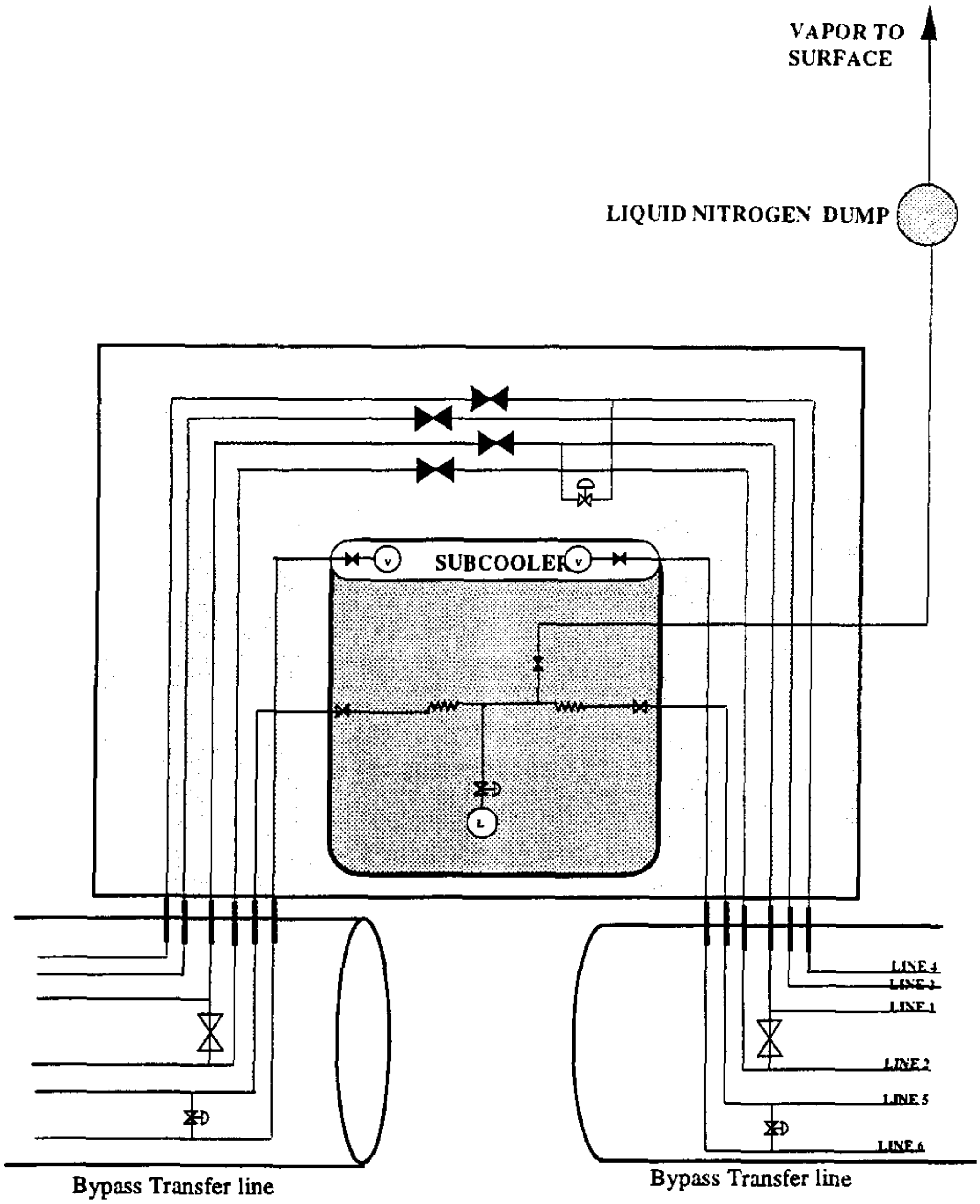


Figure 4.5-2. HEB bypass end box (SPRE) and auxiliary end box.

4.6 THE COLD COMPRESSOR BOX (CCB)

The helium cold compressor box serves as the interface point between the shaft transfer line system and the remainder of the tunnel equipment. It also contains the cold compressor that maintains the boiling temperature in the recoolers of the magnet strings at 3.95 K–4.00 K. The single-phase helium main feed flow from the surface is cooled in a heat exchanger by the return vapor and the remaining return liquid from the magnet strings. The cold compressor operates with an inlet temperature of 4.3 K and at a suction pressure of 0.75 bar, and discharges at 1.45 bar. There will be additional connections to install a second cold compressor, operating in series with the first, for conditioning of the magnet strings by a temporary temperature reduction. The appropriate bypass and isolation valves are designed into this box to perform the various utility loops and standard operating loops of the cryogenic system. Figure 4.6.1 shows a conceptual schematic of this box. An alternate design configuration involves the compression of the saturated return vapor without superheating.

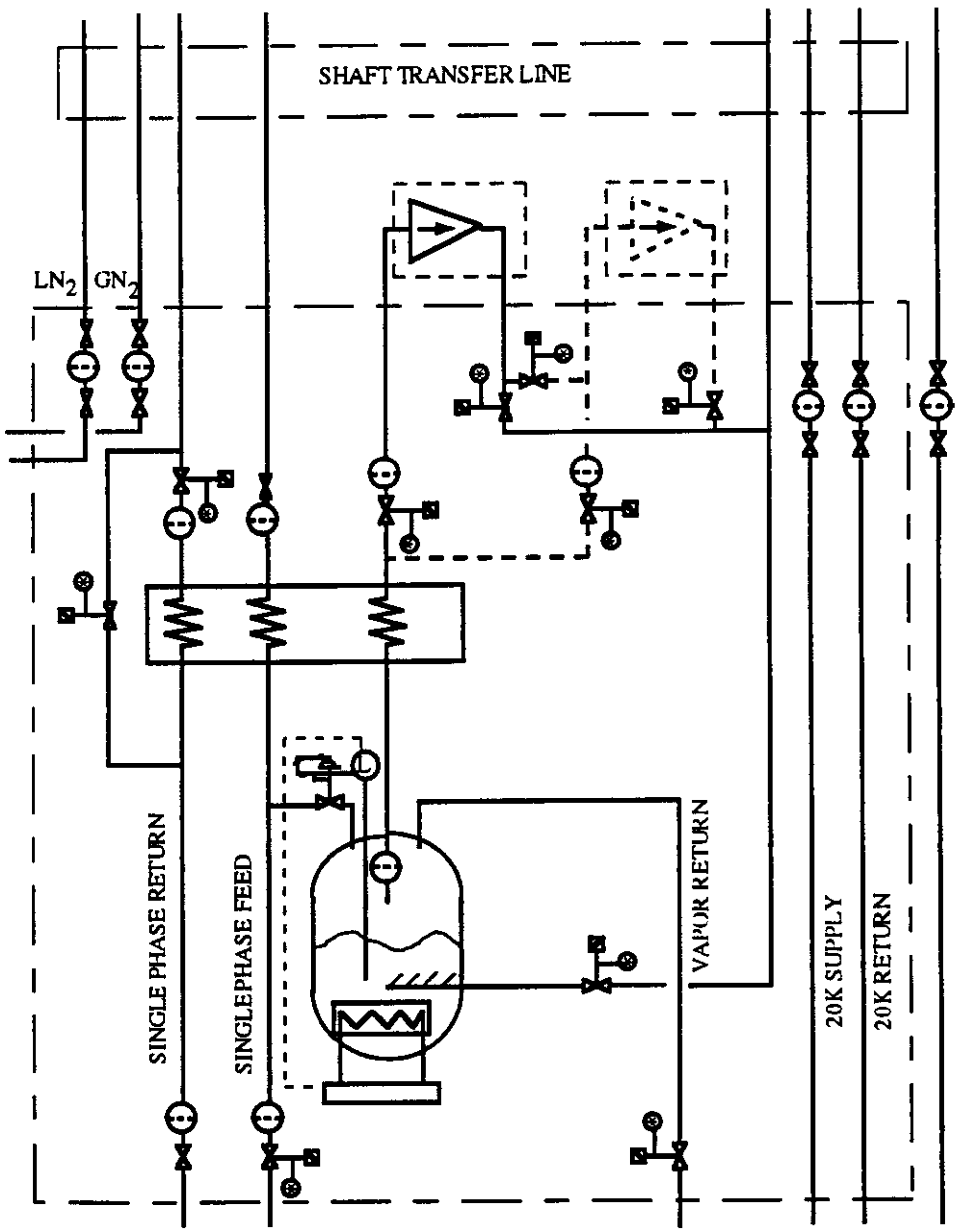


Figure 4.6-1. Cold compressor box.

4.7 Nitrogen Coldbox (NCB) and LN_2 Recoolers

The nitrogen coldbox is part of the 80 K nitrogen shield cooling system for the magnet strings. The main components in this box are:

a. A subcooler vessel and the appropriate heat exchangers to subcool the flows.

b. A circulation/booster pump for boosting the LN_2 pressure for local circulation and/or to supply the flow into the next sector.

c. A booster pump to supply liquid to the surface

d. Appropriate valving to operate the nitrogen shield cooling system in various configurations. See Figure 4.7.1.

LN_2 recoolers are located at given intervals in the tunnel to recool the liquid nitrogen stream through the 84 K shield. The vapor generated in the recoolers is returned through the GN_2 line to the helium refrigerator and vented into the atmosphere at 300 K.

4.8 Nitrogen Dump Tanks (NDT)

Two uninsulated 3000 gallon tanks are located in the tunnel feed area (odd-numbered sites N15, N25, N..., S15, S25, S...) and in the sector boundary area (even-numbered sites N20, N30, N..., S20, S30, S...). These tanks are used as emergency dump tanks. In the event of an accident to the magnet vessel which might cause LN_2 to drain into the tunnel space, the nitrogen shield system is depressurized by sending liquid to these dump tanks. Vapor generated in these tanks is vented to the surface through a vent stack. The LN_2 dump tanks can be located as shown in Figure 4.5-1, above.

5. HEAT LOAD BUDGET

Heat transfer into the components at liquid helium temperature is minimized by two thermal shields maintained at 80 K and 20 K and by an insulating space maintained at high vacuum. Heat input to the 4 K components is characterized into two loads: dynamic and static. The major portion of dynamic load is caused by the synchrotron radiation from the beam. Static load results from the heat conduction and thermal radiation loads from the warmer parts in the cryostat. This heat from the 4 K components is removed by circulating single-phase 4 K helium through these components and by recooling this single-phase stream in recoolers along the string.

The heat load from the 4 K components is reflected as a 4 K refrigeration load on the helium plant. Some components that protrude from the outside into the 4 K parts of the cryostat, such as electrical leads, are cooled by small streams of 4 K helium; this helium is returned warm to the plant and translates into a liquefaction load on the helium plant.

The temperature of the 20 K shield is maintained by circulating 3 bar helium gas through the shield at a supply temperature of 14 K. Heat into the 80 K shield is removed by an independent nitrogen cooling system. The heat loads of the various equipment are budgeted to one of the three loads on the helium refrigeration system—that is, the 4 K refrigeration load, the liquefaction load, or the 20 K shield load. The 80 K loads are budgeted to the nitrogen cooling system.

5.1 HEAT BUDGET FOR THE COLLIDER

A typical collider sector configuration is given in Table 3.4-1, above.

Collider main components heat budget

The heat budget for the main magnets is given in Table 5.1-1. The heat budget for the various spools is given in Tables 5.1-2 through 5.1-5.

Table 5.1-1. Heat budget for the main magnets

		Static heat loads (Watts)			Dynamic heat loads (Watts)					
Magnet type		Infrared and support	Intercon	Total Static	Synchro-tron Radiation	Splices	Beam Micro-wave	Beam Gas	Total Dynamic	Total Magnet
CDM-15 m Dipole	4 K	0.21	0.15	0.36	2.17	0.14	0.2	0.14	2.64	3.0
	20 K	4.7	0.32	5.0						5.0
	80 K	35	2.1	37						37.0
CDM-13 m Short dipole	4 K	0.20	0.15	0.35	1.81	0.14	0.19	0.11	2.25	2.6
	20 K	4.42	0.32	4.74						4.74
	80 K	32	2.1	34.1						34.1
CQM-Quad	4 K	0.08	0.15	0.23	0.74	0.22	0.17	0.05	1.18	1.41
	20 K	1.8	0.32	2.1						2.1
	80 K	13	2.1	15						15.0

Table 5.1-2 . SPXA-type spool heat budget (including interconnect)

Heat Budget	Liquid (G/S)	4 K (W)	20 K (W)	80 K (W)
Total static heat load	0.072	2.58	15.1	54.5
Dynamic heat loads:				
Synchrotron radiation		0.65		
Splices		0.08		
Beam microwave load		0.17		
Beam-gas load		0.04		
Total dynamic heat load		0.95*		
Total SPXA-type spool	0.072	3.53*	15.1	54.5

* The sychrotron radiation heat load is generated in the dipole magnets and some is deposited in the spool pieces. The sector heat loads listed in section account for the synchrotron heat load as being generated and deposited only in the dipole magnets.

Table 5.1-3. SPRA-type spool heat budget (including interconnect)

Heat Budget	Liquid (G/S)	4 K (W)	20 K (W)	80 K (W)
Static heat loads:				
Total static SPXA-type spool	0.072	2.58	15.1	54.5
Single-phase relief line		0.03	0.3	1.4
Recooler feed valve		0.03	0.3	1.4
Recooler level gauge		0.03	0.3	1.4
Total static		2.68	15.9	58.7
Dynamic heat loads:				
SPXA-type dynamic		0.95*		
Total SPRA-type spool	0.072	3.63*	15.9	58.7

* The sychrotron radiation heat load is generated in the dipole magnets and some is deposited in the spool pieces. The sector heat loads listed in section account for the synchrotron heat load as being generated and deposited only in the dipole magnets.

Table 5.1-4. SPRI-type spool heat budget (including interconnect)

Heat Budget	Liquid (G/S)	4 K (W)	20 K (W)	80 K (W)
Total static heat load	0.072	5.59	28.1	194
Dynamic heat loads:				
Total static SPRA-type dynamic spool		0.95*		
Synchrotron radiation		0.28*		
Four Splices		0.08		
Beam microwave load		0.32		
Beam-gas load		0.02		
Total dynamic heat load		1.66		
Total SPRA-type spool	0.072	7.25*	28.1	194

* The sychrotron radiation heat load is generated in the dipole magnets and some is deposited in the spool pieces. The sector heat loads listed in section account for the synchrotron heat load as being generated and deposited only in the dipole magnets.

Table 5.1-5. SPRF/SPRE-type spool heat budget (including interconnect)

Heat budget	Liquid (g/s)	4 K (W)	20 K (W)	80 K (W)
Static heat loads:				
Total static SPRI-type spool	0.07	5.59	28.1	194
Less bus connection		-0.1	-4.00	-15
2 pairs 6.6 kA current leads	1.58	31.7	4.00	20
Total static	1.66	37.2	28.1	199
Total dynamic SPRI-type spool		1.7*	0	0
Total SPRF/SPRE-type spool	1.66	38.8*	28.1	199

* The sychrotron radiation heat load is generated in the dipole magnets and some is deposited in the spool pieces. The sector heat loads listed in section account for the synchrotron heat load as being generated and deposited only in the dipole magnets.

Collider string heat budget

The heat budget for a typical string is given in Table 5.1-6. There is a difference in the expected heat loads for the different strings due to small variations in the design of the arc strings. The heat budget for 20 collider strings in one ring is given in Table 5.1-7. For the 4 K loads three values are tabulated: the static load (the heat leak with no particle beam in the system), the dynamic load (the addditional load due to the existence of the beam), and the total load (the sum of the two).

Collider sector heat budget

The sector heat load is calculated by summation of the loads of all strings connected to the same feed plus the additional global loads of the sector. Table 5.1-8 shows the calculated heat load for each helium refrigeration plant. Figure 5.1-1 gives the graphical comparison of the heat loads for the different sectors.

Table 5.1-6. String and sector heat budget

Item	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
String heat load (static):				
Dipoles (240)		87	1213	8880
Quadrupoles (48)		11	100	720
SPXA-type spools (24)	1.7	62	361	1310
SPRA-type spools (20)	1.4	54	318	1170
C(0.5) (48)		7	15	100
SPRI-type spools (2)	0.2	11	56	390
SPRF-Type spools (2)	3.3	74	56	400
Total Static	6.6	306	2121	12970
String heat load (dynamic):				
Dipoles (240)		633		
Quadrupoles (48)		21		
SPXA-type spools (24)		7		
SPRA-type spools (20)		6		
SPRI-type spools (2)		2		
SPRF-type spools (2)		2		
Total Dynamic		671		
String total heat load	6.6	977	2121	12970
Sector heat loads				
Sector static heat loads	26.5	1227		51880
Sector dynamic heat load		2682		
Sector allowances				
Helium storage	0.8			
Refrigeration connection box		8		150
Auxiliary end box		10		200
Transfer line		10		500
Pump box		140		400
Pump work		550		
Purifier operation				2500
Quench and cooldown recovery	3.5			
Performance and control	1.5	500		5000
Unallocated	3.7	273		4370
Sector total heat load	36.0	5400	10000	65000
Redundancy adjustment factor	1.25	1.25	1.5	
Refrigeration plant capacity required	45.0	6750	15000	65000

Table 5.1-7. The string heat loads

String Heat Loads	Liquif. g/s	4 K Watts Static	4 K Watts Dynamic	4 K Watts Total	20 K Watts	80 K Watts
N10-N15	4.39	238	325	562	1626	10223
N15-N20	6.77	314	661	975	2145	13072
N20-N25	6.26	285	596	881	1908	11742
N25-N30	6.62	309	663	972	2120	13005
N30-N35	6.91	332	724	1056	2314	14238
N35-N40	6.77	317	683	1000	2190	13403
N40-N45	6.62	306	663	968	2107	12866
N45-N50	6.62	306	663	969	2108	12870
N50-N55	6.77	314	664	978	2151	13118
N55-S10	14.04	547	566	1113	2960	17596
S10-S15	4.39	238	325	562	1626	10223
S15-S20	6.41	288	599	886	1932	11755
S20-S25	7.06	336	733	1069	2353	14366
S25-S30	6.41	291	621	912	1977	12087
S30-S35	6.34	289	607	897	1948	11970
S35-S40	7.13	343	745	1088	2401	14705
S40-S45	6.62	306	663	968	2107	12866
S45-S50	6.62	306	663	969	2108	12870
S50-S55	6.48	292	608	899	1966	11944
S55-S10	14.04	547	566	1113	2960	17596
H80-H20	9.78	493	1848	2341	2961	17093
H20-H40	6.95	345	1812	2157	2211	12305
Nominal String	6.62	307	671	977	2121	12968

Table 5.1-8. The sector heat loads

Sector	Liquifaction g/s	4 K Watts	20 K Watts
N1 (N10-N15-N20)	28.12	4333	8540
N2 (N20-N25-N30)	31.58	4966	9057
N3 (N30-N35-N40)	33.16	5372	10008
N4 (N40-N45-N50)	32.30	5134	9431
N5 (N50-N55-S10)	47.42	5441	11223
S1 (S10-S15-S20)	27.40	4157	8114
S2 (S20-S25-S30)	32.73	5223	9660
S3 (S30-S35-S40)	32.73	5229	9697
S4 (S40-S45-S50)	32.30	5134	9431
S5 (S50-S55-N10)	46.84	5285	10851
H20 (H80-H20-H40)	25.00	6200	7000
Sector Design Loads	36.00	5400	10000
Refrigerator Capacity	45.00	6750	15000

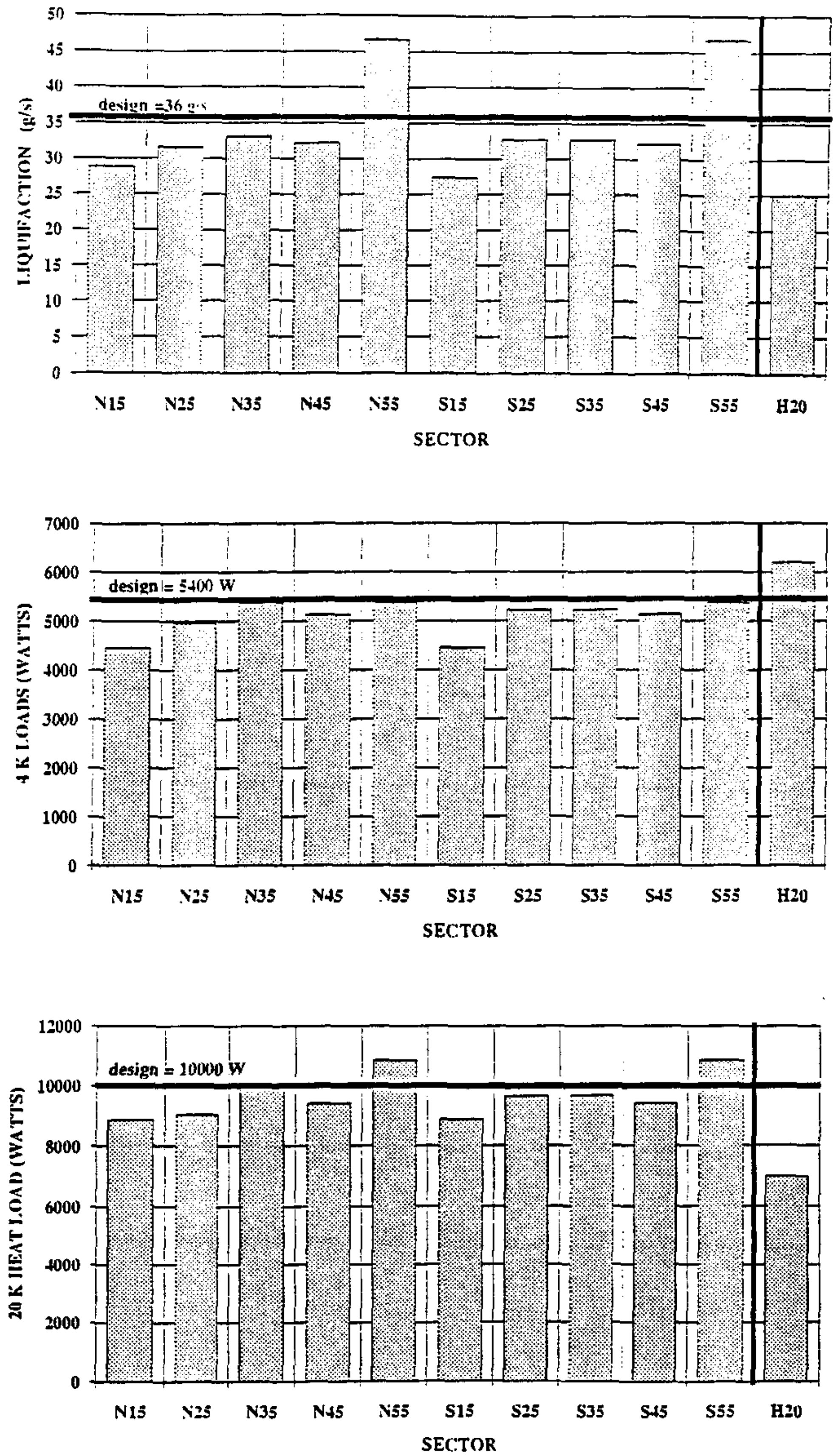


Figure 5.1-1. Sector heat loads

5.2 THE HEAT BUDGET FOR THE HEB

HEB main components heat budget

The heat budget for the main magnets in the HEB is given in Table 5.2-1. The heat budget for the various types of spools and cryogenic boxes is given in Tables 5.2-2 thru 5.2-9.

HEB string heat budget

The heat budget for the four strings of the HEB is given in Table 5.1-7, above.

HEB sector heat budget

The heat budget for the two cryogenic sectors in the HEB is given in Table 5.1-8, above.

Table 5.2.1. Heat budget for the main magnets

Magnet Type		Total Static Heat Loads (Watts)	Total Dynamic Heat Loads (Watts)	Total Magnet Heat Loads (Watts)
HDM	4 K	0.46	11.46	11.92
	20 K	5.61	-	5.61
	80 K	41.18	-	41.18
HQM	4 K	0.30	1.81	2.11
	20 K	1.90	-	1.90
	80 K	13.53	-	13.53
HQM1	4 K	0.30	1.17	1.46
	20 K	1.77	-	1.77
	80 K	12.47	-	12.47
HQM2	4 K	0.30	1.42	1.71
	20 K	1.82	-	1.82
	80 K	12.88	-	12.88
HQM3	4K	0.30	2.40	2.70
	20K	2.02	-	2.02
	80K	14.53	-	14.53
HQM4	4K	0.30	3.39	3.70
	20K	2.22	-	2.22
	80K	16.19	-	16.19

Table 5.2-2. HEB SPXA-type spool heat budget

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Infrared, support & other loads	0.072	2.22	13.81	49.17
Beam position monitor heat load		0.20	0.60	1.00
Interconnect		0.21	0.44	3.50
Total static heat loads	0.072	2.63	14.85	53.67
Dynamic heat loads		0.29		
Total dynamic heat load		0.29		
Total spool SPXA loads	0.072	2.92	14.85	53.67

Table 5.2-3. HEB SPRA-type spool heat budget

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads	0.072	2.73	15.71	57.87
Total dynamic heat loads		0.29		
Total spool SPRA loads	0.072	3.01	15.71	57.87

Table 5.2-4. Straight section and isolation spool heat budget

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads	0.012	0.67	7.97	23.14
Total dynamic heat loads		0.26		
Total spool SPX1 loads	0.012	0.93	7.97	23.14

Table 5.2-5. Spool SPR1 heat budget (including interconnect)

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads	0.012	0.77	8.83	27.34
Total dynamic heat loads		0.26		
Total spool SPR1 loads	0.012	1.03	8.83	27.34

Table 5.2-6. Spool SPRI heat budget (including interconnect)

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads	0.072	5.64	27.89	192.76
Total dynamic heat loads		0.37		
Total spool SPRI loads	0.072	6.00	27.89	192.76

Table 5.2-7. Bypass spool SPRI/SPRF heat budget (including interconnect)

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads	1.644	36.66	22.95	202.33
Total dynamic heat loads		0.16		
Total spool SPRI loads	1.644	36.82	22.95	202.33

Table 5.2-8. End box heat budget (End Box = BPEB + CBEB + Tubeset)

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads		3.15	10.14	116.89
Total dynamic heat loads		0.08	0.00	
Total spool BPEB loads		3.23	10.14	116.89

Table 5.2-9. T-box heat budget (T-Box = BPTB + CBTB + Tubeset)

Heat Budget	Liquefaction (g/s)	4 K (W)	20 K (W)	80 K (W)
Total static heat loads		3.11	9.85	115.49
Total dynamic heat loads		0.08	0.00	
Total spool BPTB loads		3.19	9.85	115.49

6. FLUIDS INVENTORY AND HEAT CAPACITY

6.1 FLUIDS INVENTORY

The fluids inventory for a typical collider sector under normal operating conditions is given in Table 6.1-1. The inventory of the HEB is given in Table 6.1-2.

6.2 SECTOR HEAT CAPACITY

The magnet mass heat capacity and the sector heat capacity for different ranges of temperatures are shown in Figure 6.2-1 and Figure 6.2-2. At 80 K the heat capacity is approximately 5% of the heat capacity at 300 K.

COLLIDER SECTOR FLUIDS INVENTORY

	Fluid	units or meters	I.D.	P	T	Density	Volume	Mass	Volume	Mass	Mass
	Type	per string	(mm)	(MPa)	(K)	(kg/l)	(liters)	(kg)	(l/string)	(kg/string)	(kg/sector)
				(nominal values)				P,T nominal		P,T nominal	
							per unit or per meter				
LINE 1	He			0.4	4.05	1.40E-01					
B (15.815 m)		236	n.a.				80	11.2	18,880	2,643	10,573
BS (13.285 m)		4					66	9.24	264	37	148
CQM (5.85 m)		48	n.a				29	4.06	1,392	195	780
Interconnect/unit (88.3 cm)		(240+48+48)	n.a.				26	3.64	8,736	1,223	4,892
Spool pieces (4.585 m)		48	n.a.				85	11.9	4,080	571	2,285
Recooler (tube side)		24	n.a.				3	0.42	72	10	40
LINE 1 Total:											**18,717**
LINE 2	He	4320	45.2	0.3	4.3	1.33E-01	1.60	0.21	6,928	921	3,686
LINE 3	He	4320	86.5	0.08	4.3	1.24E-02	5.87	0.07	25,374	315	1,259
Recooler (shell)		24	n.a.	0.08	4.3	1.40E-01	27.00	3.78	648	91	363
LINE 4	He	4320	82.6	0.3	20	6.00E-03	5.36	0.03	23,137	139	555
LINE 5	N2	4320	57.2	0.5	84	7.80E-01	2.57	2.00	11,095	8654	34618
LINE 6	N2	4320	57.2	0.13	84	5.50E-03	2.57	0.01	11,095	61	244
WARM GAS RETURN	He	4320	203	0.11	300	1.76E-04	32.35	0.01	139,748	25	49
							Collider Sector Total Helium Inventory (kg) :				**24,629**
							Collider Sector Total Nitrogen Inventory (kg):				**34,862**
STORAGE CAPACITY				P	T	Density	Volume				Mass
				(MPa)	(K)	kg/l	(liters)				(kg)
				(nominal values)							
Two Helium Dewars :				0.119	4.4	1.21E-01	230,000				**27,887**
10 Gas Tanks:				0.16	300	2.55E-03	1,150,000				**2,931**
One N2 Dewar:				0.3	87.9	7.57E+02	75,000				**56,768**
Total liquid Nitrogen consumption by the SECTOR is 272 g/s(tunnel) +128 g/s (surface) =400 g/s								or 1,440 kg/h or 34,560 kg/day or 12.6E+6 kg/year			
HELIUM PLANT AND VERTICAL TRANSFER LINES NOT INCLUDED											

Table 6.1-1. Collider sector fluids inventory

H E B FLUIDS INVENTORY

	Fluid Type	units or meters per sector short/long	I.D. (mm)	P (MPa)	T (K)	Density (kg/l)	Volume (liters)	Mass (kg)	Volume (l/sector)	Mass (kg/sector)	Mass (kg/HEB)
				(nominal values)				P,T nominal		P,T nominal	
							per unit or per meter		short/long	short/long	
LINE 1	He			0.4	4.05	1.40E-01					
B		64/64	n.a. (12.29 m)				66/unit	9.24/unit	4224/4224	591/591	4,728
HQM QF or QD		33/35	n.a (1.6 m)				8.62/unit	1.2/unit	284/301	39.7/42	327
HQM1 Q1,Q3,Q4,Q5		0/4	n.a. (0.902 m)				4.8/unit	0.67/unit	0/19.2	0/2.7	11
HQM2 Q2		0/1	n.a. (1.173 m)				6.329 /unit	0.88/unit	0/6.3	0/.88	4
HQM3 QS1		1/1	n.a. (2.258 m)				12.15/unit	17.0/unit	12.2/12.2	1.7/1.7	14
HQM4 QS2,QS3		2/2	n.a (3.347 m)				18.0/unit	2.5/unit	36/36	5/5	40
Inrterconnect/U		100/107	n.a. (88.3 cm)				26.0/unit	3.64/unit	2600/2782	364/389	3,012
Spool pieces		33/35	n.a.				69.25/unit	9.7/unit	2285/2424	320/339	2,636
Bypasses		1745m	similar to empty cryostats				4.1/m	0.574/m	7154(total)	1001(total)	1,001
Empty cryostats		717m	2x5.7 ID (20%occupied by COLD BUS)				4.1/m	0.574/m	2939(total)	411(total)	411
Recooler (tubes)		17/27	n.a.				3.0/unit	0.42/unit	51/81	7.1/11.3	74
LINE 2	He	1220/1480m	45.2	0.3	4.3	1.33E-01	1.605/m	0.2131/m	1958/2375	260/315	2,300
LINE 3	He	1220/1480m	110	0.08	4.3	1.24E-02	9.5 /m	0.1178/m	11590/14060	143.7/174.3	1,272
Recooler (shell)		17/27	n.a.			1.40E-01	27.0/unit	3.78/unit	459/729	64.2/102	665
LINE 4	He	1220/1480m	82.6	0.4	20	6.00E-03	5.359 /m	0.032/m	6538/7931	39.2/47.5	347
LINE 5	N2	1220/1480m	57.2	0.5	84	7.80E-01	2.57 /m	2/m	3135/3803	2445/2966	21,644
LINE 6	N2	1220/1480m	57.2	0.13	84	5.50E-03	2.57 /m	0.014/m	3135/3803	17.24/20.9	153
WARM GAS RETURN	He	10800m	8"=203	0.11	300	1.76E-04	349000	67.76	***	***	
								HEB Total Helium Inventory (kg):			**16,908**
								HEB Total Nitrogen Inventory (kg):			**21,797**
STORAGE CAPACITY				P (MPa)	T (K)	Density (kg/l)	Volume (liters)				Mass (kg)
				(nominal values)							
Four Helium Dewars :				0.119	4.4	1.21E-01	460,000				**55,774**
20 Gas Tanks:				0.16	300	2.55E-03	2,500,000				**5,862**
Two Nitrogen Dewars:				0.3	87.9	7.57E+02	150,000				**113,536**
Total Nitrogen consumption by the HEB is 450 g/s			or 1620 kg/h or 38,880 kg/day or 14.2E+6 kg/year								
HELIUM PLANT AND VERTICAL TRANSFER LINES NOT INCLUDED											

Table 6.1-2. HEB fluids inventory

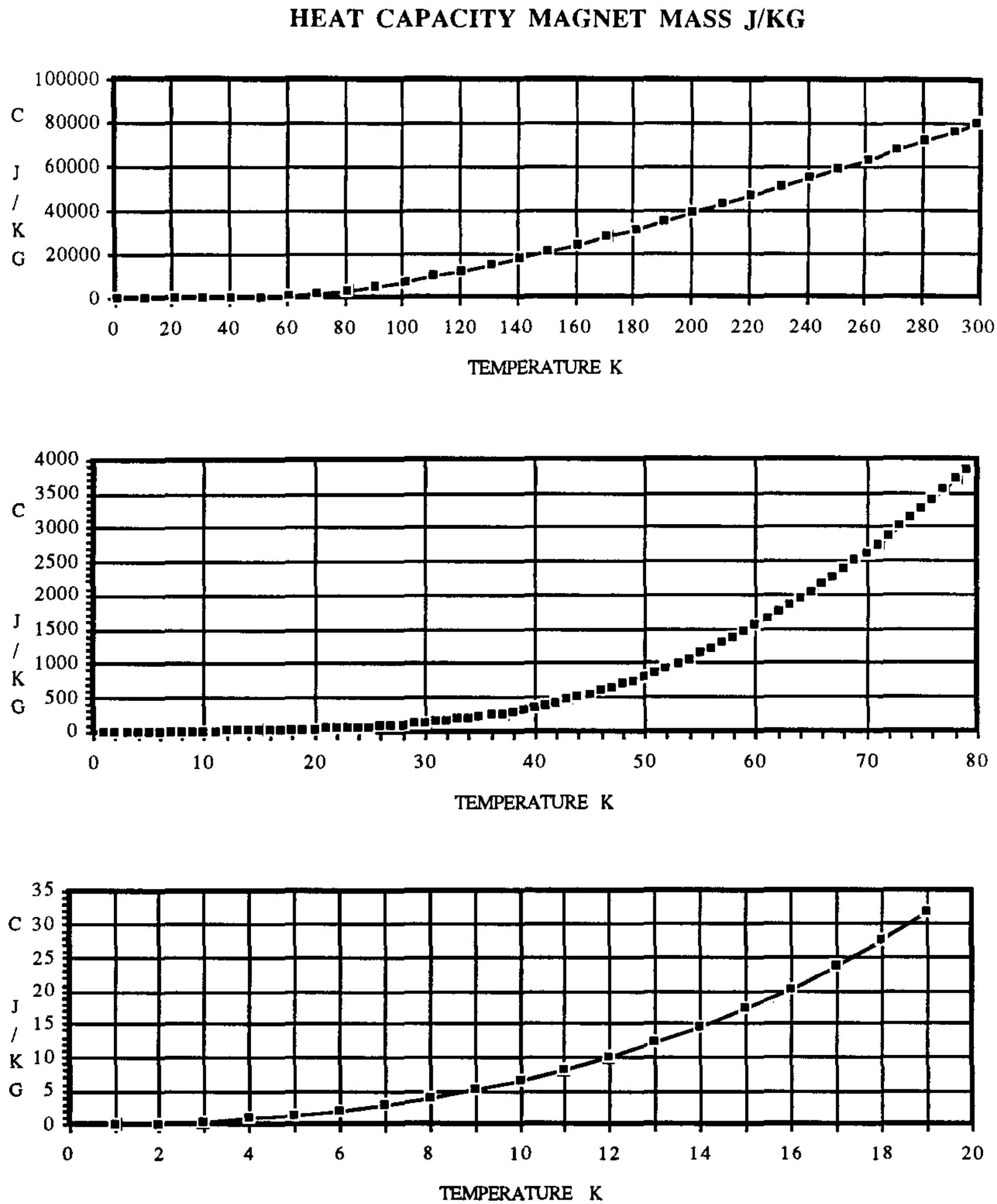


Figure 6.2-1. Magnet heat capacity

SECTOR HEAT CAPACITY

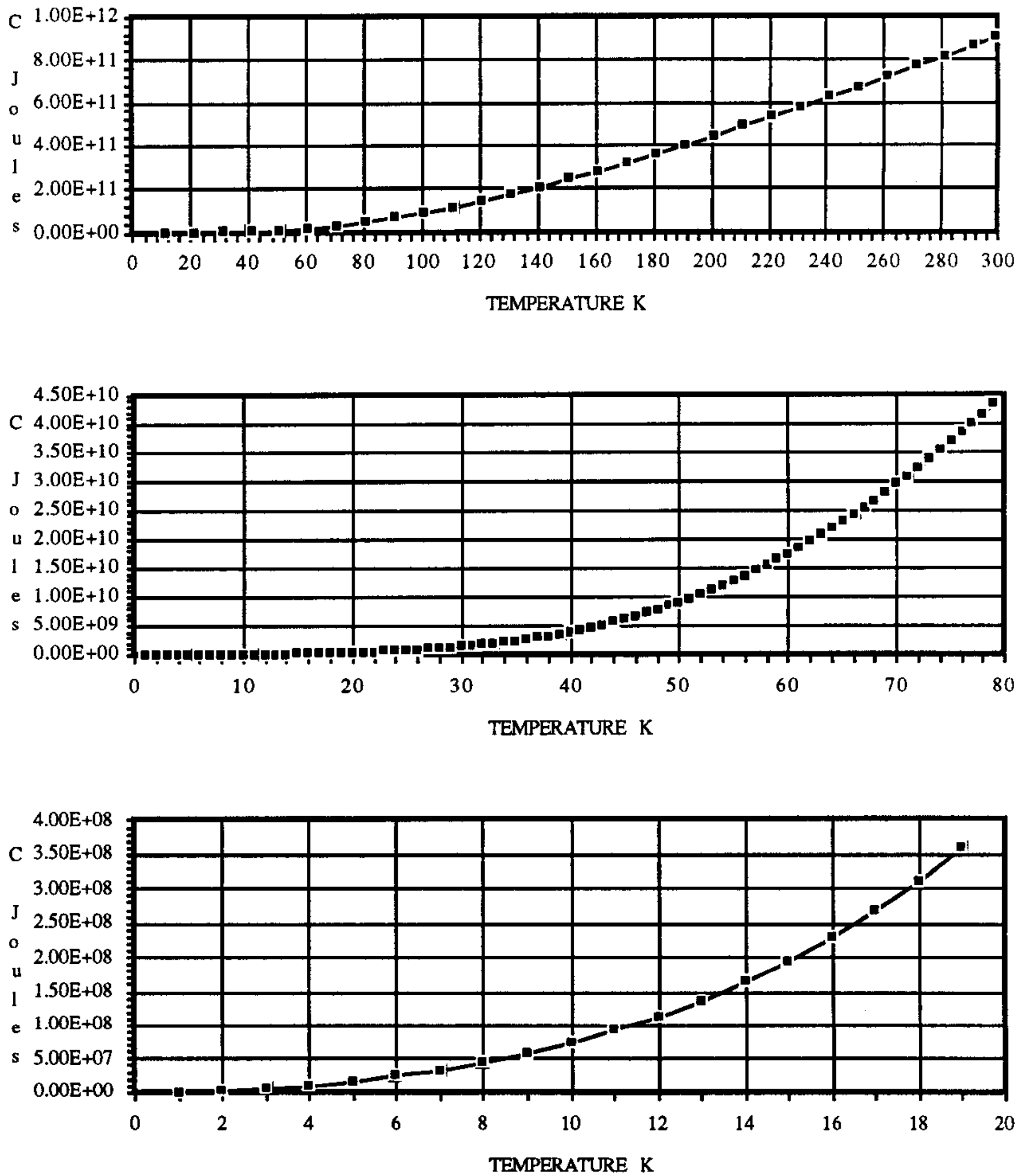


Figure 6.2-2. Sector Heat Capacity

7. REFRIGERATION SCHEMES AND OPERATING CONDITIONS OF THE SECTOR STATION CRYOGENIC SYSTEM (SCS)

7.1 SYSTEM CONFIGURATION DESIGN

The SCS is divided into the sector refrigerator surface system (SRS), the sector refrigerator tunnel system (SRT), and the sector refrigerator control system (SRC). The SRS includes all the equipment on the surface—that is, the refrigeration unit, storage facilities, and all auxiliaries associated with the refrigeration unit. The SRT includes the cold compressor box, the nitrogen coldbox, the underground distribution box, the cryogenic distribution system, the shaft transfer line system, the nitrogen dump tanks, and the auxiliary end box. The SRC is the control system for the SCS and for all of its components.

The sector refrigerator surface system (SRS) should be able to operate effectively under a variety of operating conditions. The primary function of this system is to provide refrigeration to the magnet strings. Secondary operating modes include cleanup, cooldown, warmup, and maintenance of the magnet strings. In order to meet the operating requirements for each mode, a minimum set of components is needed to enable the reconfiguration of the system by including or excluding specific subsystems to adjust the capacity and throughput of each subsystem. The design must therefore also provide the appropriate overall control philosophy of the system, in particular that of the liquid management scheme. The latter serves as the interface between the surface system and the tunnel cryogenics system, and should be capable of handling the various operating modes.

Figure 7.1-1 is a block diagram of the major components in the sector station cryogenic system. Table 7.1-1 lists the cryogenic system statepoints, with location numbers corresponding to the numbers on the block diagram.

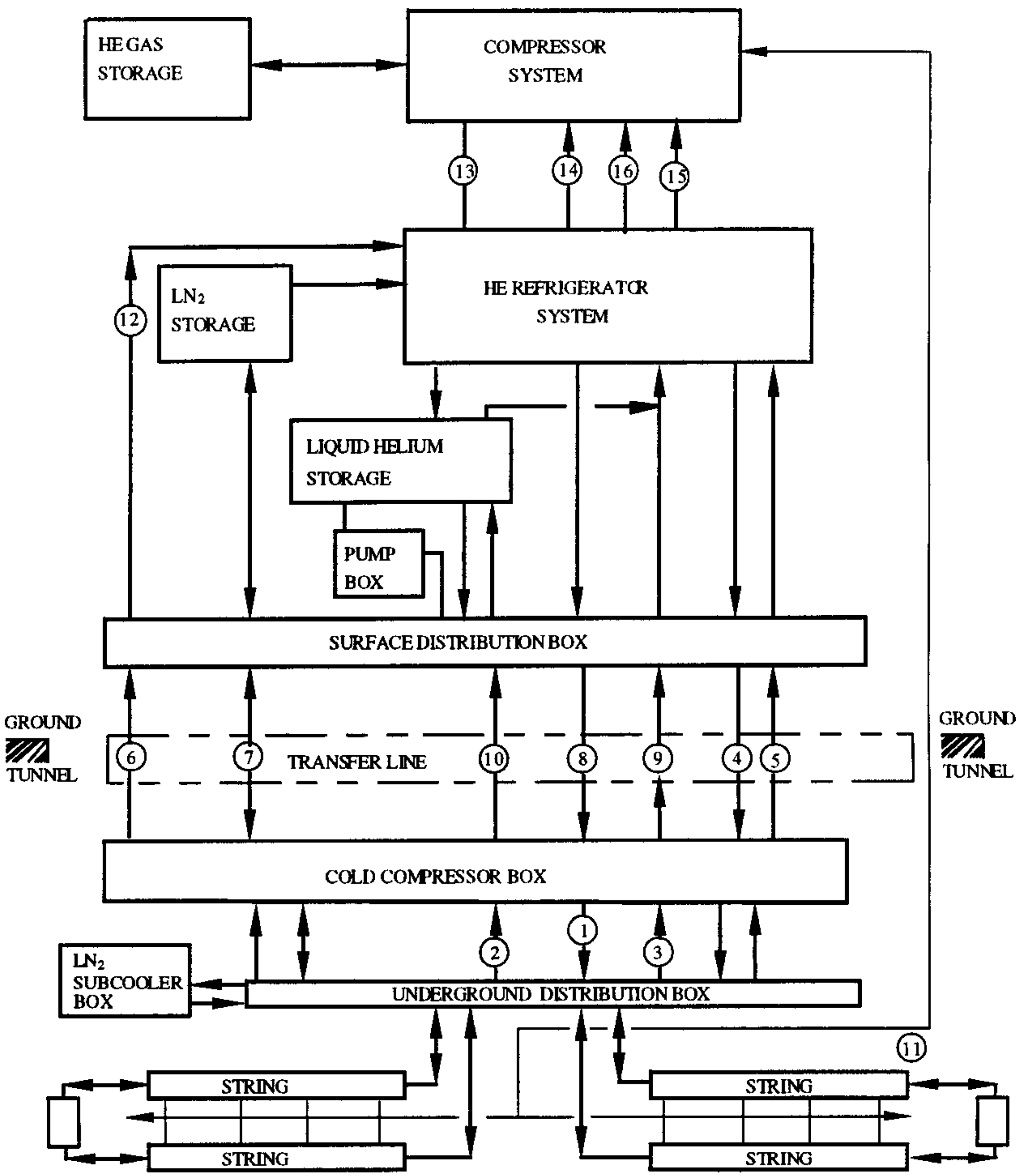


Figure 7.1-1. Sector station cryogenic system block diagram

Table 7.1-1. Sector station cryogenic system statepoints

Loc	Description	Temperature *K*	Pressure *Bar*
1	Single-phase helium feed	4.0	4.0
2	Single-phase helium return	4.0	3.5
3	Gaseous helium return	3.95	0.77
4	20 K shield feed	14-18	3.0
5	20 K shield return	28 max	2.0
6	Gaseous nitrogen return	85	1.5
7	Liquid nitrogen flow	80-85	3.0-10.0
8	LHe supply from refrigerator	4.45	4.0
9	Cold compressor return to surface	6.1	1.4
10	Single-phase helium return to dewar	4.3	3.5
11	Warm helium gas return	305	1.1
12	Nitrogen gas	85	1.3
13	High pressure helium	308	20 nominal
14	Medium pressure helium	303	3 nominal
15	Low pressure helium	303	1.05
16	20 K return pressure helium	303	1.5 nominal

Figure 7.1-2 shows the configuration chosen for the SRS. The helium refrigerator coldbox process shown in Figure 7.1-2 is somewhat similar to the process in an existing system (given as an example only), the Accelerator System String Test (ASST) coldbox.

The SRS consists of the following major systems: the compressor system (CMS, Fig. 7.1-3) and the refrigeration system (RFS, Fig. 7.1-4). A brief description of the equipment for each system follows.

Compressor System

1) Compressor group: Two-stage compression of helium gas for the refrigerator. The available power for operation at design load is 4.5MW.

2) Oil removal system: Oil removal system to remove fine oil from the compressor discharge helium flow.

3) Gas management system: A set of control valves that manages the overall inventory in and out of the system at the warm end of the refrigerator, and allows the refrigerator to follow load changes.

4) Gas storage: Warm gas storage capacity of 1,150,000 liters up to 19 bar.

5) Auxiliary equipment: Bearing gas compressor skid, oil management system for compressor system, utility stations, instrument air system.

6) Piping network: Warm piping between gas storage, compressor system and coldbox.

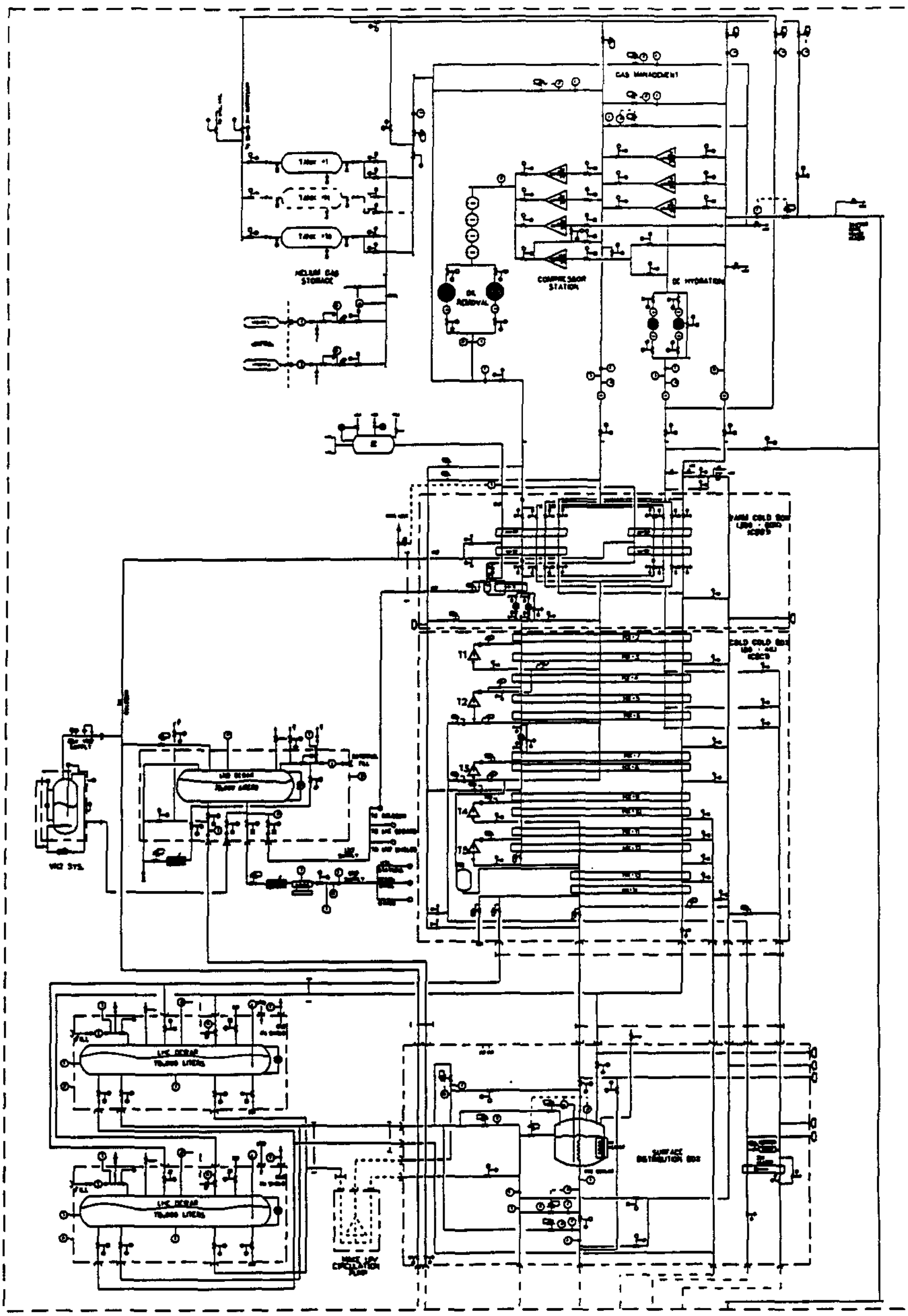


Figure 7.1-2. *Sector refrigerator surface system flow diagram*

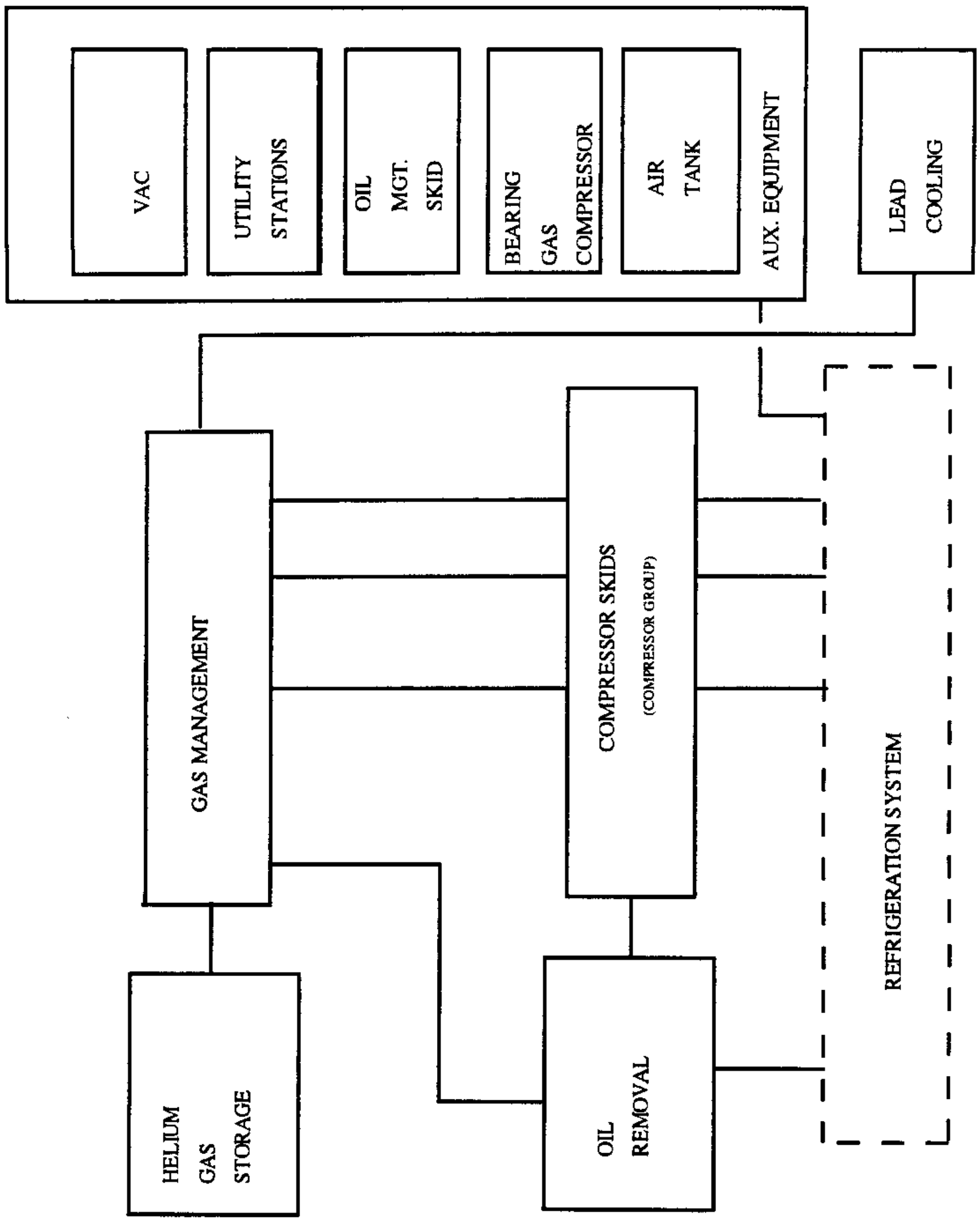


Figure 7.1-3 Compressor System

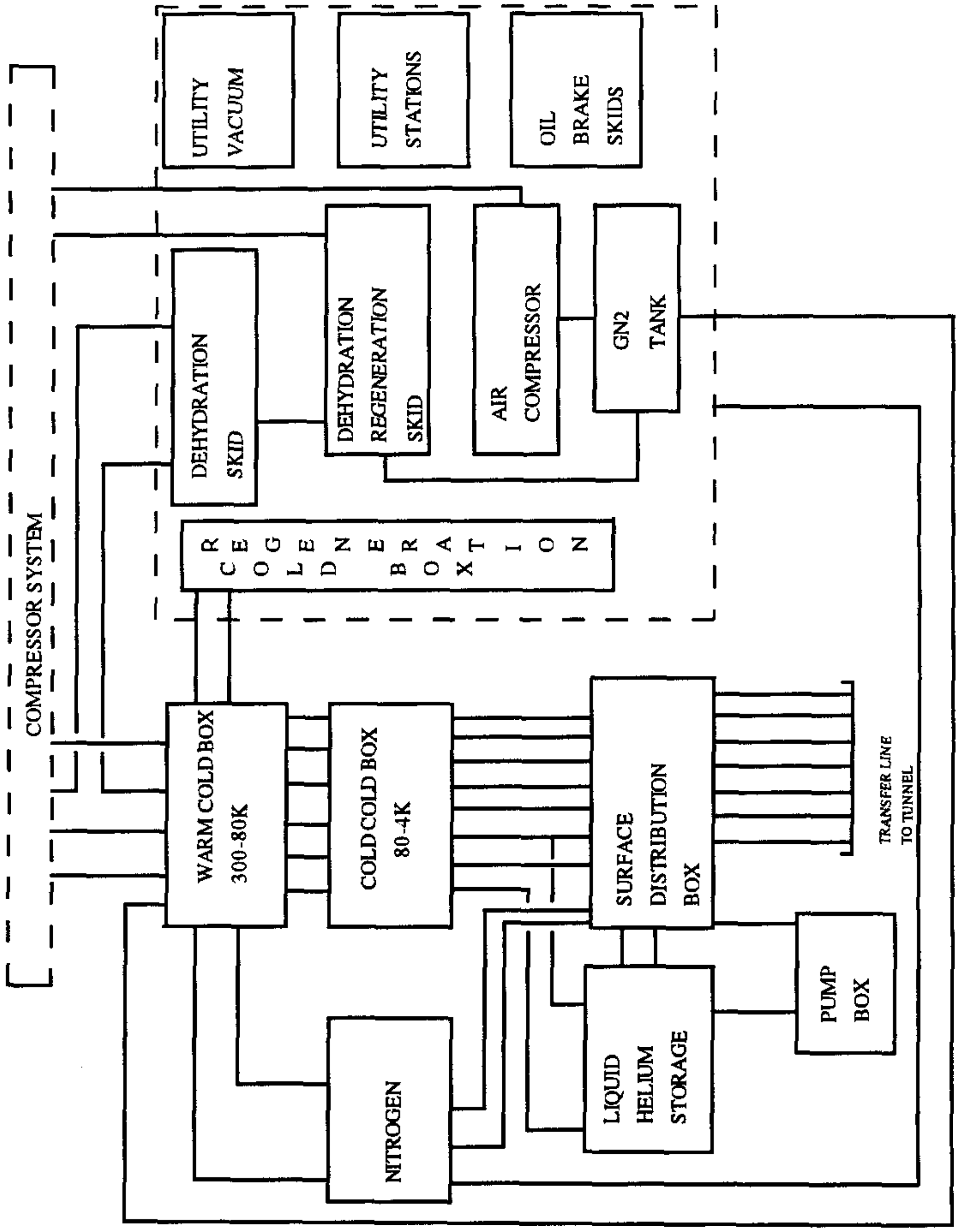


Figure 7.1-4. Refrigerator system

Refrigeration System (RFS)

1) Coldbox system: The coldbox system is configured in a series arrangement as follows: The first coldbox (300 Kto 80 K) contains dual full-size heat exchanger cores, the nitrogen boiler, and 80 K adsorber beds. The second coldbox (80 K to 4 K) contains the expanders, the low temperature heat exchangers, 20 K beds, and buffer volume.

2) Liquid management system: A special surface distribution box serves as the precooler, interface, and distribution manager between the coldboxes, the LHe storage system and the tunnel cryogenic system. Accommodations have been made for future installation of a liquid helium circulation pump.

3) Liquid helium storage system: Two 115,000-liter dewars provide liquid storage capacity to hold the entire liquid inventory of the magnets in the sector.

4) Nitrogen dewar and gas generation system: Provides liquid nitrogen for precooling in the refrigeration system and warm gas generation for use in regenerating the adsorber beds. The dewar capacity is sized for two days of normal sector usage.

5) Auxiliary equipment: Oil brake skids if oil bearing expanders are used; regeneration skids to regenerate adsorber beds in the coldbox, dehydration regeneration skid to regenerate dehydration beds, dehydration unit for moisture removal from the helium loop, additional utility stations, utility vacuum system, and an additional instrument air receiver tank.

6) Piping network: Warm and cold piping systems interconnecting the coldbox, the surface distribution box, the dewars, the regeneration skids, and the dehydration skid.

7.2 COOLING SCHEMES OF THE CRYOGENICS SYSTEM

To illustrate the refrigeration loops and other operating modes of the cryogenic system, flow diagrams showing critical details of the valving and equipment throughout the cryogenic system are provided in many of the sections that follow. For example, Figure 7.2-1 shows two simplified magnet strings, the cold compressor box, the surface distribution box, the liquid helium dewar, the coldbox (without detail), and a simplified compressor system along with the gas management valves. Not shown in the diagrams are the utility system, auxiliaries such as regeneration skids for the various beds, etc. The valve numbering scheme is given in Tables 7.2-1 through 7.2-7. General system process requirements are discussed later.

The valve numbering scheme presented below pertains to the flow diagrams in this document only, for the purpose of explaining the flow loops and operation; it is not the actual valve numbering scheme for the cryogenic system.

Table 7.2-1. SCS cell valve numbering scheme

Valve No.	Valve Description	Location
V-1	Cooldown	SPRA, SPRF, SPRI, SPRE, SPRT, SPRB
V-2	Quench	SPXA, SPRA, SPRF, SPRI, SPRE, SPRB, SPBT
V-3	Recooler level control	SPR
V-4	Power leads	SPRF, SPRE
V-5	Bypass leads	SP
V-6	Quad bypass leads	SP
V-7	Corrector leads	SP
V-8	LN_2 injection to GN_2	SPRI, SPRF, SPRE

Table 7.2-2. SCS section valve numbering scheme

Valve No.	Valve Description	Location
IV-1	LN_2 isolation	SPRI, SPRE, SPRF, SPRB, SPRT, or U-tubes
IV-2	LN_2 isolation	SPRI, SPRE, SPRF, SPRB, SPRT, or U-tubes
IV-3	GN_2 isolation	SPRI, SPRE, SPRF, SPRB, SPRT, or U-tubes
IV-4	GN_2 isolation	SPRI, SPRE, SPRF, SPRB, SPRT, or U-tubes
IV-5	N_2 recooler level	Next to SPRI

Table 7.2-3. SCS sector valve numbering scheme

Valve No.	Valve Description	Location
FEED VALVES		
V-3001	LHe feed control upper ring	Underground distribution box
V-3002	LHe return upper ring	Underground distribution box
V-3003	GHe return upper ring	Underground distribution box
V-3004	20 K return upper ring	Underground distribution box
V-3005	LN_2 80 K shield upper ring	Underground distribution box
V-3006	GN_2 80 K shield upper ring	Underground distribution box
V-3011	LHe feed control lower ring	Underground distribution box
V-3012	LHe return lower ring	Underground distribution box
V-3013	GHe return lower ring	Underground distribution box
V-3014	20 K feed control lower ring	Underground distribution box
V-3015	LN_2 80 K shield lower ring	Underground distribution box
V-3016	GN_2 80 K shield lower ring	Underground distribution box
V-3051	LHe supply to return bypass	Underground distribution box
V-3103	Cold compressor bypass	Cold compressor box

Table 7.2-3. SCS sector valve numbering scheme, cont'd

Valve No.	Valve Description	Location
END VALVES		
V-0815	LHe turnaround control	Aux end box, next to SPRE
V-0812	LHe feed string isolation	Aux end box, next to SPRE
V-0813	LHe return string isol	Aux end box, next to SPRE
V-0811	GHe return string isol	Aux end box, next to SPRE
V-0801	20 K turnaround	Aux end box, next to SPRE
V-0814	20 K string isolation	Aux end box, next to SPRE
V-0821	LN_2 string isolation	Aux end box, next to SPRE
V-0822	GN_2 string isolation	Aux end box, next to SPRE

Table 7.2-4. SCS surface distribution valve box and dewar

Valve number	Valve Description
V1513	Precooler feed from dewar
V1501	Liquid helium feed to precooler
V1507	Main liquid helium return to cooldown line crossover
V1503	Main liquid helium return to main LHe feed crossover
V1505	Main liquid helium return to dewar - control
V1504	Liquid helium feed to dewar - control
V1506	Distribution valve box cooldown
V1502	Main liquid helium feed isolation
V1510	20 K return heat exchaner bypass
V1509	20 K main return isolation
V1508	20 K main feed isolation
V1511	20 K feed to return crossover
V1532	Dewar vapor return - press control

Table 7.2-5. Surface 4-80 K coldbox valves

Valve No.	Valve Description
V1462	Main feed line to warm helium crossover
V1461	20 K to main feed crossover
V1452	J-T control valve from coldbox to precooler
V1451	J-T control valve from coldbox to dewar
V1443	High pressure feed to main feed line for tunnel cooldown
V1442	20 K feed from turbine 3 control valve
V1441	20 K feed from turbine 2 control valve

Table 7.2-5. Surface 4-80 K coldbox valves, cont'd

Valve No.	Valve Description
V1411	20 K return to cooldown return crossover
V1421	GHe return to cooldown return crossover
V1431	GHe return to LP coldbox selector 4.5 K
V1432	GHe return to LP coldbox selector 6.0 K
V1433	GHe return to LP coldbox selector 8.0 K
V1434	GHe return to LP coldbox selector 10 K
V1422	Cooldown return to coldbox selector 14 K
V1423	Cooldown return to cold box selector 22 K
V1424	Cooldown return to cold box selector 36 K

Table 7.2-6. Surface 80-300 K coldbox valves

Valve No.	Valve Description
V1361	Warm helium feed to cooldown line (HP)
V1362	Warm helium feed to cooldown line (HP purified)
V1363	80 K helium from coldbox to cooldown
V1351	80 K helium HP to MP bypass
V1321	80 K helium cooldown return to LP crossover
V1322	300 K helium cooldown return to LP crossover
V1323	300 K helium cooldown return to 20 K crossover
V1324	300 K helium warm return to 20 K suction crossover

Table 7.2-7. Surface compressor and gas management

Valve No.	Valve Description
V1003	MP to LP bypass
V1001	MP to 20 K suction bypass
V1002	HP to MP bypass
V1004	HP to 20 K suction bypass
V1005	HP to gas storage
V1006	Makeup to MP
V1007	Makeup to 20 K
V1008	Makeup to suction stage 1
V1009	Gas storage to warm header feed control
V1010	Makeup from warm return header

4.0 K cooling of the magnet string (Fig. 7.2-1)

Nominal helium flow of 400 g/s at 4 bar from the refrigerator system coldbox is supplied to the precooler. No helium pump is used for this purpose. The precooler is located in the surface distribution box. The subcooled stream exiting the precooler at 4.45 K is carried through the vertical (shaft) transfer line in the sector access shaft down to the tunnel to a heat exchanger located in the cold compressor box. There the 4 bar helium is subcooled to 4.0 K before delivery to the underground distribution box by exchanging heat with the vapor and the single-phase helium streams returning from the magnet strings.

In the tunnel distribution box, this 4 bar flow is split equally, supplying each of the four strings with 100 g/s. Each helium stream is recooled in the SPRF feed spool recoolers before entering the first cell. This helium flows through the magnet cold mass to remove the heat generated. The supercritical flow through each string is recooled every 180 m by recoolers located in spool pieces (SPRA). At the far end of each string (in the SPRE) the flow is returned through the liquid return line, which is mounted alongside the magnet cold mass in the cryostat. The returning helium supplies the recoolers, located along the string. Boil-off from the recoolers is collected in the gaseous helium return line and returned to the cold compressor box.

During full load operation of the collider a total of 264 g/s is expanded into the recoolers in each sector. The excess liquid helium from the return line is expanded to saturated liquid in the surface precooler vessel and is used for precooling the helium flow to the tunnel. The control valve on the single-phase return line in the surface distribution box is used to control the pressure of the streams in the magnet strings. The main J-T valve (V-1452 on the coldbox) is used only as a backup pressure control for the supply stream. The valve on each feed line controls the flow of each supply stream. The control valve on the single-phase return line in the surface distribution box, together with the liquid consumption in the recoolers, maintains the Δp across the magnet string and provides the 100 g/s helium flow through each string.

Excess liquid produced by the refrigerator is diverted to the dewar via a parallel J-T valve. The vapor is returned from the recoolers at approximately 0.77 bar. It is then compressed by a cold compressor to 1.45 bar and returned to the main coldbox. The return vapor streams from the dewar and from the cold compressor flow are combined at the appropriate temperatures and pass through the low pressure side of the heat exchangers to the first-stage compressors. The operating scheme of this cooling loop for the HEB is slightly different because of the higher heat load.

Lead cooling (Fig. 7.2-2)

Liquid is tapped off along the string for cooling of power leads for the main magnets and corrector magnets. Valves at the warm end of the leads control the flows through the leads to minimize the 4 K helium consumption without danger of burning out the leads. A maximum of 36 g/s per sector is used to cool the leads. The lead cooling flow is returned to the warm helium return header in the tunnel. The warm gas is returned to the first-stage compressors through a vertical line from the return header to the refrigeration plant.

20 K shield (Fig. 7.2-3)

In order to cool the 20 K radiation shields in the cryostats, a helium stream is tapped off the appropriate expander outlet flow at a temperature of 14–15 K and supplied through a separate circuit at 3 bar nominal pressure. The flow is divided into two 100 g/s streams. One 100 g/s stream passes through the lower string 20 K shield (designated Line 4) and returns through the upper string. The other 100 g/s passes through the upper string and returns through the lower string in the other half of the sector. In the nominal operating case, the 100 g/s flow travels a distance of 8.6 km, and the expected load through each loop is 5 kW for a total of 10 kW per sector. The return flow is brought back at 2 bar through a separate pass in the upper heat exchangers. The 20 K loop pressure will be maintained below the 4 K loop pressure to avoid any leakage from 20 K to 4 K. During a quench the 4 K magnet cold mass flow may also be vented into the 20 K shield line.

84 K shield (Fig. 7.2-4)

A nitrogen cooling loop provides the cooling for the 84 K shield of the magnet cryostats. Two nitrogen lines run through each cryostat, one carrying vapor and the other liquid. Cooling of the shield is accomplished by recooling the liquid nitrogen stream with recoolers along the string and with the injection of liquid into the nitrogen vapor line; thus the vapor line operates as a continuous recooler. The vapor produced in the recoolers is returned to the surface refrigerator for helium precooling and is vented to the atmosphere at 300 K. The 84 K shield cooling system will not be described in detail here, but the reader should refer to the publication entitled: "Nitrogen System for the SSC," cited in Section 2.2, above.

7.3 Operating Conditions and Pressure Drops

Single-phase 4 K helium – Line 1

The flow rate of the single-phase helium through the magnet string is designed to be 100 g/s for both the collider and the HEB. Due to heat load, there is a temperature rise in the single-phase flow between recoolers . The recoolers cool the supercritical flow to 4.05 K, the highest recooling temperature allowed. At design conditions the predicted pressure drop for a 4320 m string is 0.5 bar (this excludes the static head which can be as much as ~0.18 bar). The temperature changes in the arc cells resulting from the predicted heat loads are shown in Figures 7.3-1 and 7.3-2. The distance between recoolers in the collider is 180 m and in the HEB 65 m.

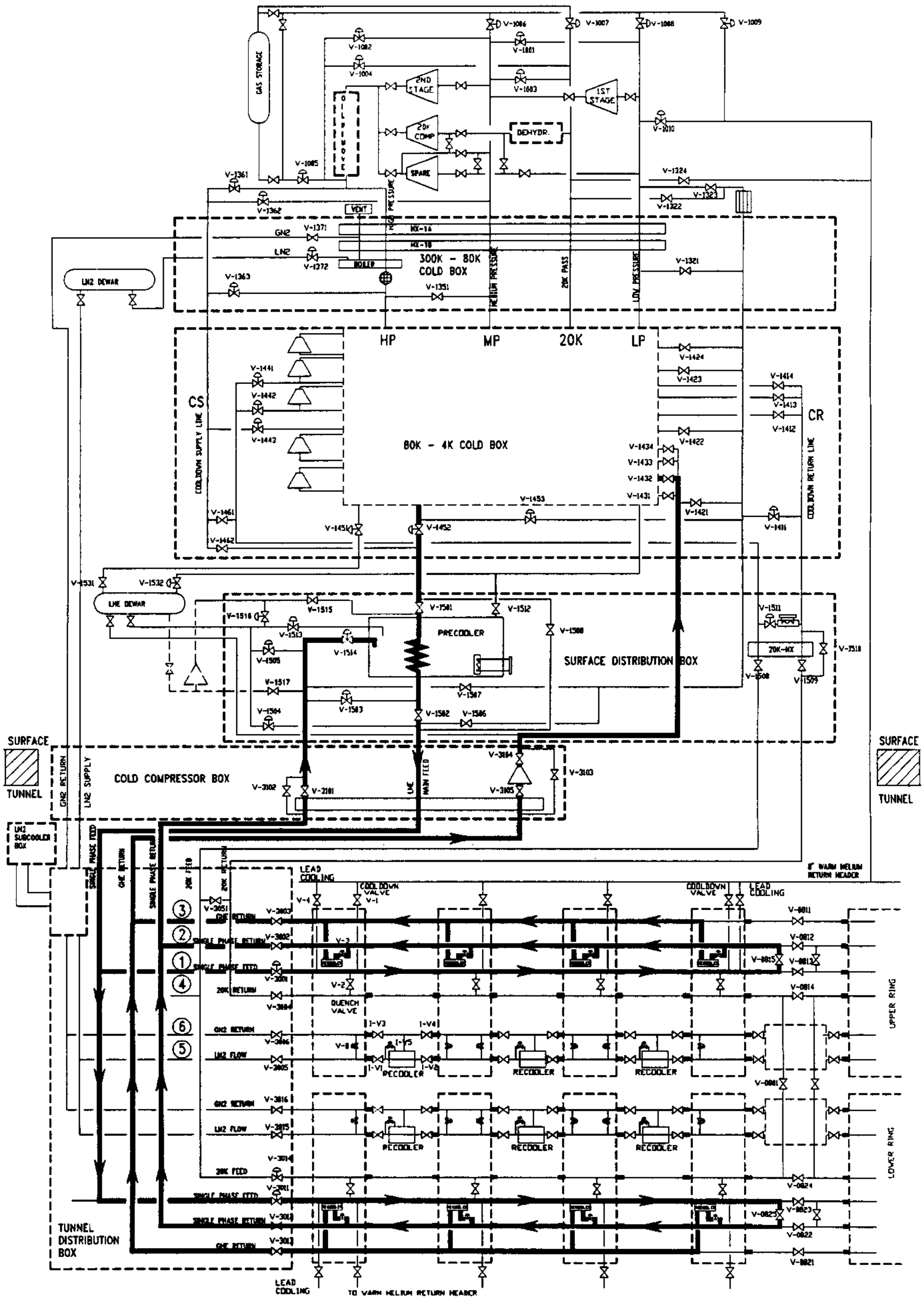


FIGURE 7.2-1 4.0K REFRIGERATION LOOP

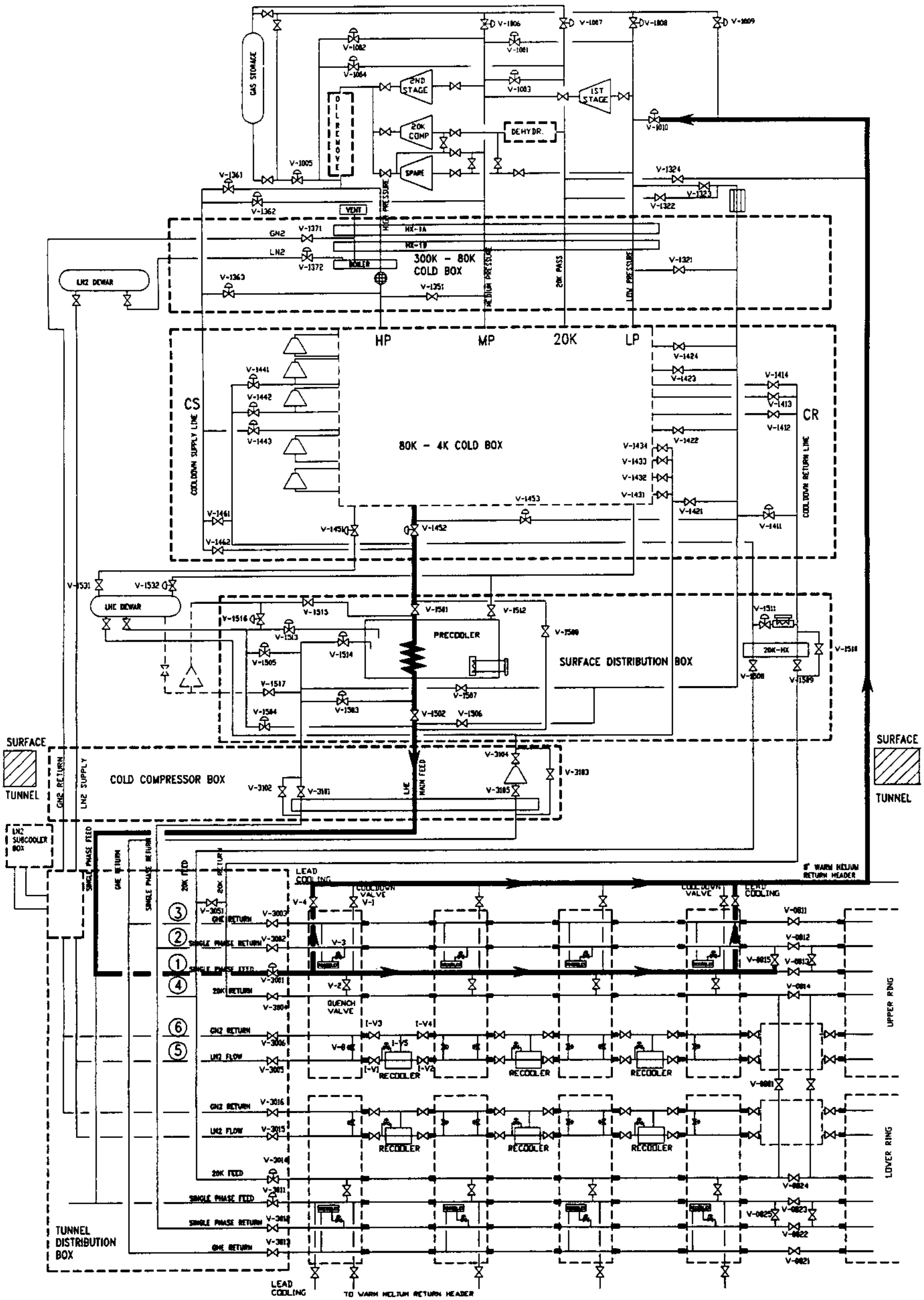


FIGURE 7.2-2 LEAD COOLING LOOP

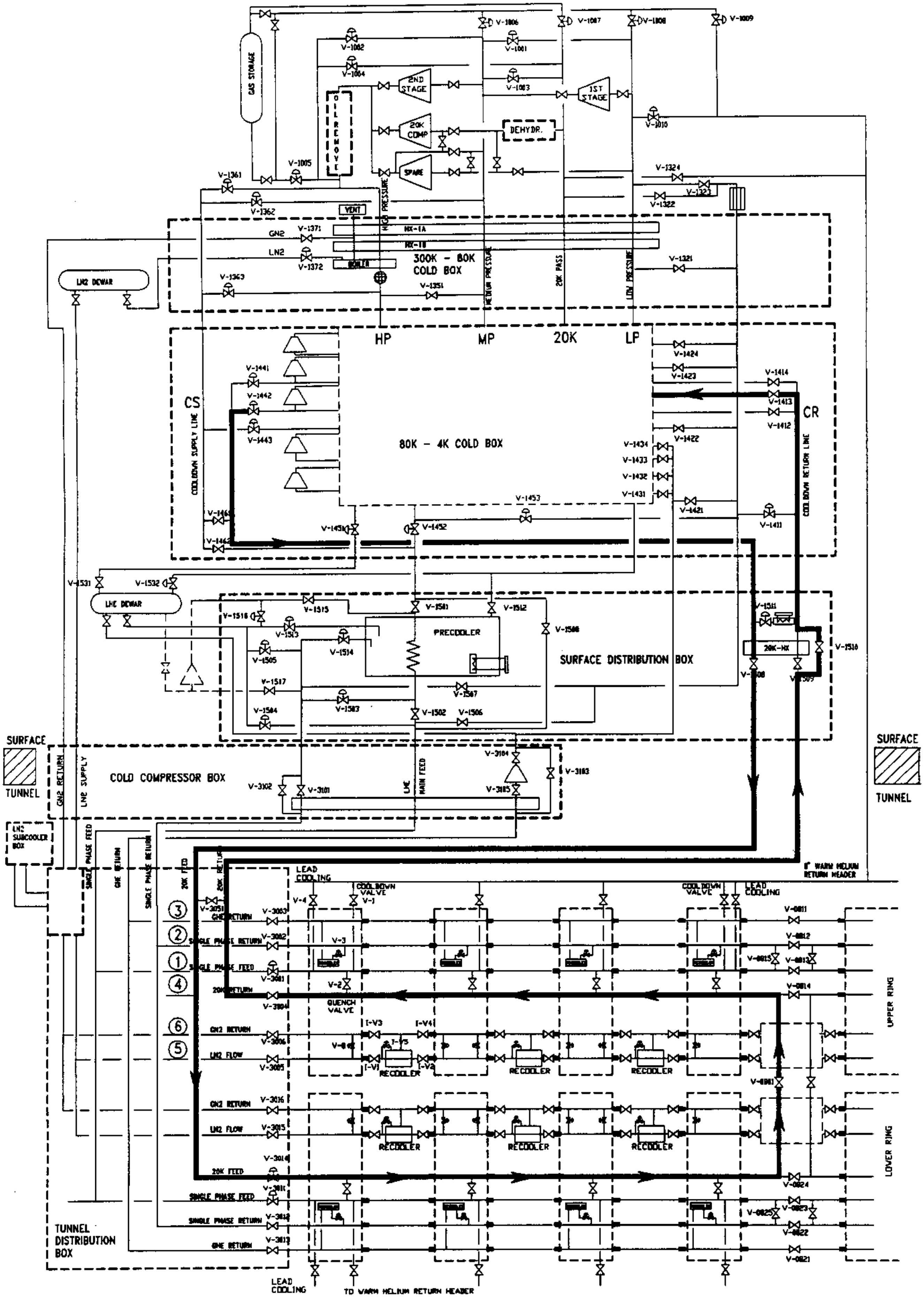


FIGURE 7.2-3 20K SHIELD LOOP

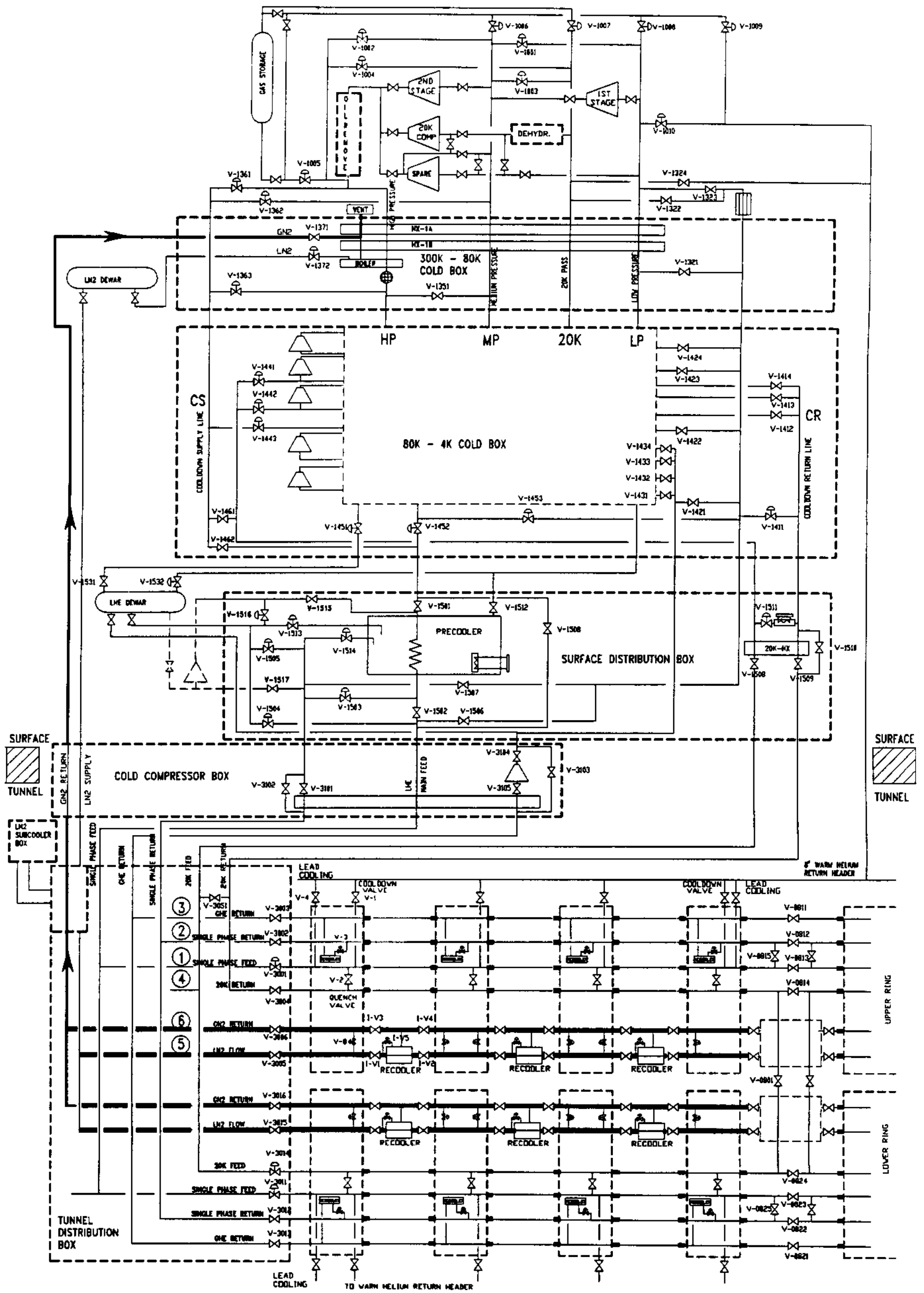
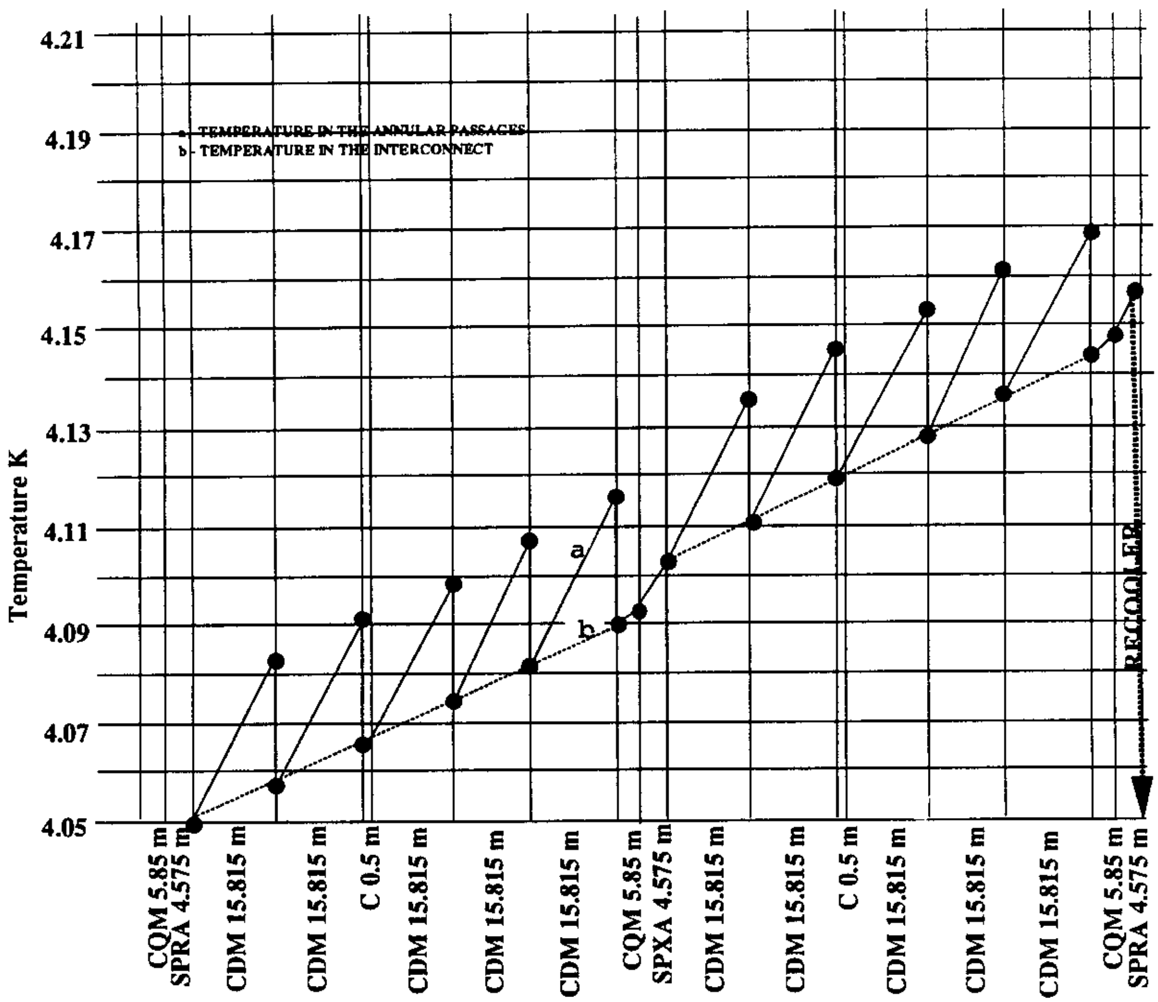


FIGURE 7.2-4 84K SHIELD



Temperature variations in a collider cell located on the right side of the feed at the end of the string (where the recooling temperatureis the highest).

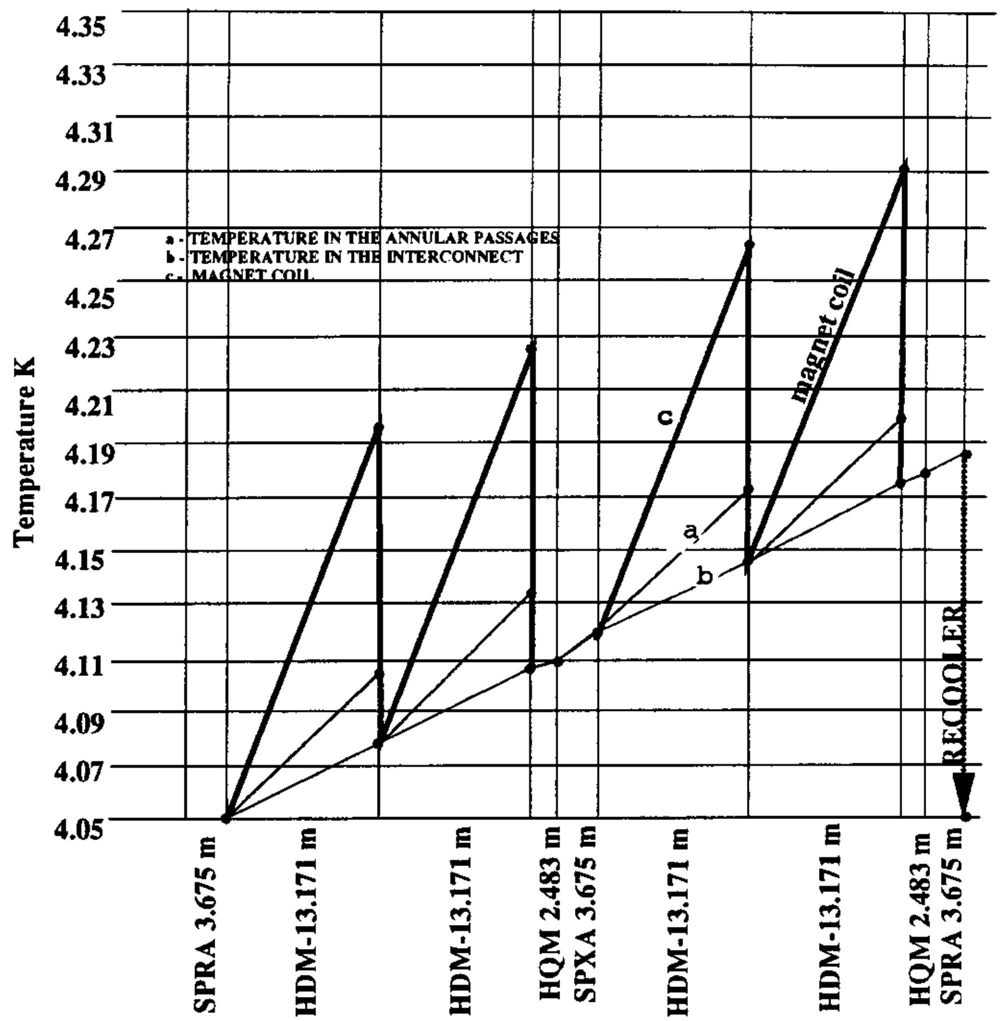
For a similar cell located on the left hand side of the feed, the highest temperature expected in the last dipole is higher by 14 mK.

For a cell located on the left hand side of the feed and starting with an isolation spool the maximal temperature is higher by 14 mK as above, plus 20 mK due to the heat leak in the SPRI and U-tubes Which are located after the recooler.

The expected change in the recooling temperature between the Feed-Spool to the End-Spool is 50 mK.

The designed temperature approach in the recooler is 50 mK.

Figure 7.3-1. Temperature changes in an collider arc cell



Temperature variations in a HEB cell located on the right side of the feed at the end of the string (where the recooling temperature is the highest) based on preliminary design of magnets with cross flow cooling.

For a similar cell located on the left hand side of the feed, the highest temperature expected in the last dipole is higher by 14 mK

The expected change in the recooling temperature between the Feed-Spool to the End-Spool is 50 mK.

The designed temperature approach in the recooler is 50 mK.

Figure 7.3-2. Temperature changes in an HEB cell

Single-phase return 4K helium – Line 2

The single-phase return line carries the single-phase flow exiting the magnet string to the surface refrigerator system. The returning flow is throttled into the recoolers along the string, providing refrigeration to the system. The amount of flow exiting the string at the end of the sector is equal to the amount of the feed flow minus the lead cooling flows. The amount of flow lost to lead cooling is about 9 g/s per string. At nominal loading the amount required for refrigeration will be around 264 g/s per sector; thus the total flow returning to the refrigerator is normally ~100 g/s or 25 g/s per string. Under nominal conditions, the pressure drop through Line 2 is under 0.03 bar for a string length of 4320 m.

4K vapor helium return – Line 3

The vapor return line, Line 3, collects the boil-off vapor from all the recoolers distributed along the string. The flow rate at the end box is zero and by the time the flow exits the string it will have grown to a value in the range of 68 g/s for the collider and 212 g/s for the HEB. Requirements of the operating temperature limit the pressure changes allowed through this line. The overall change allowed is 5 kPa per string.

20 K helium loop – Line 4

In a collider sector, under nominal operating conditions, a flow of 100 g/s at 3 bar, 14 K is supplied to one string and returned through the second string at 2 bar and about 24 K, all within the sector. In the HEB, the flow through the 20 K helium loop originates in one helium plant and is returned to the second helium plant.

80 K liquid nitrogen loop – Line 5

This line is used to refrigerate the 84 K shield. It is also used for distribution of liquid nitrogen supplied to the whole system at two collider locations, at a total feed rate of 4.7 kg/s. The expected maximum flow rate per line under normal conditions is 1.2 kg/s. In certain parts of the system the local flow rate needs to be increased by means of sector circulation pumps. The heat absorbed by the liquid nitrogen is removed by recoolers located at the end of each 1080 m section, and by a continuous recooling system based on injection of liquid into the vapor return line.

80 K vapor nitrogen return – Line 6

This line is used to return the boil-off vapor from the nitrogen recoolers. It is also used as a continuous recooler by injecting liquid nitrogen at section boundaries. This type of recooler is possible due to the dip or inclination of the whole collider. Details are given in "Nitrogen System for the SSC," cited in Section 2.2, above.

8. Design Requirements and Definitions of Operating Modes

The following are the primary modes and operational requirements of the SCS. The design of the system must meet these operating modes and requirements.

Normal operating modes

These modes cover the steady operation of the system without the beam, the change in operation when the beam is turned on, and the change in operation when the beam is turned off.

Minimum/maximum capacity modes

For the minimum mode, the system is operated at the lowest capacity that will maintain equipment at liquid helium temperatures and will process dewar boil-off. The minimum mode is achieved by operating the plant with a the least possible number of compressors and expanders.

In maximum capacity mode, all compressors and expanders are running except for redundant or spare equipment.

Utility modes

These modes cover the warm gas circulation for cleanup; the cooldown from 300 K to 4 K, magnet conditioning, emptying of the sector, and warmup of the sector and the procedures required for magnet repair.

Features and requirements

The following features of the refrigeration system are required in order to operate the entire cryogenic system . The system must allow for the adjustment of the local capacity, and must allow fast transition between the operating conditions of the rings. The refrigeration plant must operate efficiently over a wide range of operating conditions. The system must be designed to be reliable and a redundancy scheme must be provided to allow operation during equipment failures. The system must handle upset conditions, such as quenches, without any severe interruption to its operation. The magnet system may release a considerable number of contaminants during its operation, and the cryogenic system must be tolerant to this discharge.

8.1 Capacity Adjustment, Efficiency, and Gas Management Scheme.

The dynamic load of the collider contributes to about half the 4 K refrigeration heat load on the cryogenic plant. When the beam is down, the load on the plant is reduced to less than half, and when a section is under repair the load is considerably less. In order to have a cost-effective and efficient operating scheme for the collider, the refrigeration plant must be capable of efficient turndown when required. In the plant's basic refrigeration mode, it will be capable of operating anywhere between the maximum capacity and the minimum capacity obtainable without bringing a compressor or expander offline. Within this range, the gas management scheme, together with the coldbox control scheme, will allow the plant to turn up and down according to the demands of the loads (4 K refrigeration, liquefaction, and 20K shield).

The response of the refrigeration plant to the different loads is determined by the main control loops—in particular the gas management system—and this response is summarized as follows:

a. First-stage compressors: Flow to the first-stage compressors is fed from:

   1) the flow returning from the coldbox low pressure side,
   2) the makeup from gas storage (controlled by V-1008), and
   3) the lead cooling flow (controlled from the warm return header, V-1010).

   To prevent the suction pressure from dropping to a subatmospheric level, there is a bypass across the first stage through valve V-1001 that keeps the first stage fully loaded. The net mass flow contribution from the first stage to the second stage is equal to the net flow to the first stage (1 + 2 + 3, above).

b. Second stage compressors: The second stage suction (interstage) pressure varies according to the mass flow to the second stage compressors. This flow is the sum of the recycle mass flow returned from the medium pressure pass and the net mass flow contribution from the first stage.

   For small loads the suction pressure of the second stage drops to the level controlled by the second stage bypass (V-1002). When the coldbox system and compressor system reach the equilibrium necessary to handle this load, each expander settles to its own operating condition and the discharge pressure of the second stage compressor is at a value determined by the net inventory in the coldbox. As a result, the second stage compressor pressures (suction and discharge) settle to the respective values required to handle this flow.

c. 20 K compressor: At steady state the suction pressure of the 20 K compressor is determined by the rate of flow returning from the 20 K shield loop. The discharge pressure of this compressor is determined by the system discharge pressure necessary to handle the total load as described in the previous paragraph.

The gas management bypass valves are:

a. Medium pressure to low pressure bypass (V-1001). This controls the minimum pressure to which the first stage suction is allowed to drop; as a result, the net flow from the first stage into the second stage is equal to the flow from the load return plus makeup. This valve is also used for running the first stage compressors independent of the coldbox and is sized for full flow bypass.

b. High pressure to medium pressure bypass (V-1002). This controls the minimum pressure to which the second stage suction is allowed to drop, and is also used for running the second stage compressors independent of the coldbox. It is sized for full flow bypass.

c. Medium pressure to 20 K suction bypass (V-1003). This allows the system to process more gas when the second stage runs out of displacement capacity. V-1003 is used only if the required flow rates through the 20 K shields can be maintained.

d. High pressure to 20 K suction bypass (V-1004). V-1004 controls the minimum pressure at which the 20 K compressor suction is allowed to operate. V-1004 is also used to run the 20 K compressor independent from the coldbox and should be sized for the full capacity of the 20 K compressor (at 4 bar suction).

e. High pressure discharge overload to storage (V-1005).

f. Makeup into second stage suction (V-1006).

g. Makeup into 20 K suction (V-1007) is supplied through the dehydration skid. This allows moisture to be removed from contaminated helium supplied from warm gas storage.

h. Makeup from gas storage to first stage compressors (V-1008).

i. Warm gas supplied from storage into warm return header (V-1009) for inventory management.

j. Gas makeup from warm return header (V-1010) to first stage compressors. (Under normal operation, this makeup is equal to the liquefaction load.)

In summary, the refrigerator capacity changes according to the load (total of 4 K refrigeration, liquefaction and 20 K shield). Makeup allowed into the system from storage constitutes an additional load. Change in capacity is reflected by a change in the second stage discharge pressure; this change occurs when there is a change in the net equilibrium inventory in the plant (coldbox/compressors). Any excess liquid produced is stored in the dewar. At lower loads, one or more compressors or expanders may be shut down to maintain efficiency in operation of the system. The basic control philosophy remains the same in this case but the system is operating at a lower capacity.

8.2 Liquid Inventory Management and Redundancy Scheme

Liquid inventory management

The liquid inventory management system serves as the interface between the surface refrigerator and the tunnel cryogenic system, and its hardware configuration and control scheme are critical for smooth operation between the surface refrigerator and a very demanding cryogenic load. The liquid inventory management system must be able to handle the following minimum functions:

a. Manage the single-phase return flow. The sector requires a circulation flow of 400 g/s. Under normal operating loads, the single-phase return flow from the 4 K refrigeration loop is returned to the surface precooler (V-1514), and additional precooling capacity comes from the refrigerator indirectly—that is, via JT-valve V-1451 into the dewar, and from there via control valve V-1513 into the precooler bath. This configuration allows the refrigerator to deliver extra liquid into the dewar. The flow to the precooler can be delivered from the dewar independent of the refrigerator's capacity during transients. Normally all the return flows are flashed into the precooler via V-1514. During transients, excess flow is returned to the dewar via pressure control valve V-1505.

b. Control pressure during transients such as quenches and inventory changes of the strings: Pressure control valves V-1504 and V-1505 allow flow to the dewar from both the single-phase feed and the return line.

c. Interchange single-phase feed and return flows. This reverses flow through the magnets strings for instrumentation calibration. V-1502 is closed and the single-phase feed is supplied through V-1503 with the return handled through V-1504. Most of the precooling supply comes through V-1513.

d. Allow the liquid helium storage dewar to act as a storage buffer. Excess flow from the single-phase return not used for precooling is stored in the dewar via V-1505. Additional excess liquid from the refrigerator is sent via parallel JT valve V-1451 to the dewar.

e. Allow the liquid helium storage dewar to act as a capacity buffer. When the refrigerator output changes at a rate slower than the load, liquid from the dewar is used for precooling of the feed stream (V-1513). This allows the supply flow rate to be increased when necessary for load variations.

f. Allow transfer of liquid helium from neighboring sectors. When additional liquid inventory is required from neighboring sectors, V-1514 and V-1505 can be used to lower the local system pressure, and allow the neighbors to transfer liquid into the sector.

g. Maintain the circulation flow through the strings in the range of 100 g/s per string and a pressure higher than 3 bar.

Redundancy scheme

In the event of failure of any expander, the system must continue to operate with at least the steady-state nominal load capacity given in Table 9.2-2. Some liquefaction capacity may be borrowed from neighboring plants. This requires that each system be designed with excess capacity. Due to the flow rate limitations of the cold piping in the magnet strings, it is difficult to transfer 4 K refrigeration between sectors. However, liquefaction loads can be transferred relatively easily by shifting the warm gas flow to neighboring sectors—that is, the neighboring plant takes more gas out of the warm return header. Single-phase flow is transferred from one sector into the other at the sector boundary in the auxiliary end box through a flow control valve. Because of the liquid inventory in the sector dewars there is no need for immediate aid from the neighboring sectors. Capacity and inventory can also be shifted between sectors by handshaking 20 K flows across sector boundaries. In this case, the maximum allowable imbalance of the 20 K flows in the refrigerator is determined by the remaining liquefaction capacity of the plant.

The refrigerator is designed to provide 15 kW of cooling to the 20 K shield at 4 bar supply pressure. The nominal load for an average sector is 10 kW. Two neighboring plants can together provide 20 K refrigeration to a sector when required. In this case one leg of each neighbor's 20 K loop will be approximately 17 km long.

8.3 CONTAMINATION TOLERANCE

Since there are 16 km of magnet coils and laminations connected to each plant, it is reasonable to expect a high level of contamination and impurities, and the system should be designed to be insensitive to these. Appropriate adsorber beds must be provided in the coldbox and 20 K loop. Trace gases are removed in adsorber beds at 80 K and 20 K. In order to remove moisture, a mole sieve bed is installed inline on the return stream of the 20 K loop ahead of the compressor. This mole sieve is used during nominal and low loads and during cleanup and cooldown to 80 K. Moisture not removed by the beds is condensed in the 300 K–80 K heat exchanger. To allow the system to operate without interruption while the first heat exchanger is being derimed, a second, parallel, 300 K–80 K full size heat exchanger is required.

Since the initial charge and all makeup helium are supplied to the system as liquid, there is no appreciable system contamination from the helium supply itself. However, warm gas that may be contaminated with moisture must first be processed through the dehydration skid.

8.4 QUENCH TOLERANCE AND RECOVERY

The refrigeration plant and system must tolerate the quench of single and multiple half-cells, and must support rapid quench recovery. The main concern is protection of expanders. A cold buffer volume connected downstream of the last expander is one possible means of protection. The helium returning through the single-phase feed and return lines to the surface is sent to the dewar. During a quench, a portion of the helium from the 4 K loop is vented into the 20 K loop. The 20 K expander must continue working and must discharge its flow to the coldbox instead of to the 20 K feed line. On the 20 K return side, an independent pass through the heat exchanger stack to an independent compressor allows the pressure in the 20 K system to rise, minimizing the effect on the rest of the plant. The increase in suction pressure allows the 20 K compressor to process more flow during quench recovery. Excess inventory that cannot be reliquefied by the refrigerator goes to warm gas storage.

8.5 CLEANUP, COOLDOWN, FILLUP, AND WARMUP REQUIREMENTS.

Separate lines that bypass the coldbox on the supply and return sides are required to handle the flows during cleanup, cooldown, and warmup.

For cleanup, the plant provides clean warm gas to the system. To remove contamination from the helium stream, the helium is cooled to 80 K. Cooling the helium to 80 K allows impurities to be adsorbed in the 80 K beds. The helium is then warmed to ambient temperature before it is sent back to the system. To allow for this mode of operation, certain bypass and control valves are required in the plant: a bypass valve (V-1351) from the high pressure to the medium pressure pass after the 80 K beds, and a control valve (V-1362) to regulate the warm flow to the supply lines of the system. Crossover valve V-1324 allows the dehydration unit to process gas from the warm return header.

Cooldown from 300 K to 80 K requires 450 kW refrigeration capacity using nitrogen. The liquid nitrogen boiler must be appropriately sized for this duty. A control valve (V-1363) regulating cold flow into the cooldown line is needed for this service. For cooldown to 20 K, a crossover valve from the 20 K expander to the cooldown supply line is required. Crossover valves are required from the cooldown return line into the heat exchanger stacks at 80K (V-1321) and ~20K (V-1423). On the vapor return line from the tunnel (cold compressor discharge), crossover valves (V-1431, 1432, 1433, and 1434) into the heat exchanger stack at approximately 5 K, 7 K, and 9 K are required to return the flow during upset conditions, magnet conditioning, and the last phase of the cooldown process.

For warmup, the plant must be able to supply clean warm gas from the coldbox, or gas obtained from the compressor system after the gas exits the fine oil removal skid. The same loop used to generate clean gas for cleanup is used for the warmup process. Warm gas obtained from the compressor system may be used when high purity gas is not of concern (V-1361).

8.6 EXPANDABILITY

The collider is an instrument under development and some of its operating requirements cannot be known in advance. It is desirable that provision be made for a future upgrade in the system capacity to as much as 150% of the initial delivered rating. It is expected that this upgrade would be accomplished by adding an extra coldbox and additional compressors at a later date. The SRS must provide for connections for upgrade—that is, additional connections in the surface distribution box and compressor system. The equipment layouts must also allow enough space for additions.

9. Operating Modes

9.1 Operating Modes of the Refrigeration Plant

The nine refrigeration plants for the collider and the two for the HEB are identical in design and capacity. However, variations in sector design results in corresponding variations in the refrigeration and liquefaction loads for each plant. The plant is designed to handle a range of situations—when the beam is active, or when the beam is not active; when a neighboring plant needs assistance; when an quench occurs; and when cooldown, warmup, or maintenance takes place. For each of these situations the refrigeration plant operates in a different mode. When the beam is active the plant operates in normal mode. When the beam is not active the plant operates in standby mode. When a quench occurs the plant operates in quench recovery mode. When a neighboring sector needs assistance the plant operates in assist mode, and when cleanup, cooldown, warmup, or emptying needs to be performed the plant operates in one of the utility modes.

The plant is also designed to operate in other modes—in special modes for single ring operation, and in a minimum capacity mode when loads are very low. The system's states and plant operational modes are defined on Figure 9.1-1. The design load and the normal operating and special modes are described in this section; the utility modes are described in chapter 10.

The plant is operating in the normal mode when the system is cold and the beam is on. In this mode, the load on the refrigeration plant may vary according to the beam intensity.

The plant is operated in the standby mode when the system is cold with no beam operating and there is no current in the magnets. In this mode, the load on the refrigeration plant depends on the static heat load.

The plant is operated in the assist mode when part of its capacity is being transferred to a neighboring plant. In this mode, capacity is transferred by shifting cryogens through sector boundaries.

The plant automatically changes to the quench recovery mode after a quench is detected in a string.

The plant is operated in one of the utility modes during cleanup, cooldown, warmup, or maintainance.

The plant operates in special modes for different types of configuration—e.g., single ring operation.

The plant is operated in the maximum capacity mode when the sector loads are high, or when gas needs to be processed from truck deliveries, or to refrigerate more than one sector for long term cold storage of the ring.

The plant is operated in the minimum capacity mode when the sector heat loads are low—e.g., to refrigerate only one sector for long term cold storage of the ring.

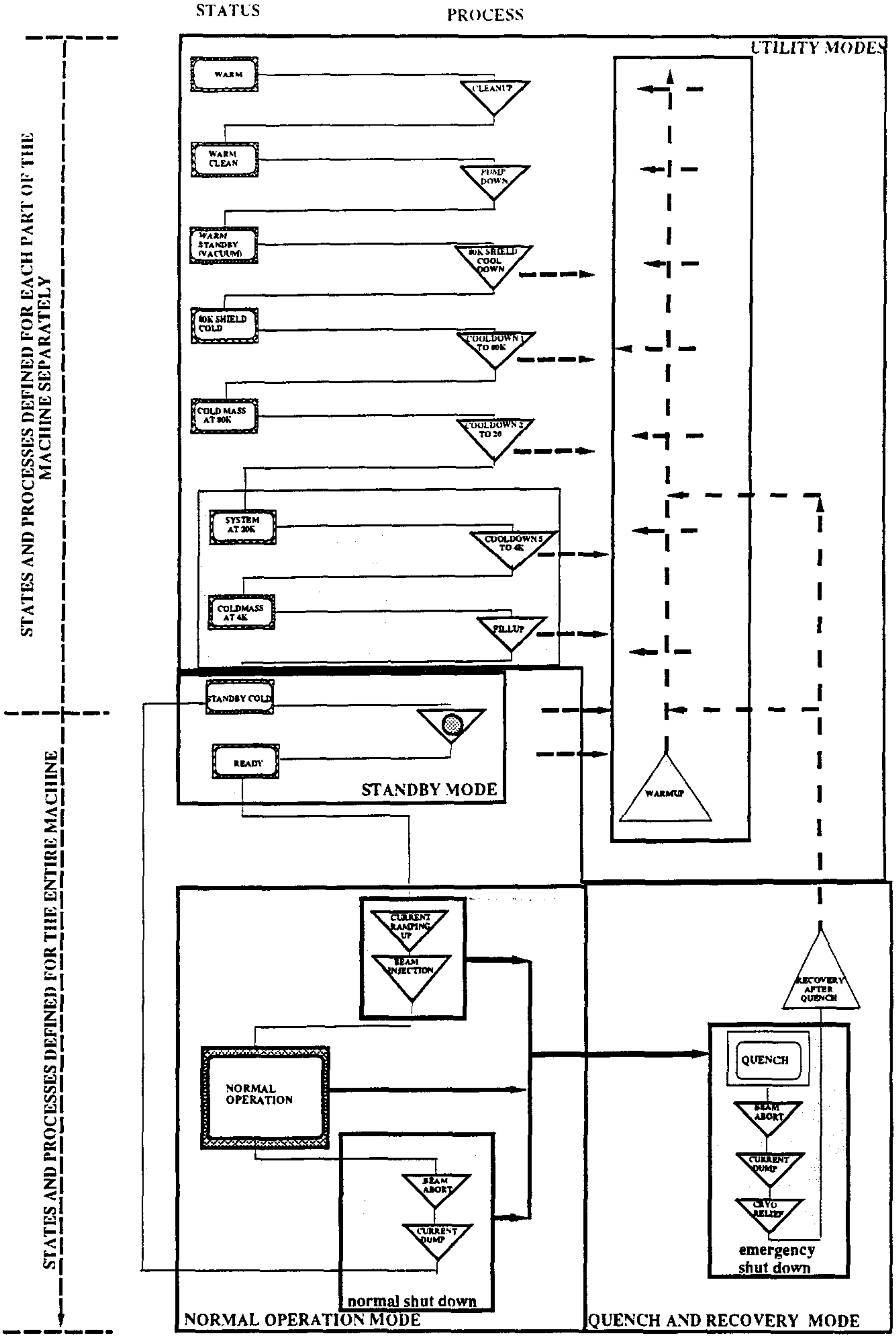


Fig 9.1-1. *Definition of the Plant States and the Refrigeration Plant Operating Modes*

Design load (Table 9.2-1)

The refrigeration system is designed with a specific capacity to meet each of the various normal loads, to meet all the loads during specific upset conditions, and with extra capacity to meet redundancy requirements. The system is able to reach its maximum design capacity, given in Table 9.2-1, when all of its components are functioning properly. The capacity required for normal operation of a nominal collider sector is less than this design capacity.

In the event of failure of any single expander, the system must continue to operate with at least the steady-state capacity given in Table 9.2-2. Furthermore, when a neighboring sector needs assistance in the form of liquefaction or other loads, the refrigerator must turn up to provide this assistance. Due to the flow rate limitations of the cold piping in the magnet strings, it is difficult to transfer 4 K refrigeration between sectors. However, liquefaction and 20 K loads can be transferred relatively easily by shifting the warm gas flow to neighboring sectors or by handshaking 20 K flows between sectors.

This extra capacity allows for quick recovery after a quench. During and after a quench the recovery process must begin quickly, with the plant turned up to handle this transient.

The sectors are not all equal in length, as shown in Table 2.1-2. The larger sector will have capacity to handle its loads locally, and the shorter sectors will have excess capacity. The various loads on each sector refrigerator will vary from sector to sector (see Figure 5.1-1 and Table 5.1-9).

Normal operating modes

Normal mode - nominal load (Table 9.2-2)

In the collider sector, this is the nominal heat load expected when the beam is on and at full power. The load for a nominal collider sector is given in Table 9.2-2. This load will vary slightly from sector to sector because of the difference in length and design of the sectors.

Normal operation of the HEB is for approximately two hours per day. During the remaining time the HEB will be idle, in "standby cold" status. It has a very high dynamic load compared with the collider load. If necessary during the normal operation, helium from the dewar will be used and when the system is in standby status, the dewar is refilled.

There is only one ring in the HEB (Fig. 9.1-2), and therefore its 20 K shield loop is routed differently from that of the collider. The routing of the the 4 K loops is similar to that for the collider. The HEB's 20 K shield route starts at one helium plant and ends in the other helium plant, and a similar scheme is proposed for the collider. If inventory accumulates in one plant, the 20 K supply flows may be temporarily adjusted to return the excess inventory (otherwise inventory may be exchanged through the warm return header).

Standby mode – standby load (Table 9.2-3)

When the rings are cold and there is no beam and no current, the only refrigeration loads are the static conduction and thermal radiation loads. Flow through the leads is also decreased, reducing the liquefaction loads from 36 g/s to about 25 g/s. This is the standby mode. If a quench occurs, the proton beam is dumped and the refrigeration system in the sector where the quench took place goes into the quench recovery mode. The currents in the magnets of the remaining sectors are ramped down to zero and their refrigerators are turned down from normal mode to standby mode until recovery is completed in the quenched sector.

Assist mode – assist load (Table 9.2-4)

In the event of a more serious failure in one sector—that is, if more than one expander should fail to the extent that its refrigerator is unable to handle the nominal operating loads—the neighboring plants can be turned up to their maximum capacity to take the liquefaction load from the sector requiring assistance. In this mode the *assisting* plant must be capable of absorbing at least half the liquefaction load (18 g/s) of the sector requiring assistance; the other neighboring sector will absorb the remaining half.

Quench and recovery mode (Figure 9.1-3)

In the event of a quench, the quench protection system is designed to dump the stored energy into specific energy dumps. However, some of the half-cell stored energy is dissipated in the magnet windings, causing them to warm up. When a quench is detected in any magnet, a quench is induced in the entire half-cell (90 m) for protection. The half-cell stored energy of roughly 8 megajoules is divided between the helium and the cold mass, with about 3 megajoules going to the helium. As the temperature and pressure of the helium increase, the inventory of the half-cell—~600 liters—must be absorbed by the SRS in a few minutes in order to relieve the system. The quench detection system opens the half-cell quench relief valve (V-2) to vent the warm helium to the 20 K shield line. If the warm helium flow is not vented, it may induce a quench in the rest of the string.

If many half-cells quench at any given time, the temperature in the 20 K line drops and the pressure rises. This low temperature helium returns (20 K return line) to the plant, exchanging heat with the 20 K feed flow by closing V-1510 and opening V-1509. The rising suction pressure on the 20 K compressor increases its mass flow capacity, thus aiding the quench recovery and the inventory management associated with the quench recovery process. The gas management allows the 20 K compressor to operate at a suction pressure that varies between 2 bar and 4 bar. The 4 K helium loop provides the additional inventory necessary to cool and fill the magnets, and to restore normal operating conditions. As the quenched section is cooled down, helium vents from the coldmass through the quench valve into the 20-K line until it reaches normal operating temperatures. The remainder of 5 megajoules per half-cell of energy is removed from the cold mass during this recovery period.

Excess inventory that cannot be reliquefied goes to the warm storage. When the single-phase return flow is insufficient due to depletion during the recovery period, liquid from the dewar is used to aid subcooling in the surface precooler. The plant is able to absorb the 5 megajoules released by one half-cell in approximately 30 minutes. During a quench the amount of energy released by a half-cell in the HEB ring is less than the amount of energy released by a half-cell in the collider arcs. The amount of energy stored in these half-cells differs, due mainly to differences in length. The half-cell of the HEB is only 32.5 m long compared with 90 m in the collider arcs.

Special modes

Single ring operation (Figure 9.1-4)

When one of the collider rings is down for a long period of time, it may be desirable to operate the second ring for beam studies. The downed ring may be warm or cold. The interaction regions where the two parallel cold masses are packaged into one cryostat require special treatment. Operation of a single ring in the collider is similar to the operation of the HEB ring (particularly with regard to the 20 K shield).

Maximum capacity modes

In maximum capacity mode, all compressors and expanders are running except for redundant or spare equipment. One exception is the maximum 20 K mode, when all of the equipment may not be required (see below). When warm gas is to be liquefied from external delivery, the refrigerator operates in maximum liquefaction mode. When cold gas must be processed during external liquid delivery, the refrigerator operates in maximum refrigeration mode. To maintain the system at 20 K (or slightly colder) the refrigerator operates in maximum 20 K refrigeration mode.

Maximum capacity modes are listed as follows:

a. Maximum liquefaction mode for full (100%) liquefaction capacity. The plant will liquefy warm gas from storage.

b. Maximum refrigeration mode for full refrigeration capacity during reliquefaction of vapor during liquid delivery to the dewar.

c. Maximum 20 K refrigeration mode for maximum 20 K cooling delivered to the system. When the rings are maintained in cold storage, between 10 K and 30 K, the refrigerator must be able to provide cooling to the 20 K shield for two sectors (approximately 20 kW of cooling). Alternating plants may be shut down. The 20 K supply pressure is at least 4 bar and the supply temperature is as low as possible. *Two compressors may be sufficient for this mode.* The spare compressor may be used instead of the 20 K compressor to operate the 20 K suction pressure to 1.05 bar. Operating at a suction pressure this low also allows the system to process boil-off from the dewar.

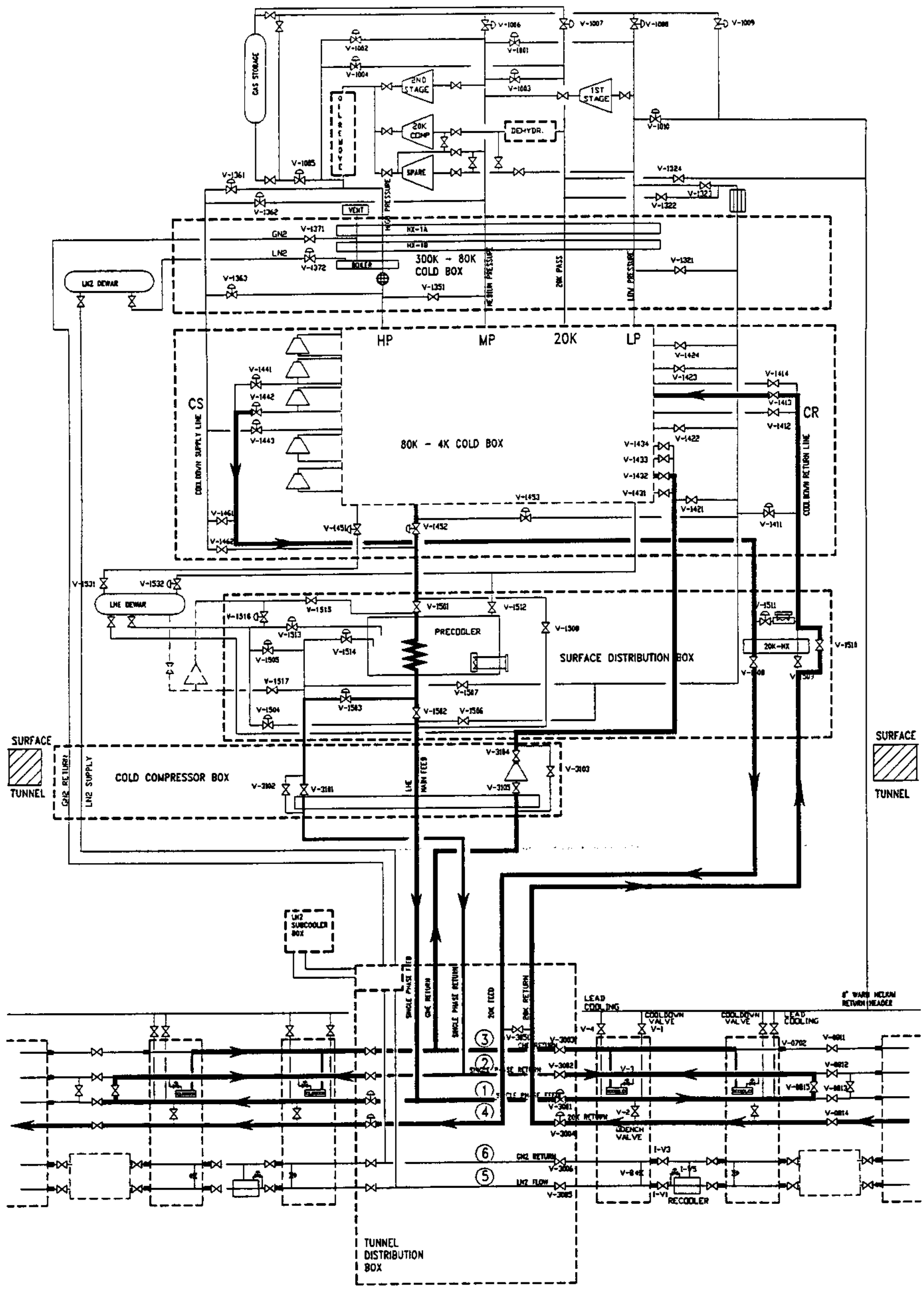


FIGURE 9.1-2 HEB NORMAL OPERATION

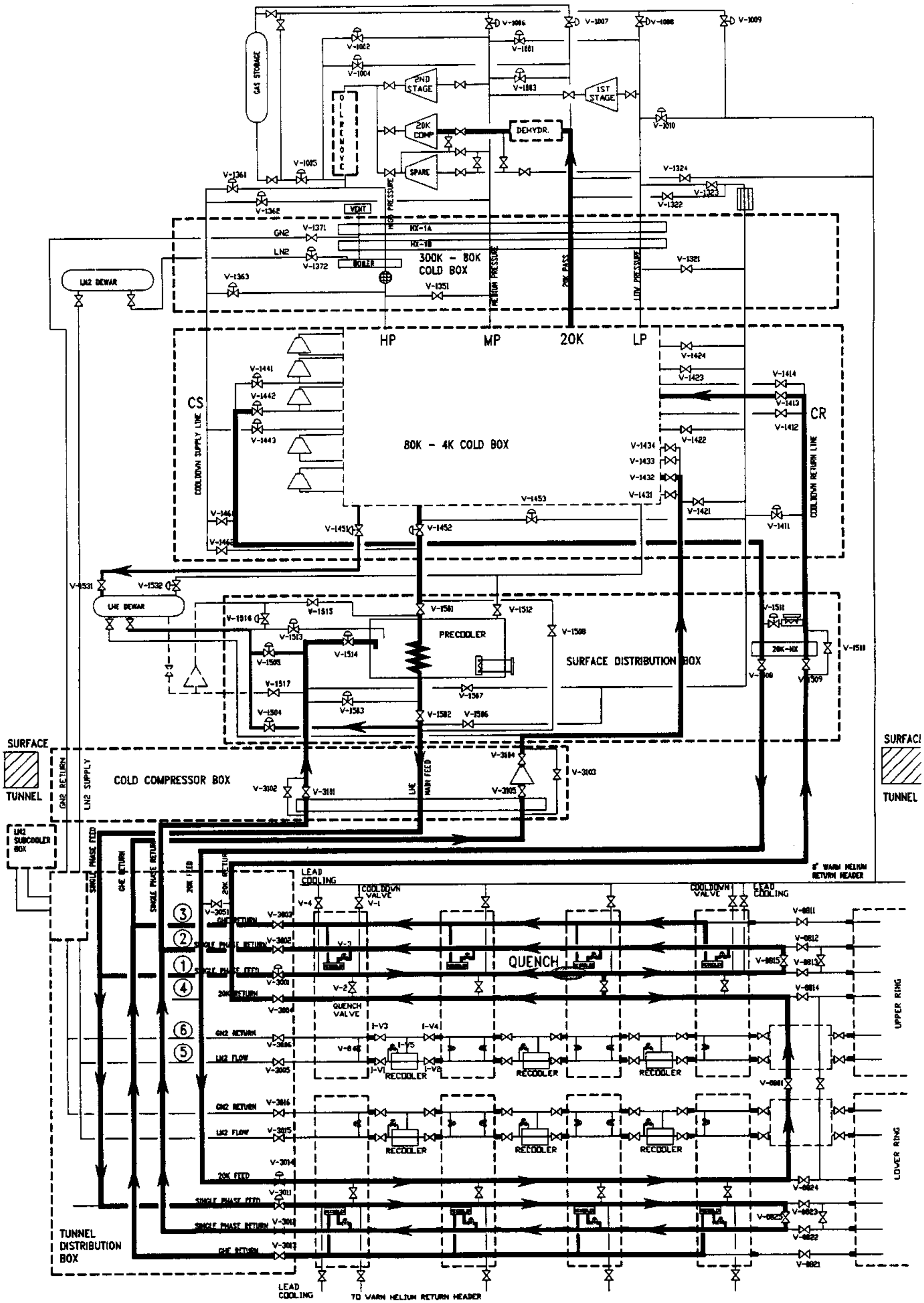


FIGURE 9.1-3 QUENCH AND RECOVERY

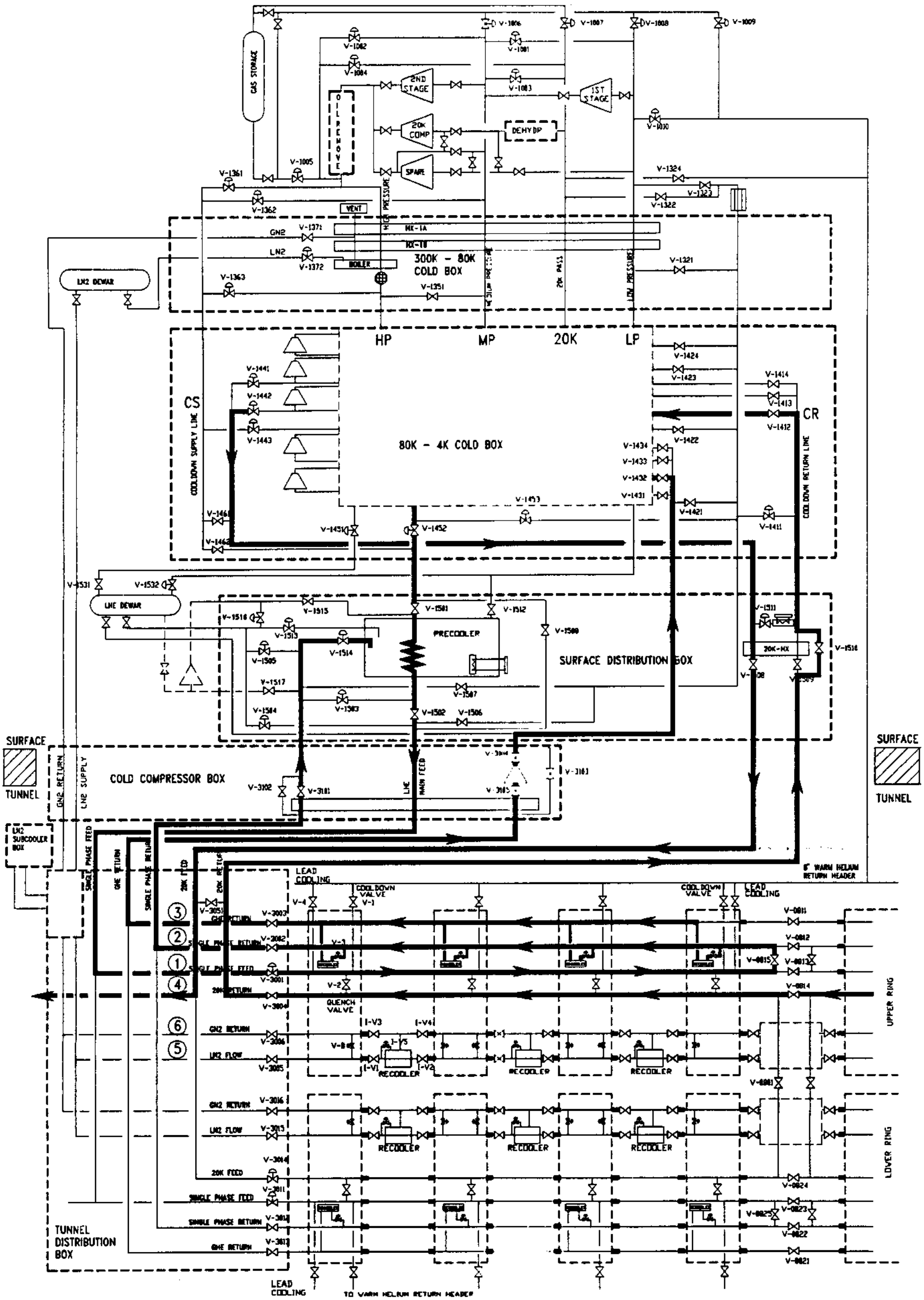


FIGURE 9.1-4 COLLIDER SINGLE RING OPERATION

Minimum capacity modes

When 4 K cooling of the magnet strings is not required for a prolonged period of time, such as during repair, maintenance, or cold storage of the collider rings at 80 K or 20 K, the plant runs at a minimum capacity—i.e., with a minimum set of compressors (one first and one second stage)—to process boil-off from the dewar and to keep the 20 K shield cold. One or more expanders may be shut down so that the refrigerator can run in this mode. In this minimum capacity arrangement, the plant must be able to operate in full liquefaction mode, full refrigeration mode, any liquefaction/refrigeration ratio (mixed) mode, or 20 K refrigeration mode at this minumum capacity.

9.2 REFRIGERATOR SYSTEM LOADS

Table 9.2-1. Design mode heat loads

	PI *bar*	TI *K*	HI *J/G*	SI *J/G-K*	PO *bar*	TO *K*	HO *J/G*	SO *J/G-K*	FLOW *g/s*	LOAD *W*	Wcar *kW*
REFR	4.0	4.00	10.18	3.07	0.77	3.95	30.65	8.86	330	6750	574
LIQUEF	4.0	4.00	10.18	3.07	1.05	305.0	1599.	31.57	45		320
20-K SYS	4.0	14.0	83.92	12.60	2.00	27.8	158.9	17.80	200	15000	302
TOTAL LOAD CAPACITY REQUIRED											1196
COLD COMPR.	0.75	4.3	33.44	9.57	1.45	6.07	41.76	10.08	330	2745	48
APPROXIMATE TOTAL SYSTEM CAPACITY REQUIRED											1244

Table 9.2-2. Nominal mode heat loads

	PI *bar*	TI *K*	HI *J/G*	SI *J/G-K*	PO *bar*	TO *K*	HO *J/G*	SO *J/G-K*	FLOW *g/s*	LOAD *W*	Wcar *kW*
REFRIG	4.0	4.00	10.18	3.07	0.77	3.95	30.65	8.86	264	5400	461
LIQUEF	4.0	4.00	10.18	3.07	1.05	305.0	1599	31.57	36		256
20-K SYS	3.0	14.0	84.91	13.25	2.00	23.2	134.9	16.9	200	10000	208
TOTAL LOAD CAPACITY REQUIRED											925
COLD COMPR.	0.75	4.3	3344	9.57	1.40	6.06	41.92	10.16	264	2235	45
APPROXIMATE TOTAL SYSTEM CAPACITY REQUIRED											970

Table 9.2-3. Standby mode heat loads

	PI bar	TI K	HI J/G	SI J/G-K	PO bar	TO K	HO J/G	SO J/G-K	FLOW g/s	LOAD W	Wcar kW
REFRIG	4.0	4.00	10.21	3.07	0.77	3.95	30.65	8.86	138	2800	238
LIQUEF	4.0	4.00	10.21	3.07	1.05	305.0	1599.	31.57	25		178
20-K SYS	3.0	14.0	84.91	13.25	2.00	23.2	134.9	16.9	200	10000	208
TOTAL LOAD CAPACITY REQUIRED											624
COLD COMPR.	0.75	4.3	33.44	9.57	1.35	6.05	42.08	10.25	138	1191	27
APPROXIMATE TOTAL SYSTEM CAPACITY REQUIRED											651

Table 9.2-4. Assist mode heat loads

	PI bar	TI K	HI J/G	SI J/G-K	PO bar	TO K	HO J/G	SO J/G-K	FLOW g/s	LOAD W	Wcar kW
REFRIG	4.0	4.00	10.18	3.07	0.77	3.95	30.65	8.86	264	5400	461
LIQUEF	4.0	4.00	10.18	3.07	1.05	305.0	1599.	31.57	54		384
20-K SYS	3.0	14.0	84.91	13.25	2.00	23.2	134.9	16.9	200	10000	208
TOTAL LOAD CAPACITY REQUIRED											1053
COLD COMPR.	0.75	4.3	3344	9.57	1.40	6.06	41.92	10.16	264	2235	45
APPROXIMATE TOTAL SYSTEM CAPACITY REQUIRED											1098

10. UTILITY MODES AND FLOW DIAGRAMS

The modes of operation for the collider and the high energy booster are defined by different *states*. Such states are determined by steady temperatures, pressures, or other measured parameters, and by *processes*, which are the required transients to change the conditions of the collider to a new status. The logic diagram for the different states and processes corresponding to the utility modes and other operating modes is shown in Figure 9.1-1. The following is a listing of the utility modes of operation.

a. Warm gas circulation (cleanup)

b. Cooldown of sector

 1. 300 K to 80 K
 2. 80 K to 20 K
 3. 20 K to 5 K and fill

c. Magnet conditioning

d. Emptying (liquid helium inventory handling)

e. Warmup of sector

f. Magnet repair

 1. String emptying
 2. Section isolation
 3. Section warmup
 4. Section cooldown after magnet repair
 5. String fillup.

10.1 SECTOR CLEANUP

Initial commissioning of the collider requires the circulation of clean warm helium gas through the magnet strings and associated equipment to remove contaminants, particularly moisture and residual gases in the windings and piping. The 20 K compressor with appropriate suction pressure (2 to 4 bar) and outlet at the system design pressure to provide 200–400 g/s of 300 K helium flow is used for cleanup. The flow is routed through the high pressure side of coldbox heat exchangers HX-1A and HX-1B, and through the 80 K bed. From there the flow is bypassed through V-1351 to the medium pressure circuit of HX-1A. The stream is warmed to room temperature and is discharged at high pressure through valve V-1362 to the cooldown supply line. The warm clean gas is supplied to the magnet string and to the various helium flow loops through the cooldown supply line. The return flow is routed directly to 20 K compressor suction. Molecular sieve adsorber beds in the compressor suction line remove moisture and contaminants. The dryer bed should be sized for operation at these flow and pressure conditions.

Initial Status

The cleanup process is performed prior to cooldown of the collider. The whole system is warm, and the lines are full of dry air. Before the warm circulation process is initiated the system is purged, evacuated, and charged with helium.

Refrigeration Plant Operation

The 20 K compressor is used to provide 200 to 400 g/s of 300 K helium flow for cleanup, operating at appropriate suction pressure (2–4 bar nominal) and at the system discharge pressure. The helium flows through the high pressure side of coldbox heat exchangers HX-1A and HX-1B, and through the 80 K bed, and is bypassed to the medium pressure circuit of HX-1A (via V-1351) at the operating pressure for warmup to room temperature. The high pressure 300 K helium is routed through valves V-1362, V-1462, and V-1506 to the main supply (single-phase main feed) line to the magnet strings. The low temperature coldbox is not operated. The boil-off from the dewar goes to the first stage compressor. If necessary, the compressors may be operated to process this gas.

There are several loops to be cleaned: the magnet string, the single-phase return, the gas helium return, the 20 K lines, the helium recoolers, the power leads, etc. The return flow has several routes:

a. The return flow is directed through the warm return header, through cooldown valves (V-001; Figure 10.1-1 shows the circulation process of the magnet strings and current leads), and returns to the dehydration skid through valve V-1324.

b. The return flow is directed through the GHe return, through recooler valves (V-003; Figure 10.1-2 shows the cleanup process of the magnet string, single-phase return line, helium recoolers, and vapor return line), and returns to the dehydration skid via valves V-1421 and V-1323.

c. The return flow is directed through the 20 K feed and return lines, through the quench relief valves (V-002) located in the spool pieces (Figure 10.1-3 shows the cleanup process of the magnet string and the single-phase return line), and returns to the dehydration skid via valves V-1411 and V-1323.

d. The return flow is returned through the single-phase return line and via valve V-1507 to the compressor (Fig. 10.1-4).

Flows and operation

A maximum flow rate of 100 g/s per string is available for cleanup. Flow resistance limits the flow through the magnet string to a maximum of 40 g/s. The flow rate through the system varies, depending on the cleanup routes.

System final status

The status of the system after warm circulation is "WARM CLEAN." The cold lines and passages are at 300 K, and the quench valves, cooldown valves, and recooler control valves are closed. The system is clean and ready for insulating vacuum pumpdown and ready for cooldown.

Process time

The entire volume in the sector has to be circulated at least five times. The volumes of the piping and magnet flow channels are listed in Tables 6.1-1 and 6.1-2. The minumum cleaup time is approximately 20 minutes per loop.

10.2 SECTOR COOLDOWN

Cooldown of the magnet strings is carried out in various phases. Before any cooldown processes are initiated, the insulating vacuum space and the beam tube must be pumped down to the appropriate level of 1.3×10^{-2} Pa. The 80 K liquid nitrogen shield lines are cooled down before initiation of (helium) cooldown of the magnets.

The helium refrigeration system is designed for a nominal supply of 400 g/s of helium flow to the magnet string for cooldown from 300K to 80 K. The supply pressures and temperatures in various phases of cooldown are given in Table 10.2-1. The system is designed to enable the control of the cooldown feed flow temperature by mixing the warm and cold helium supplies (V-1362 and V-1363). Some or all of the expanders may be used in various cooldown phases. During successive cooldown phases, the return flow is valved into the refrigerator return side at various temperatures. The goal is to control the cooldown process of the different parts of the cryostat to minimize cooldown time and cooldown cost, and to prevent excessive thermal stresses.

Table 10.2-1. Cooldown conditions

Starting temp *cold mass*	Ending temp *cold mass*	Supply pressure *bar*	Return Pressure *bar*	Supply flowrate *g/s*	Cooling capacity *kW*	Wave speed *m/hr*	Cooldown time *days*	Sector inventory *kg*
300 K	80 K	16	4	400	450	8.2	22.0	83
80 K	20 K	16	1.2	140	≅50	15.8	11.4	330
20 K	5 K	4	1.2	≅500	>12*	≅360	≅0.5	≅22000

* With liquid consumption from dewar.

The string cooldown process may be started after the insulating vacuum has been successfully pumped down (a software interlock will inhibit the cooldown start-up if vacuum conditions are inadequate).

The cooldown of a string is performed in three major steps following cooldown of the 80 K shield from 300 K to 80 K.

Step 1: Cooldown from 300 K to 80 K

Step 2: Cooldown from 80 K to 20 K

Step 3: Cooldown from 20 K to 5 K and fill

The cooldown of the 80 K shield may be performed simultaneously with step 1. If an upset occurs during the first step of cooldown contamination may be released. The expanders are not operated because they may be damaged due to release of contamination during an upset condition:

During each of the steps the flows of the cryogens at different temperatures are routed in different ways. There will be software interlocks to prevent disorder in the cooldown process.

Sector cooldown to 80 K

Initial status

Collider initial status is "WARM STANDBY." The collider equipment is warm and clean, and the insulating vacuum vessel is at a pressure lower than 1.3×10^{-2} Pa.

Refrigeration plant operation

A helium flow rate of 400 g/s at 80 K is supplied to the magnet strings, 100 g/s per string. Liquid nitrogen from storage is supplied to the 80 K shields, 64 g/s per string for a total flow rate of 256 g/s. The required capacity for cooling the 400 g/s warm helium to 80 K is achieved by boiling 1125 g/s of liquid nitrogen. The refrigeration plant requires a continuous supply of 1125 g/s of liquid nitrogen for the helium system and 256 g/s for the 80 K shield (for a total of 4,972 kg/hour or 119 tons/day ≅ 6 trucks/day).

Only the warm coldbox system is operating during sector cooldown to 80 K. Liquid nitrogen is vaporized and warmed up to 300 K by heat exchange with the helium stream coming from the compressor system. During cooldown from 300 K to 80 K the pressure drop is as much as 10 bar. The refrigeration system is capable of supplying 80 K helium at 16 bar. Under normal operation the warm return header is pressurized to 4 bar, and only the 20 K compressor is required to provide the 400 g/s of circulation needed. If the return header cannot be pressurized to 4 bar, the system must be operated at lower flow rates to prevent damage to the dehydration bed. The flow exiting the 80 K adsorber beds is routed to the cooldown supply line through V-1363 and to the single-phase main feed line via crossover valve V-1462. The flow bypasses the surface precooler through valve V-1508. If the precooler is still warm, it should be cooled to 80 K by opening valve V-1514, with the warm gas vented through V-1512. A flow of 100 g/s is directed to each magnet string.

Flows and operation

The first step is to cool down the 20 K shield. This cooldown needs to be carried out at a controlled rate to prevent excessive thermal stresses on the shield. The 20 K shield can be cooled independently to 80 K using either of the following two methods:

a. Using helium flows through crossover valve V-1461, V-1508, and control valve V-3014.

b. While the quench valves are opened the 20 K shield may be cooled simultaneously by 80 K helium flow from the single-phase feed through control valve V-3001. The flow rate is controlled by V-3001 to prevent excees thermal stresses on the shield during the cooldown. Once the 20 K shield is cold, the flow rate to the string is increased to 100 g/s.

There are also two possible ways to cool down the magnet string.

a. The first method (Fig. 10.2-1) is to cool down the magnets in parallel by supplying 80 K helium through the 20 K lines as follows: Every half-cell has a quench valve and every full cell a cooldown valve. During this process every other quench valve and every cooldown valve are kept open. The 80 K helium supplied to the 20 K shield lines flows through the quench valves to the magnet half-cell and then through the cooldown valves to the 300 K warm return header.

b. The second method (Fig. 10.2-2) is to simultaneously supply the 80 K helium at one end of the string to both the single-phase feed and single-phase return lines. The warm flow is returned through the cooldown valves to the warm return header. Each of the recoolers' valves (V-003) is kept open, and the cooldown valves (V-001) are also opened. A cooldown wave develops and travels along the string. Each cooldown valve is closed as the cooldown wave progresses along the string.

A small part of the flow may be diverted directly to the warm header through the current leads and bypass leads .

At this point, although all the cooldown valves are now closed, parts of the system may still be warm. The 80 K helium is then supplied through the single-phase feed and returned at the end of the string through the single-phase return line. The recooler valves are kept open. This flow scheme is maintained until the remaining parts of the system are cooled to 80 K.

The cooldown supply temperature can be controlled by mixing warm gas through V-1351 and V-1362 with cold gas supplied from V-1363.

System final status

The status of the system after cooldown to 80K is "COLDMASS AT 80 K." The 80 K shield is refrigerated by nitrogen at a nominal flow rate. Cooldown valves (V-001), quench valves (V-002) and recooler valves (V-003) are closed. All parts of the string are at

80 K and at pressures of 0.1 to 0.2 MPa, and the 20 K shield is also at 80 K. Valves V-3004 and V-3014 are closed. No flow is required in the cold mass. The helium inventory in the collider sector is about 83 kg.

Process time

The cooldown process from 300 K to 80 K will take approximately 22 days.

Sector cooldown to 20 K

Initial status

Collider initial status is "COOLDOWN AT 80." The 80 K shield, 20 K shield and the cold mass of the four strings are at 80 K. Liquid nitrogen flows in the 80 K lines.

Refrigeration plant operation

The cooldown process from 80 K to 20 K is designed to be performed in one step (Fig. 10.2-3). However, if necessary, this cooldown may be accomplished in multiple steps by mixing 20 K helium with warmer gas. High pressure 15 K–20 K gas from V-1443 is fed through the cooldown supply line to the main single-phase feed line. The magnet string, the 20 K shield, the 4 K return line, and the GHe return line are cooled from 80 K to 20 K during this process.

For 80 K to 20 K cooldown the available cooling capacity is approximately 50 kW, defined by the expander capacity. Helium at approximately 15 K at high pressure can be supplied at the rate of 140 g/s from the high pressure tap through valve V-1443, located below the third expander. The cold flow is supplied to the single-phase feed line through valves V-1462 and V-1501, to V-3001 and V-3011 and to the single-phase return line through valves V-1503 and V-3102 to valves V-3002 and V-3012.

The return flow to the plant is a combination of the flows through the quench valves, through the 20 K lines to valves V-1508, V-1510, and V-1411, and through the recoolers and the vapor return line, through V-3103, V-3104, and V-1421. This flow is returned through valve V-1321 to the first stage compressor(s).

At the end of this process the nominal 20 K flow is established.

Flows and operation

Nitrogen flows maintain the 80 K shield at the nominal shield temperature range. The available helium flow rate is about 140 g/s. In the collider this flow is divided into four streams of 35 g/s each, and in the HEB this flow is divided into two streams of 70 g/s each. The flow rates and pressure ranges for this cooldown phase are given in Table 10.2-1.

System final status

The status of the system after cooldown to 20 K is "SYSTEM AT 20K." The 80 K and 20 K thermal shields are kept at their nominal temperature range by nitrogen and helium flows. All helium valves in the string—i.e., the cooldown (V-1), the quench (V-2), the recooler level (V-3) and lead cooling (V-4) valves are closed. No flow is necessary in the cold mass. The helium inventory in the collider sector is approximately 330 kg.

Process times

Table 10.2-1 gives the estimated cooldown time and wave speed for the various cooldown phases.

Sector cooldown to 5 K and fill

Initial status

Collider initial status is "SYSTEM AT 20." The 80 K shield and 20 K shield are at the nominal temperature ranges. Liquid nitrogen flows in the 80 K lines, and 20 K helium flows in the 20 K shield lines. The cold mass temperature is in the range of 20–25 K.

Refrigeration plant operation

Before starting this process the helium dewar is filled with liquid delivered from external sources. This is the final stage of cooldown, during which the magnet string is cooled to 4–5 K and filled. The refrigerator supplies 4 bar, 4.5 K flow through V-1502 and through the single-phase feed lines to V-3001 and V-3011 (Fig. 10.2-4). Flow can be supplied directly from the dewar via valve V-1504 (Fig.10.2-5) or, if a pump is available, flow can be supplied to the surface precooler through valve V-1515 (Fig.10.2-6). As the cooldown wave travels through the string, inventory accumulates behind the wave. As a result the returning flow rate is much lower than the supply flow rate (3–5% of the supply flow).

During the final cooldown, the refrigerator will experience an imbalance in flows and will operate mainly in liquefaction mode. The coldbox flows are balanced by additional flow from the dewar; this flow is evaporated in the precooler. The 20 K vapor returning from the tunnel bypasses the heat exchanger (V-3102) and is diverted through V-1507 and returned to the coldbox heat exchanger stack via V-1422. It is preferred that the final cooldown and fill not be made directly from the dewar, as this would result in two-phase flow to the strings.

Flows and operation

The flow rates in the 80 K and 20 K shields are kept at their nominal rates. About 500 g/s of 4.5 K, 4 bar helium from the precooler (valve V-1502) is supplied to the single-phase main feed supply line.

System final status

Collider status after cooldown to liquid temperatures is "COLDMASS AT 4 K," and the system is pressurized to 3–4 bar. The 20 K and 80 K shield are running normally. About 22000 kg of helium inventory is present in the magnet strings when the cooldown and fill process is completed.

Process times

At 500 g/s the process takes approximately 12–15 hours to complete.

Temperature setting and control.

After cooldown to 4 K–5 K the recoolers are filled and their level control loops may be activated. At this point the cold compressor is started and the vapor return line pressures are lowered to their nominal values. After all the operating parameters have settled to their nominal values—in particular, when the operating temperatures reach those in Figures 7.3-1 or 7.3-2—the status of the ring is changed to "STANDBY COLD."

10.3 Magnet Conditioning

Conditioning involves operating the string of magnets at a reduced temperature and cycling up the current to a point above the nominal operating current of the ring. A separate cold compressor will be mounted in series with the existing cold compressor onto the helium cold compressor box. This arrangement will allow the temperature of the helium supplied to any one of the four strings of magnets to be reduced to 3.5 K. One string will be conditioned at a time, while the other strings are kept cold (at 20 K) with only the 20 K shield active or, if necessary, near 5 K if a neighboring sector refrigerator is available to help maintain the string temperature. The SRS will have sufficient capacity to handle conditioning of one string at a time.

Initial status

The refrigeration system supplies the nominal flow rates to the rings at the nominal 4 K temperature and 4 bar pressure. The helium recooling scheme is activated. The heat load to the ring is only static (no beam, no high current).

System operation

The surface refrigeration system is operating in its nominal mode. The second cold compressor located in the tunnel is operated in series with the first cold compressor to lower the vapor pressure in one string.

Flows and operation

The vapor pressure is lowered to 0.4 bar and only one string is refrigerated.

System final status

The system is back to nominal operating conditions, "STANDBY COLD."

Process times

The time for magnet conditioning will vary, depending on requirements.

10.4 Sector/String Emptying

Emptying the system is required for two main purposes:

a. Warmup cycle for the desorption of gas from the beam tube.

b. Warmup for maintenance.

The liquid inventory of the magnets is to be transferred to the storage dewars on the surface. High pressure 20 K gas from the shield is allowed into one end of a magnet string, pushing liquid out. The emptying process is controlled in order to maintain supercritical pressure during this procedure.

Initial status:

Collider initial status is "STANDBY COLD." Strings are cold at 4 K and no flow in the cold mass. The 20 K shield and 80 K shield are running.

Refrigeration plant operation

The lower temperature loops including expanders may be deactivated. The 20 K helium loop is operating nominally.

Flows and operation

By opening the quench valves in the magnet string and lowering the pressure in the 4 K lines, the 20 K helium is allowed into the magnet cold mass channels. The supercritical 4 K helium is pushed out of the magnet strings, displaced by the 20 K helium gas.

System final status

After emptying, the temperature in the magnet ring is allowed to go up to 20 K.

Process times

At a flow rate of 100 g/s in each string, it will take approximately 12–15 hours to empty all four strings. About 22000 kg of helium is removed from the sector to the surface dewars. This emptying process for gas desorption is performed at regular intervals.

10.5 Sector Warmup

For warmup to 300 K, warm clean high pressure gas from the refrigerator is supplied to the 4 K supply line through the cooldown supply line (Fig. 10.5-1). Magnet stresses are managed with the supply temperature of the warmup gas controlled by mixing warm and 80 K gas. One or more strings may be warmed up simultaneously while the remaining strings are kept cool by helium flow, either from the local refrigerator or from the neighboring plants.

Initial status

Collider initial status is "SYSTEM AT 20 K." Thermal shields are at nominal temperatures and nominal flow rates. The cold mass is at 20 K and at low pressure (1–2 bar).

Refrigeration plant operation

The string can be warmed up by supplying warm gas from the refrigerator. This requires the discontinuation of the cooling loops to the other three strings. While one string is being warmed the other strings are kept cold. The isolation valves between sectors are opened, allowing the other neighboring sectors to provide cooling for the remaining strings. The single-phase feed and return lines are used in these warmup loops.

The supply temperature of the flow for sector warmup can be varied by mixing warm and cold 80 K gas if a smaller temperature gradient must be maintained along the magnets. Warm pure high pressure gas is supplied through control valve V-1362 and via crossover valve V-1462 into the single-phase main feed line. The surface precooler is bypassed by opening bypass valve V-1508 and closing V-1501 and V-1502. An alternative is to pressurize the warm return header to at least 2 bar in order to supply warm gas; in this case, the cold flow is returned through the 20 K lines via the quench valves. This allows a parallel warmup of the shorter lengths of the string, decreasing the warmup time required. This also "softens" the warmup rate, thus reducing the stresses in the magnets during warmup (see Figure 10.5-2).

For long-term storage of the system at nitrogen temperatures the 80 K shields are operated at nominal conditions and the 20 K and 4 K flows may be disconnected.

Flows and operation

Flow resistance limits the warm flow that can be circulated through the string. The warmup rate will vary depending on the routes used for the supply and return flows. If all the flow is supplied through the single-phase feed and exits along the 20 K line through the quench valves, flow rates (for an entire sector) will vary from over 400 g/s at the start of the warmup phase to 40 g/s when the warmup wave reaches the end of the sector.

Excess inventory from the rings is stored on the surface in the gas tanks.

System final status

The warmup process can be stopped at different temperatures levels; the temperature level will define the status of the system.

Process time

The time required to warm up an entire sector varies depending on the routes used during warmup and how much the warmup rate needs to be controlled to manage mechanical stresses in the magnets. Warmup takes about 22 days if only 400 g/s is used. The parallel warmup method allows for the fastest warmup and should cut the time by more than half.

10.6 SECTION REPAIR

The repair of a component in a section requires the isolation of the section from the rest of the ring. The flows through the section must be rerouted to keep the rest of the sector cold. To remove or repair a specific component, such as a magnet or a spool, requires the breaking of the vacuum in a half-cell; this is done at room temperature. A section in the collider ranges between 360 m to 1350 m and in the HEB from 1220 m to 1480 m. See Tables 2.1-2 and 2.2-2. The section is the smallest part of the ring that can be isolated and warmed up as a unit.

String emptying

For repair of a specific section, the entire string is emptied. This is done by the same procedure described in Section 10.4.

Section isolation

All the cryogenic lines are depressurized to one atmosphere. The cryogenic flows in the neighboring sections are reconfigured to keep the rest of the system cold—in particular, to keep the nitrogen in the 80 K lines running. (See Figure 10.6-1.)

Section warmup (Figures 10.6-2, 10.6-3, and 10.6-4)

The warmup of a single section without warmup of the remainder of the strings, requires an external warm helium circulation. There are three options for warmup of a section.

a. Warmup using low pressure helium from the warm helium return header requires a blower and heaters. The warmup rate will be limited by the blower's head production. Warm gas from the warm return header is compressed by a blower, and the flow is split to the magnet cold mass channels, the single-phase return line, and the GHe return line. The quench valves can be opened to allow flow into the 20 K line. The flow exiting the other end of the section can go to a common header and be heated before it is returned to the warm return header. If the warm return header can be pressurized (see below) no blower will be required for warmup.

b. Warmup without a blower, using helium from the 20 K line, requires a helium stream from the refrigeration loop. Some flow from the 20 K loop can be used for this warmup process. The supply pressure is higher in this case and a higher flow rate can be achieved, and in turn a higher warmup rate can be achieved. The 20 K flow is heated and delivered to the single-phase supply line and also delivered to the single-phase return line. The recooler valves are opened to allow flow into the gas return line. The quench valve can be opened to allow flow into the 20 K line. The cold gas exits at the end of the section and is collected into a common header, and heated before it is sent to the warm return header.

c. Warmup without a blower can also be accomplished using helium from the pressurized warm return header. Warm gas from the warm return header is supplied into one end of the section via the cooldown valves. The cold gas exits the other end of the section through a quench valve into the 20 K line. To prevent damage to the shields, care should be taken toward the end of the warmup sequence to prevent warm gas entering the 20 K shield at an uncontrolled rate.

Section cleanup

To get clean gas for removing contamination after repairs, some of the 20 K flow must be used. The same arrangement used in (b), above, for warmup of the section can be used for cleanup. Another option is to supply high purity helium from portable pressurized gas cylinders.

Section cooldown after magnet repair

The 80 K shield is cooled down by allowing nitrogen into the section. Then the 20 K shield is cooled by a controlled and moderate 20 K flow. The cold mass is cooled by opening the quench valves and allowing the 20 K flow into the cold mass, and the warm gas is vented through the cooldown valves to the warm return header. When the temperature of the warm gas drops below a setpoint value the cooldown valves and the quench valves are closed. (See Figure 10.6-5)

Section cooldown to 5 K and fillup

The entire string must be cooled down to 5 K and filled once the repaired section is cooled to 20 K. For this purpose, the same process is used as defined in Section 10.2.

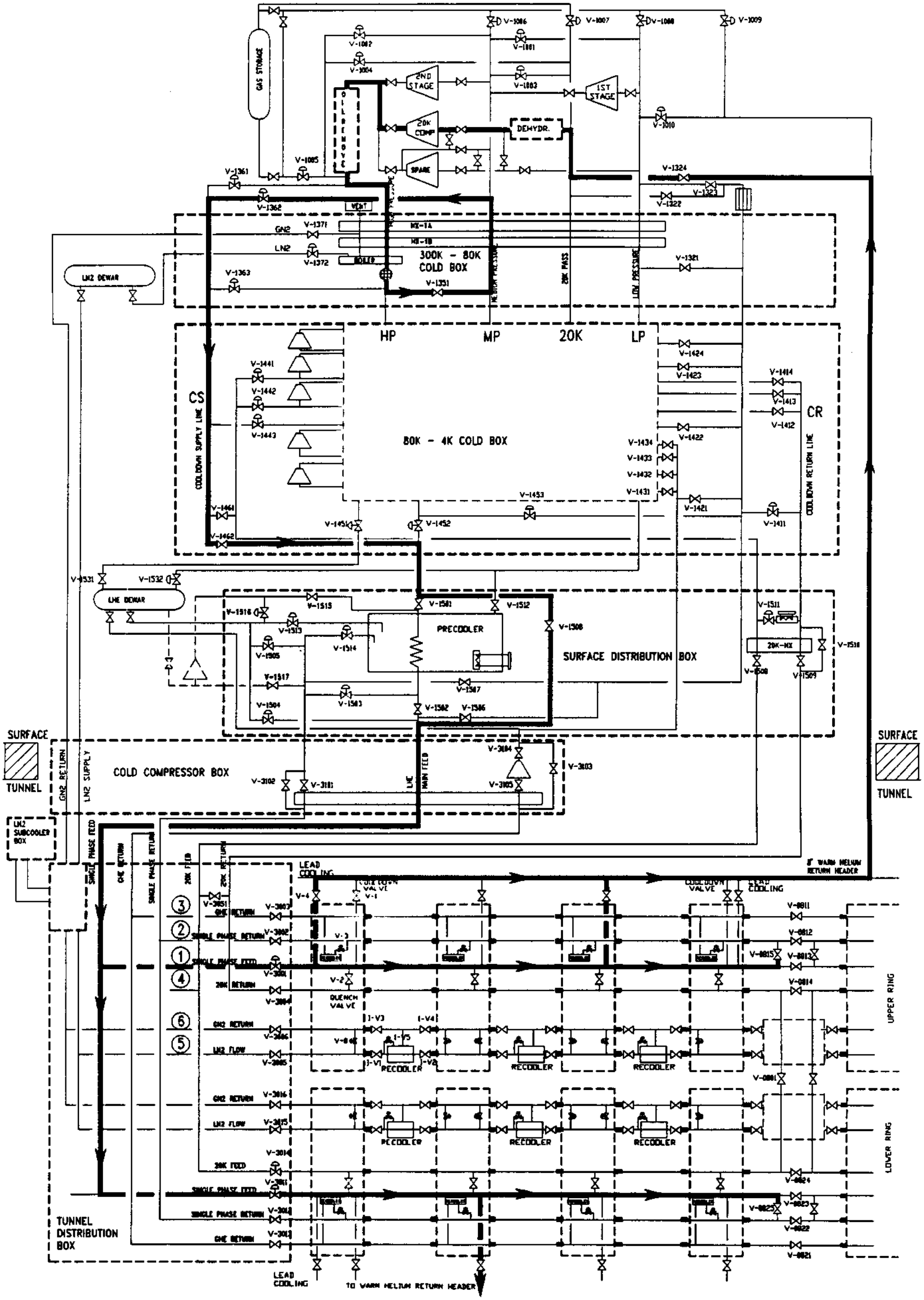


FIGURE 10.1-1 WARM GAS CIRCULATION: MAGNET STRINGS, WARM RETURN HEADER, CURRENT LEADS

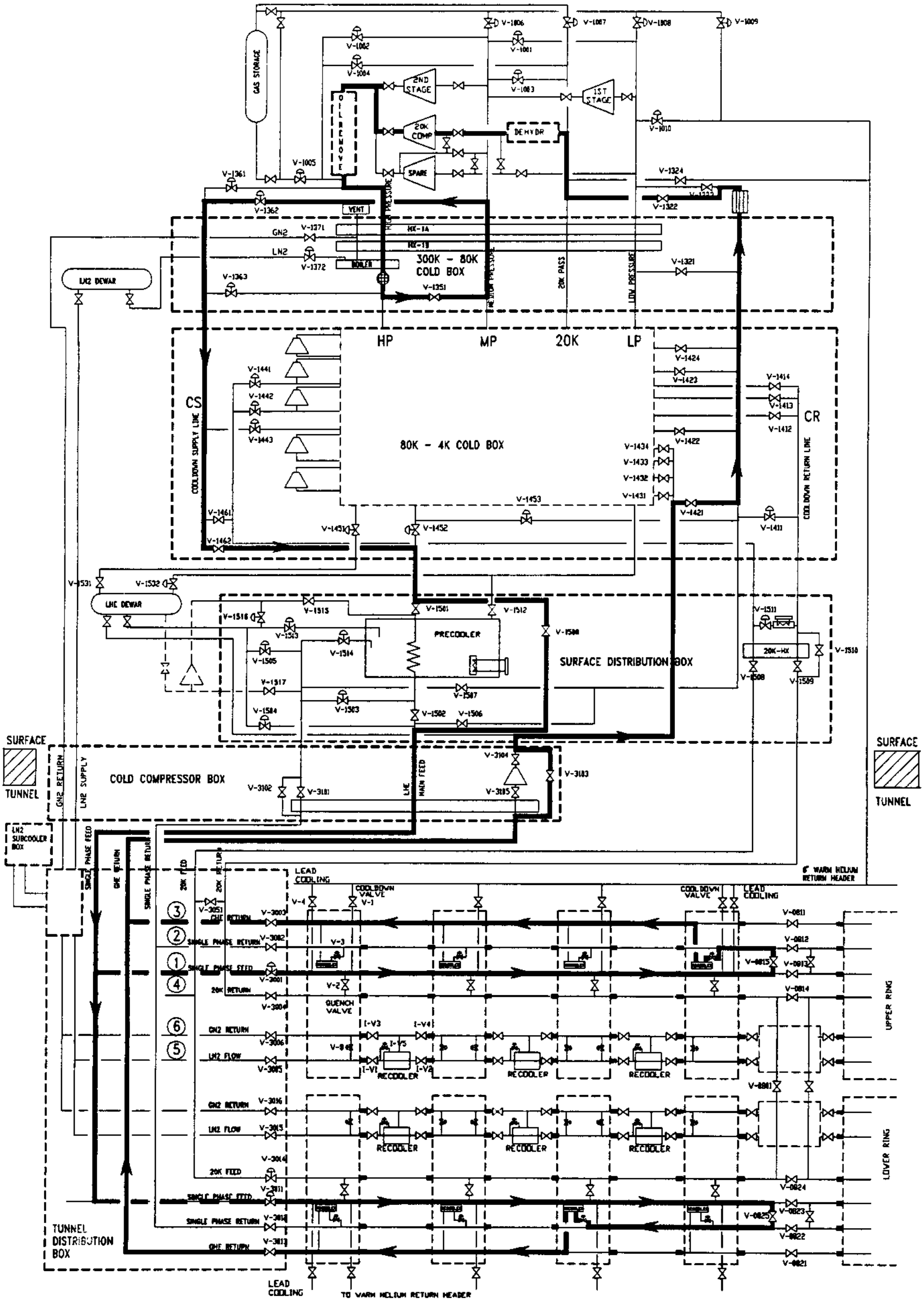


FIGURE 10.1-2 WARM GAS CIRCULATION: MAGNET STRINGS, SINGLE PHASE RETURN, RECOOLERS, GHE RETURN LINE

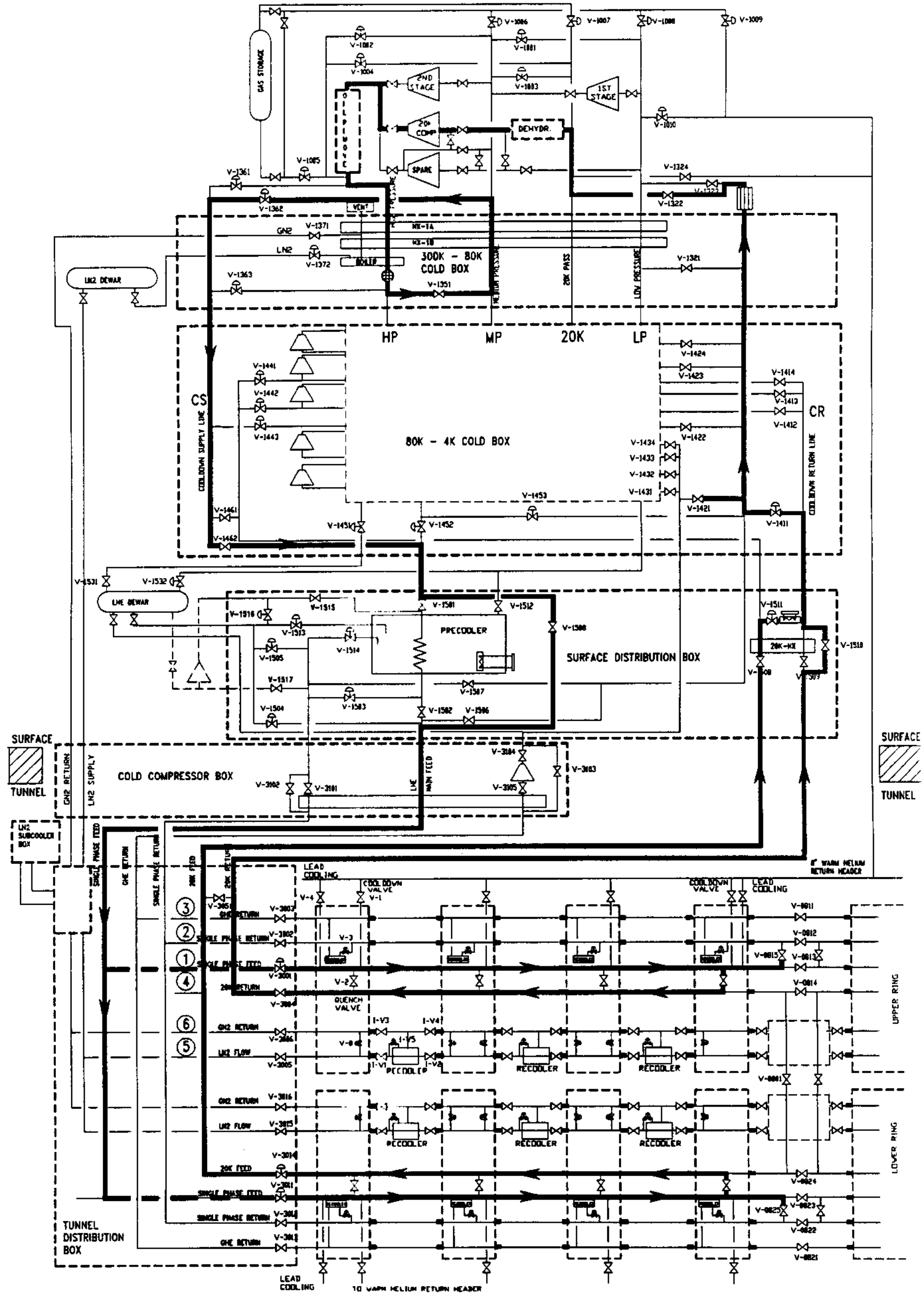


FIGURE 10.1-3 WARM GAS CIRCULATION: MAGNET STRING, 20K LINES

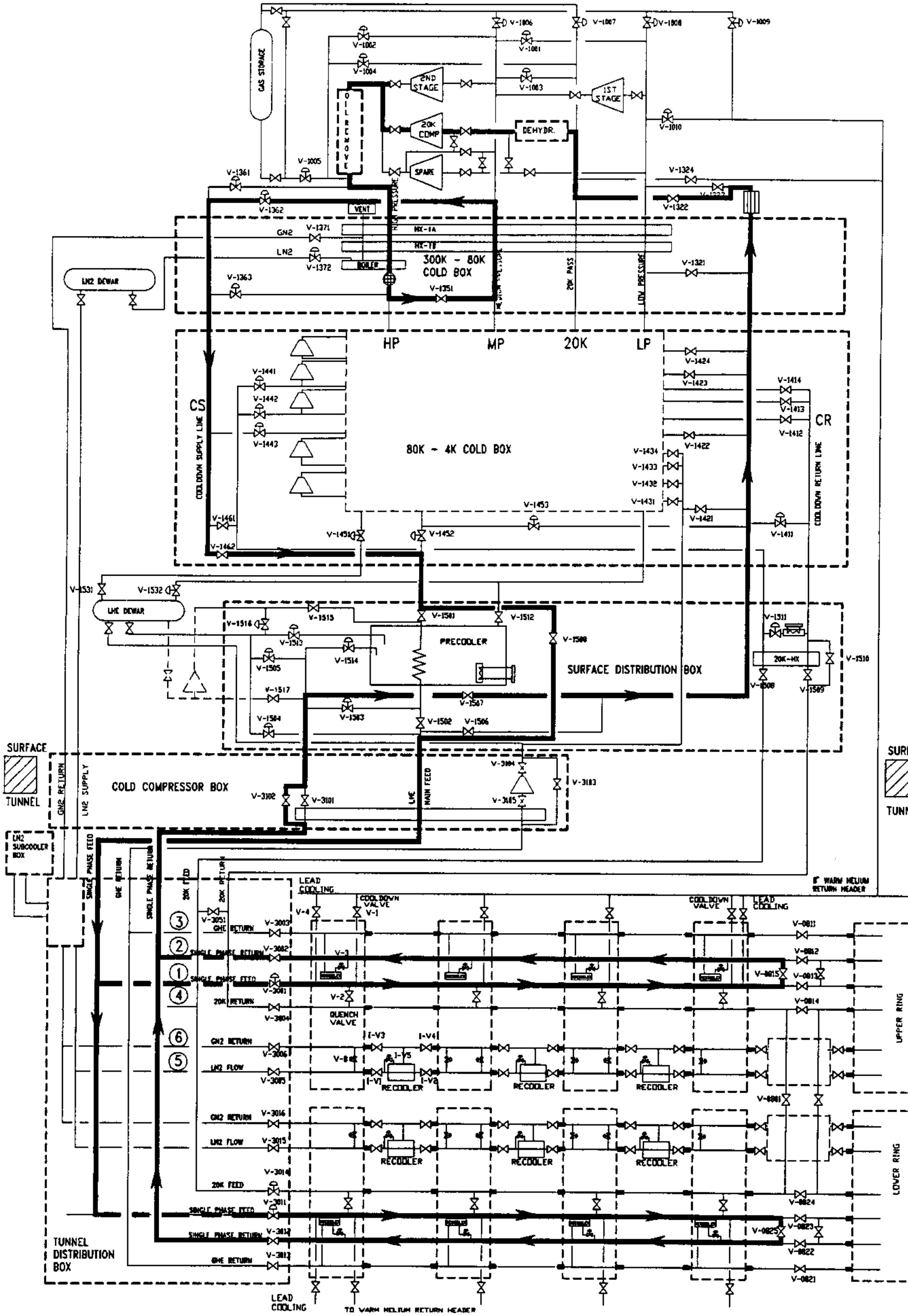


FIGURE 10.1-4 WARM GAS CIRCULATION: MAGNET STRINGS, SINGLE PHASE RETURN LINE

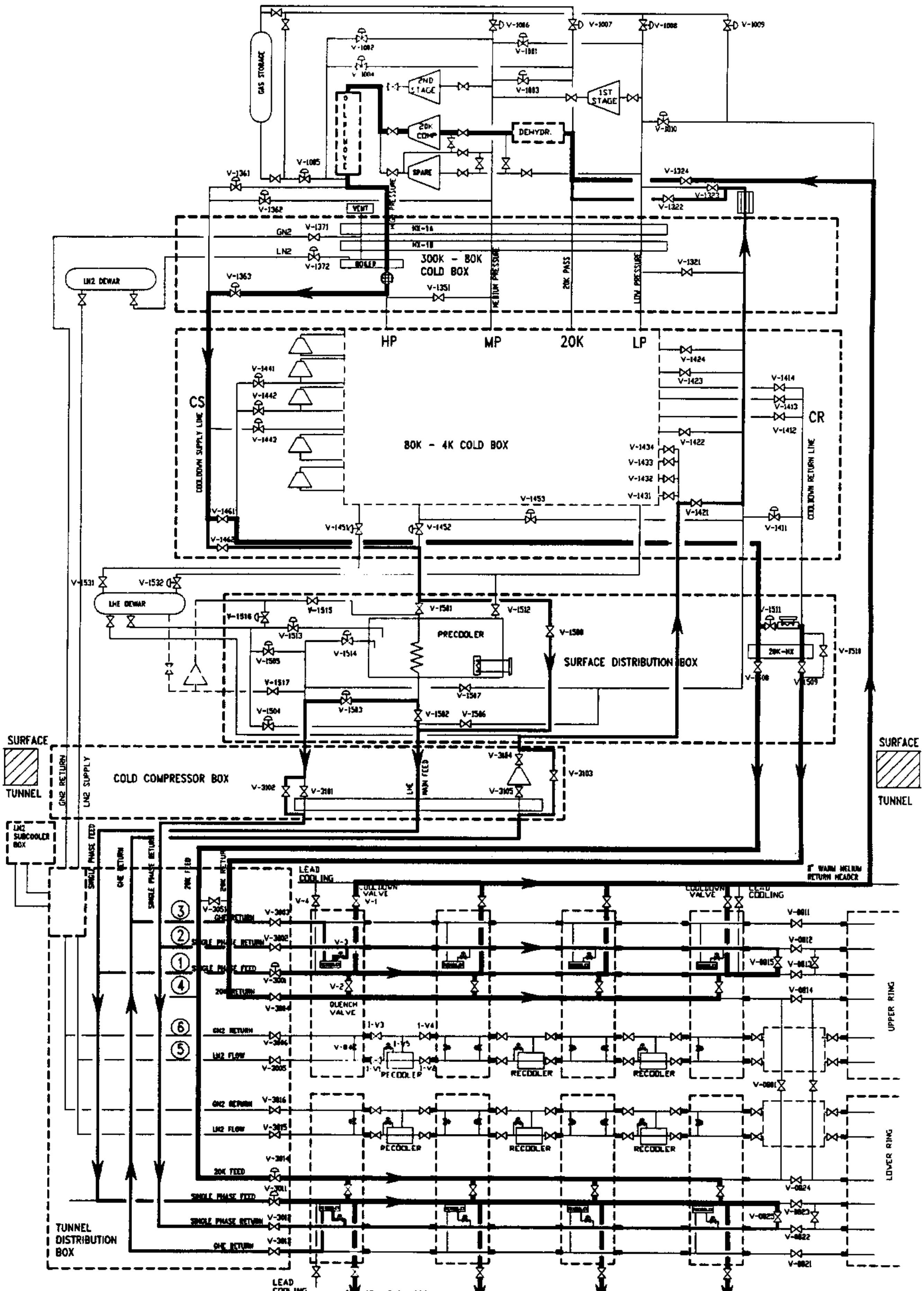


FIGURE 10.2-1 SECTOR COOLDOWN 300K TO 80K

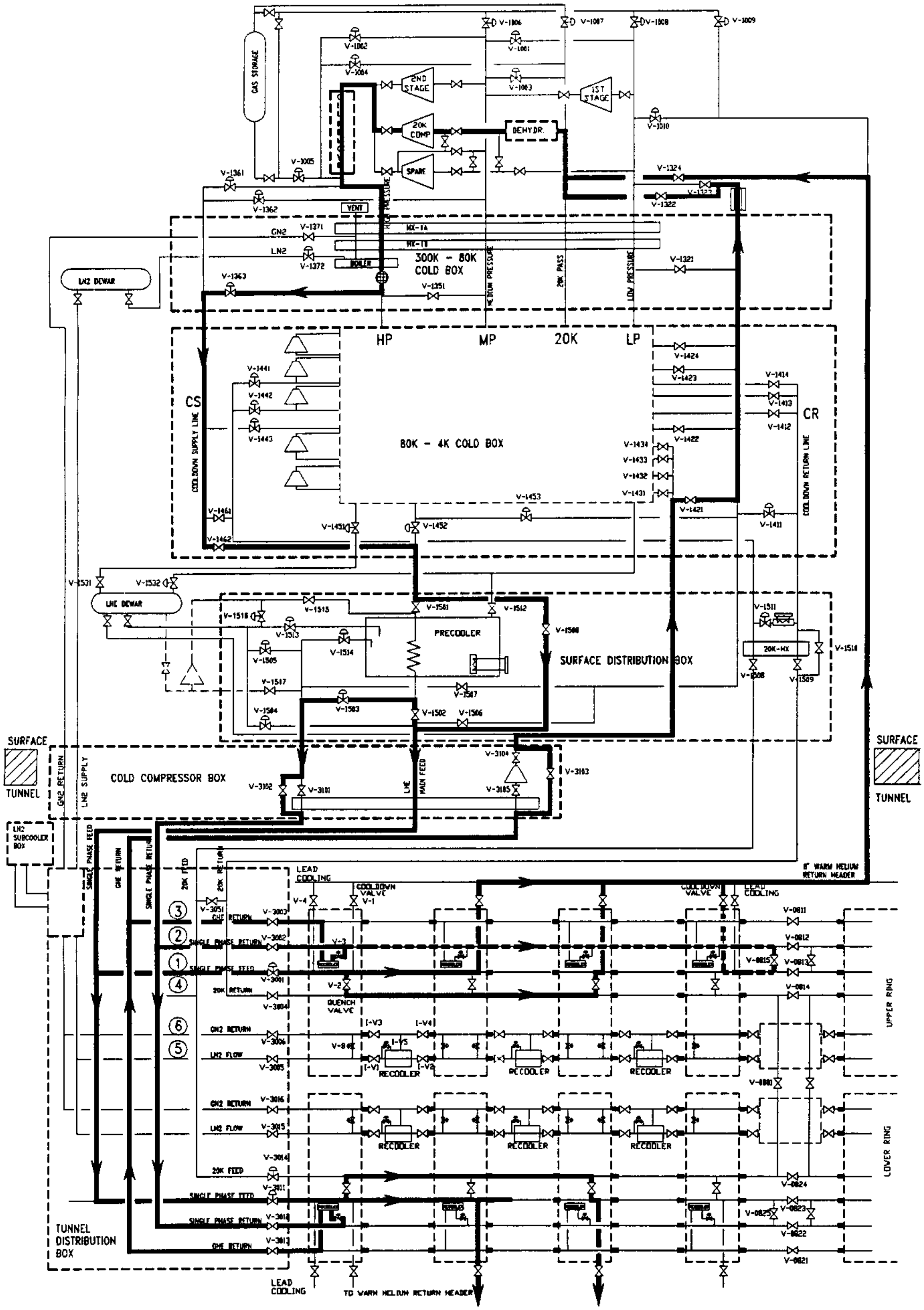


FIGURE 10.2-2 SECTOR COOLDOWN 300K TO 80K

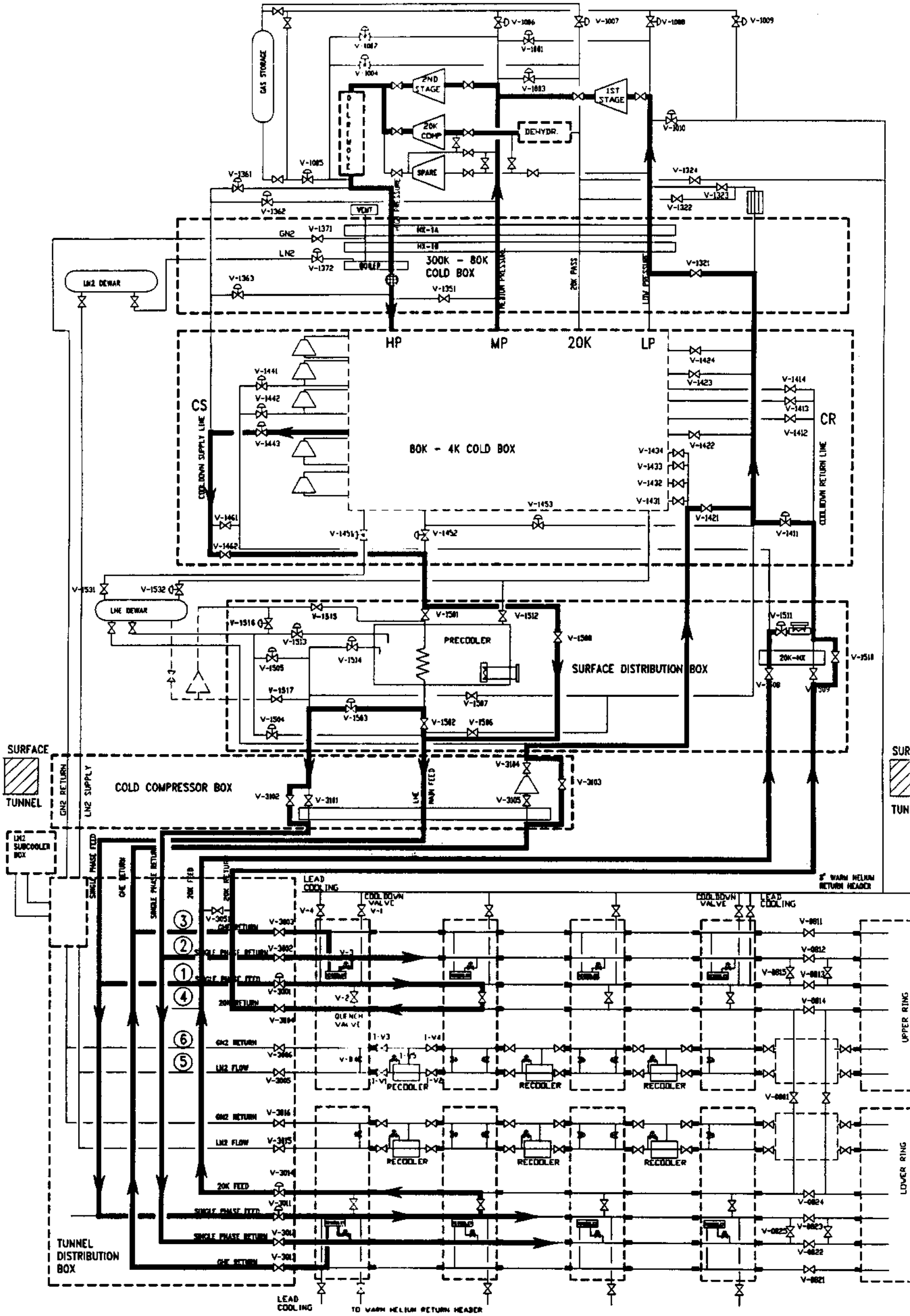


FIGURE 10.2-3 SECTOR COOLDOWN 80K TO 20K

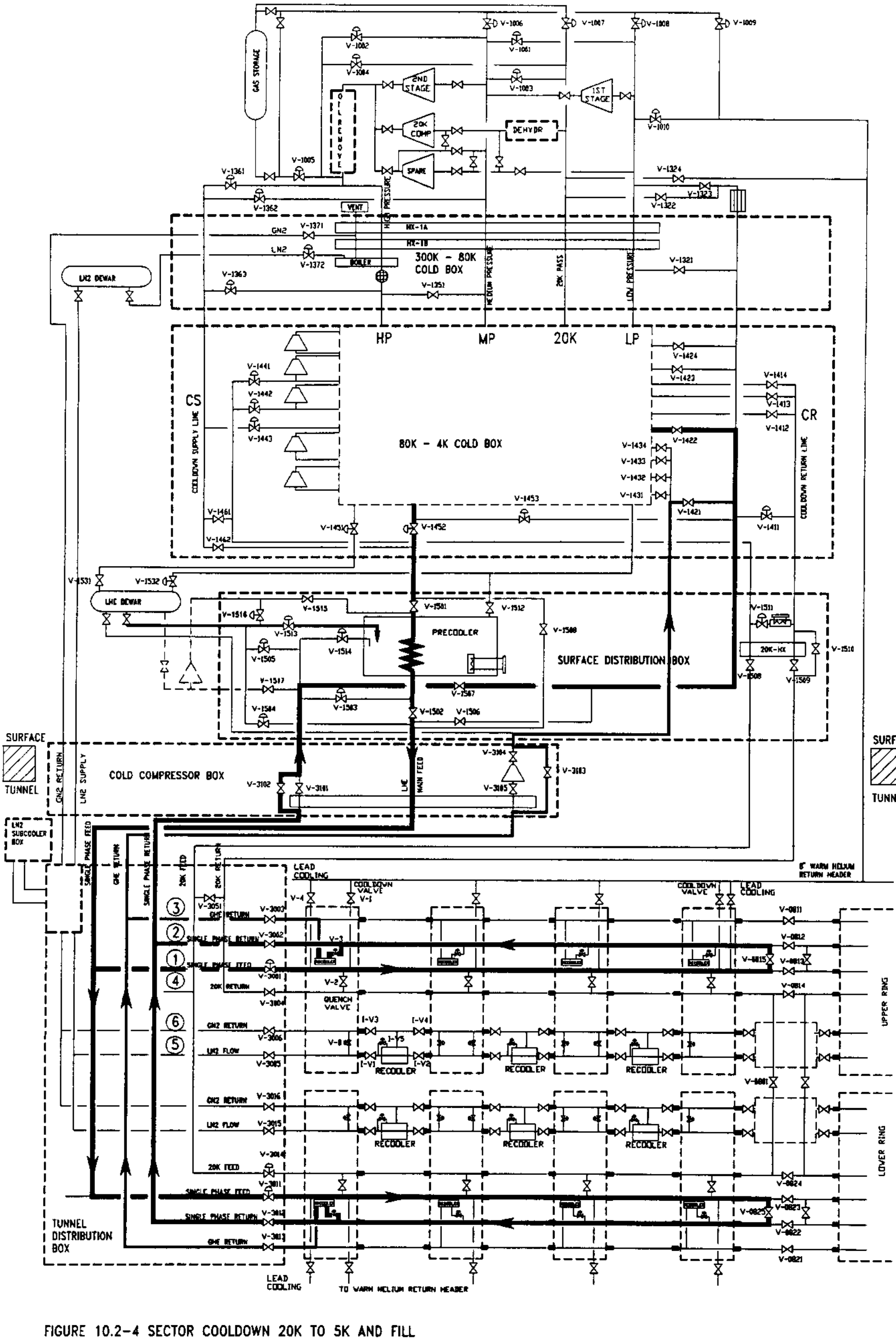


FIGURE 10.2-4 SECTOR COOLDOWN 20K TO 5K AND FILL

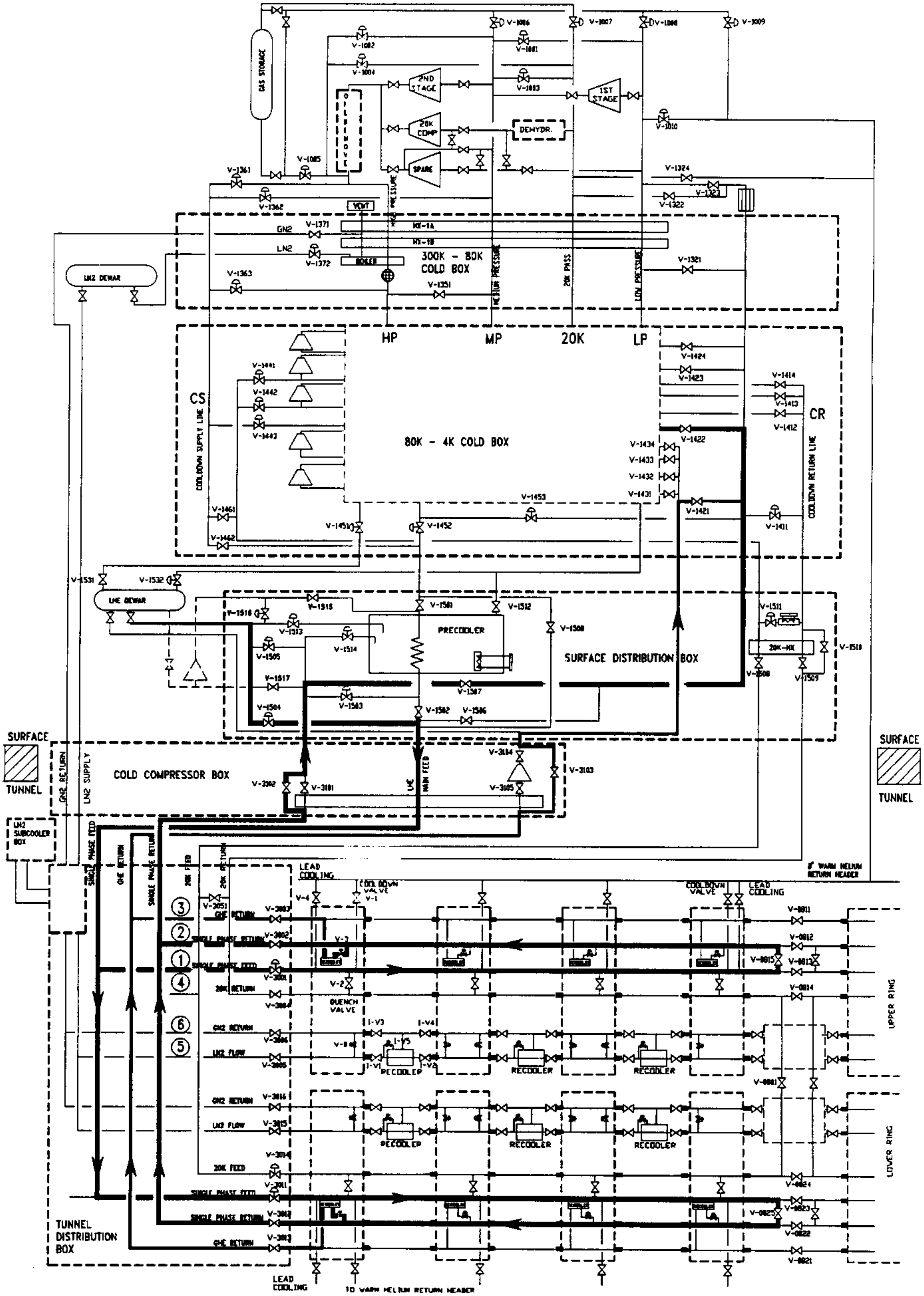


FIGURE 10.2-5 SECTOR FILL FROM DEWAR

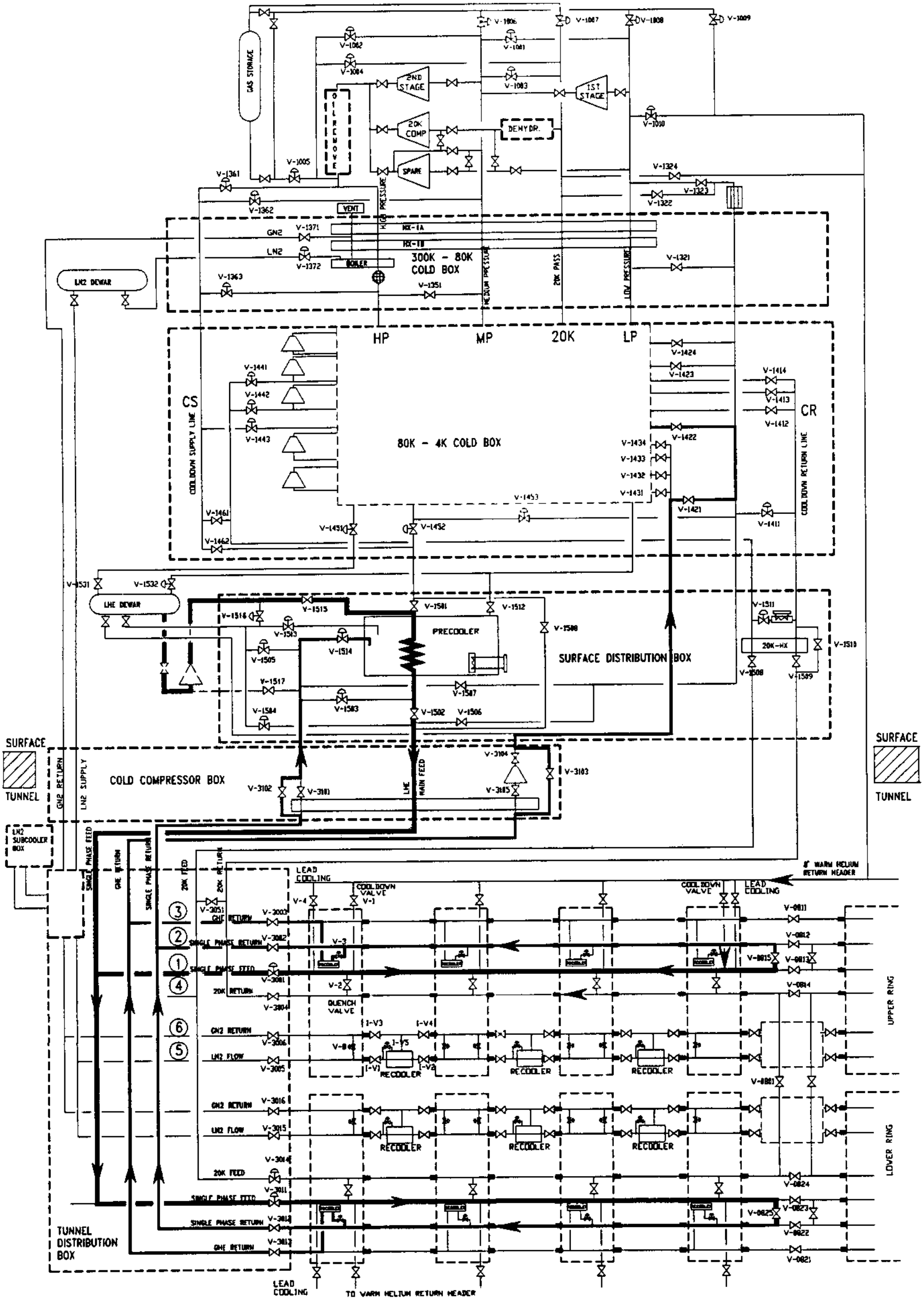


FIGURE 10.2-6 SECTOR FILL FROM DEWAR USING PUMP

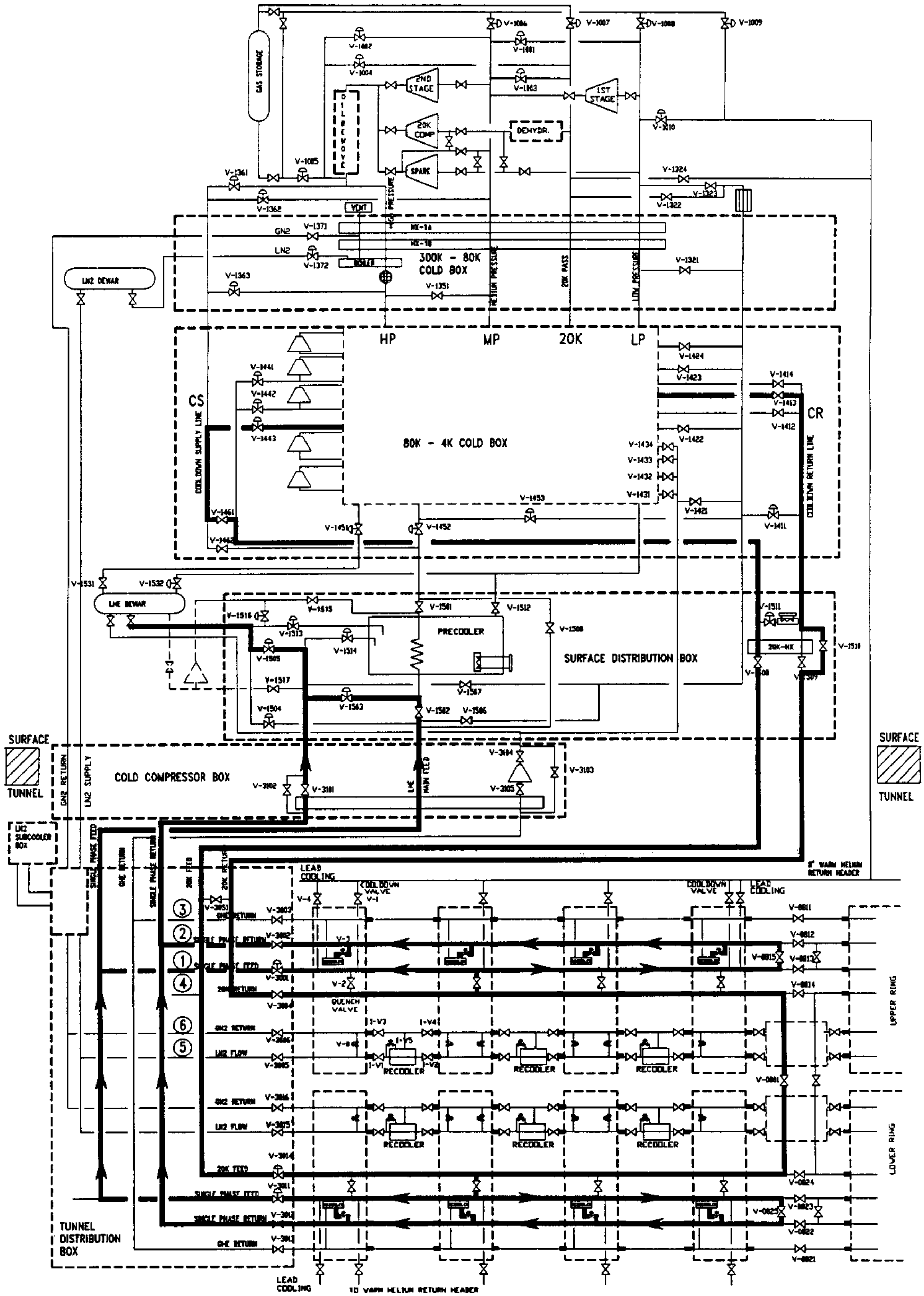


FIGURE 10.4-1 SECTOR EMPTYING

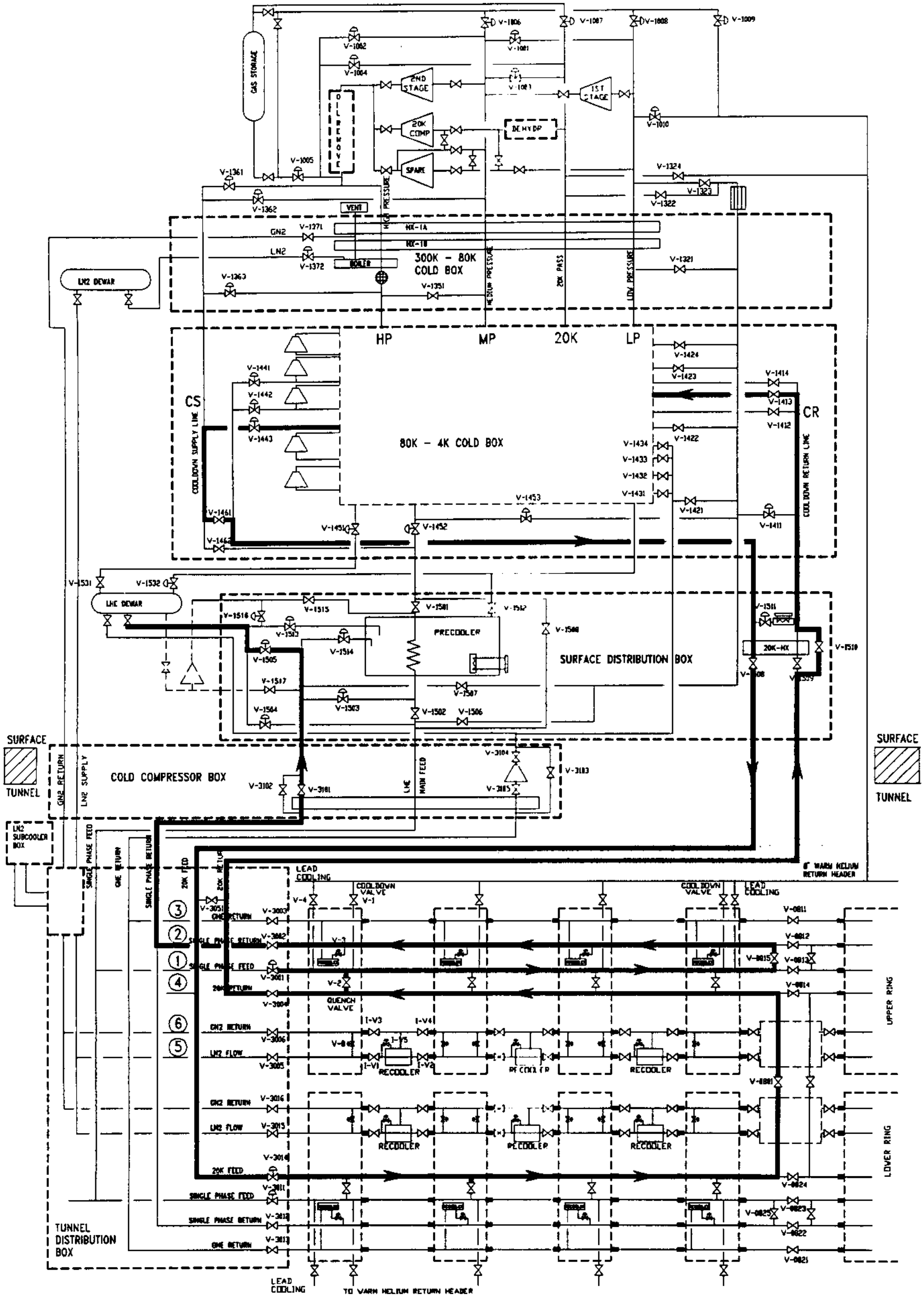


FIGURE 10.4-2 STRING EMPTYING

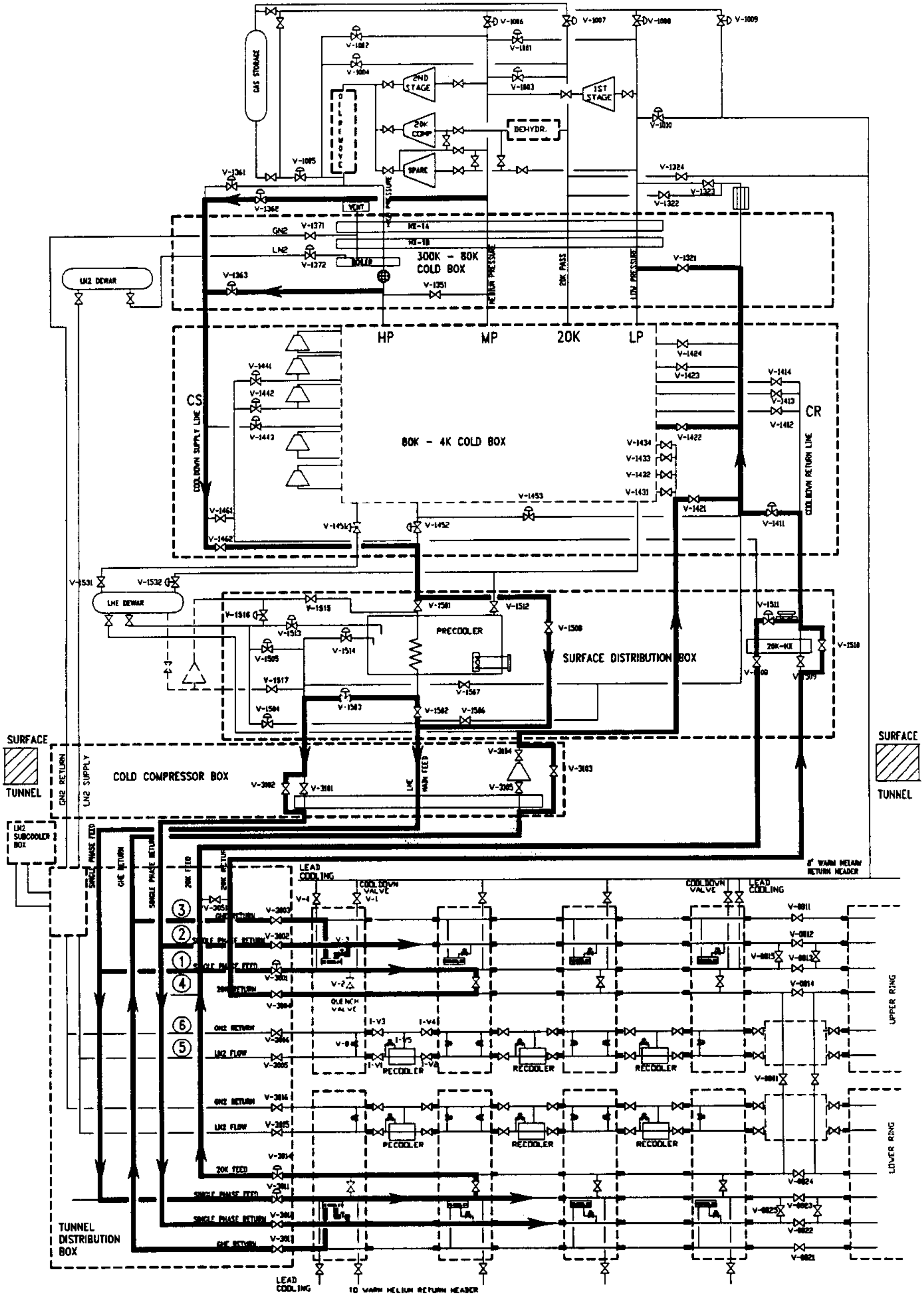


FIGURE 10.5-1 SECTOR WARMUP

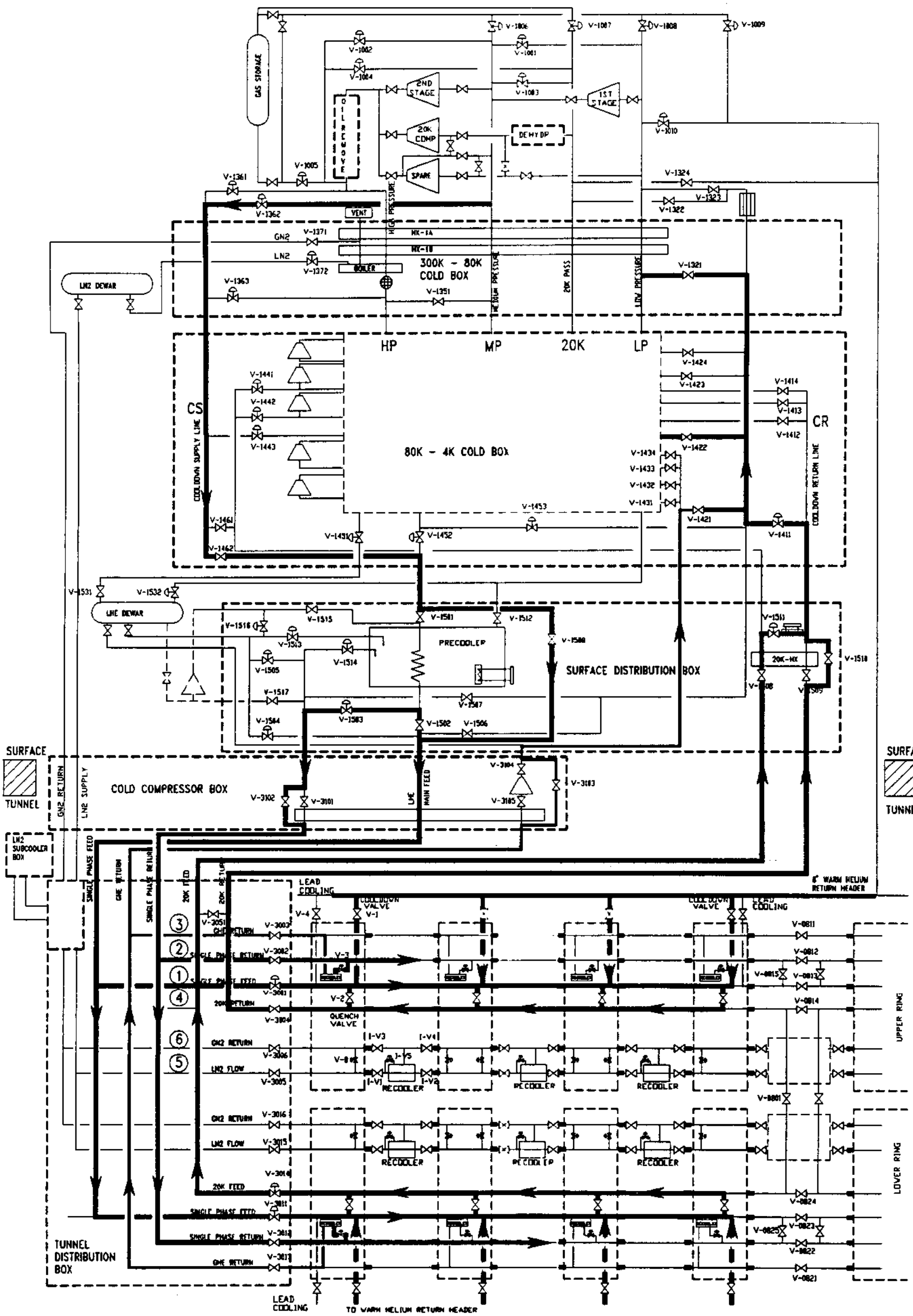


FIGURE 10.5-2 SECTOR WARMUP, WARM GAS SUPPLY FROM PRESSURIZED WARM RETURN HEADER

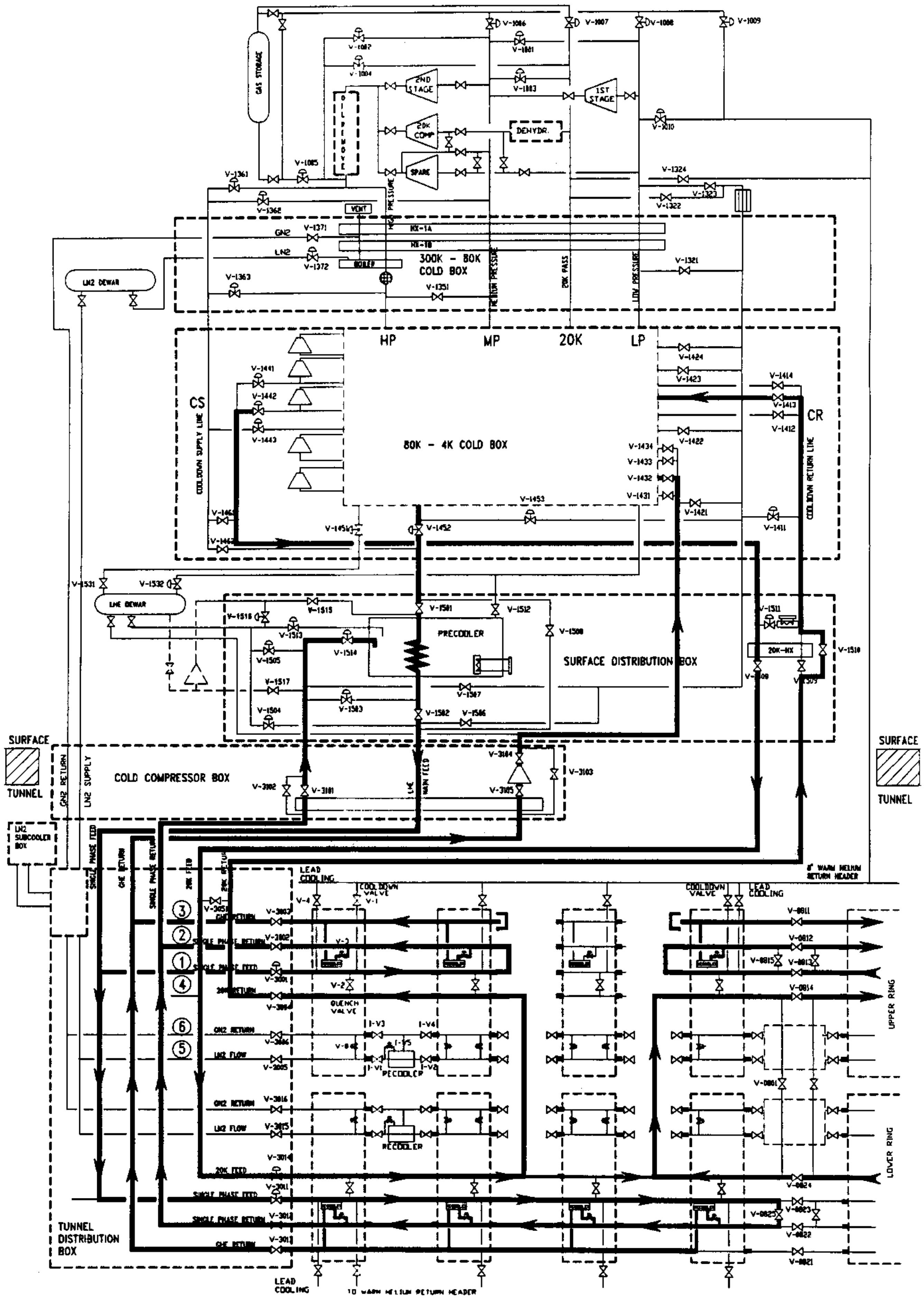


FIGURE 10.6-1 SECTION REPAIR

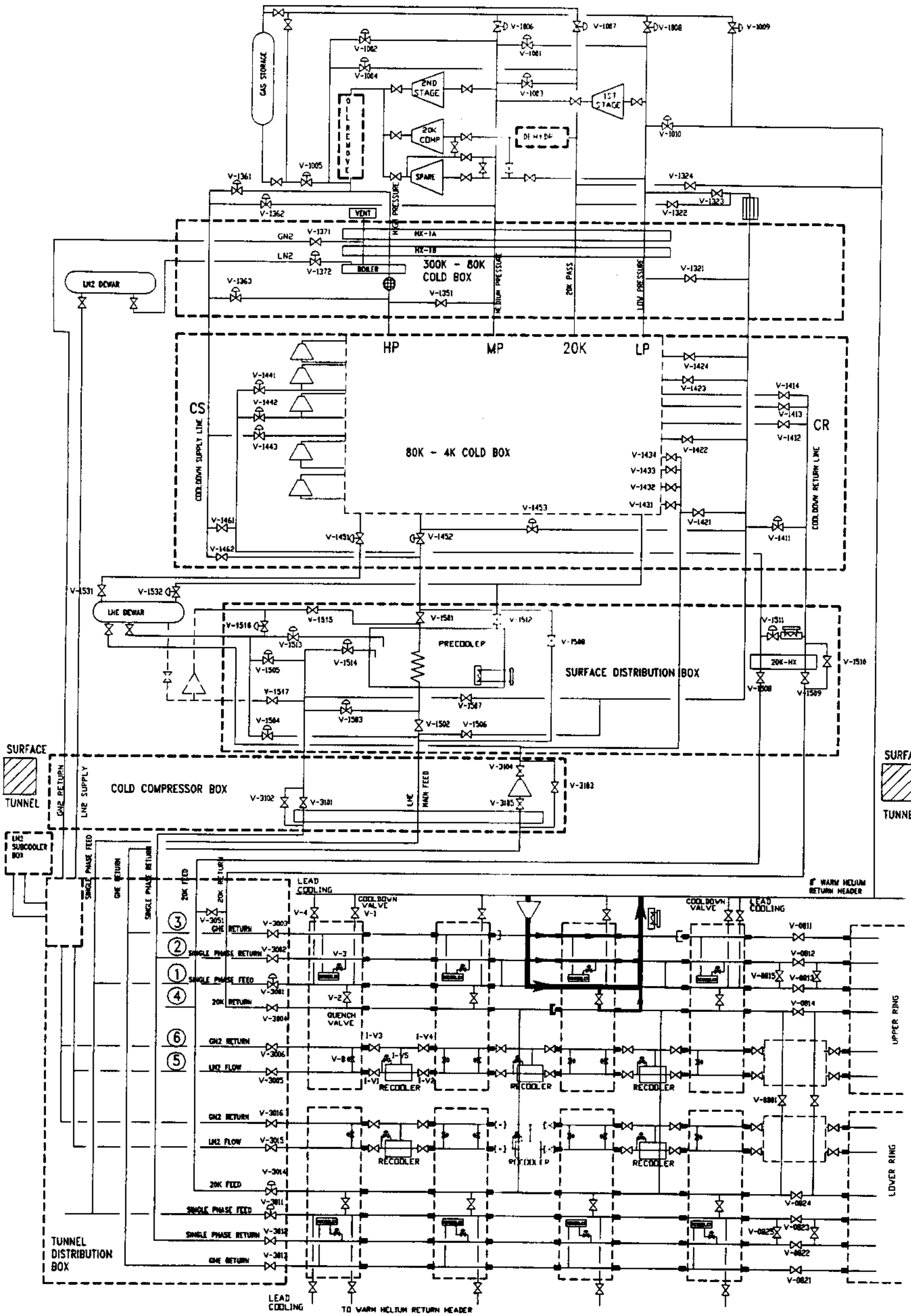


FIGURE 10.6-2 SECTION WARMUP USING WARM HEADER GAS AND BLOWER

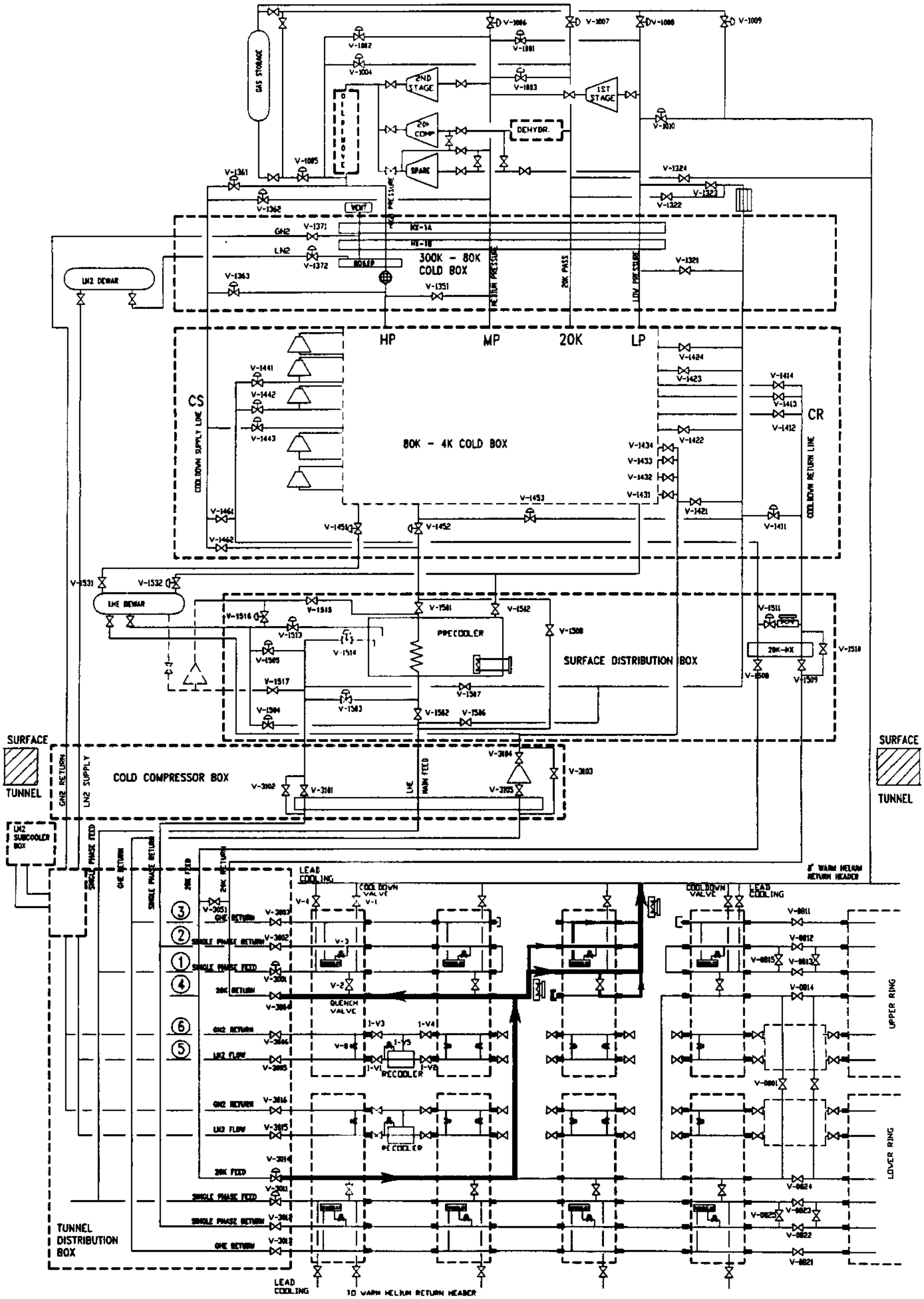


FIGURE 10.6–3 SECTION WARMUP USING 20K FLOW AND HEATERS

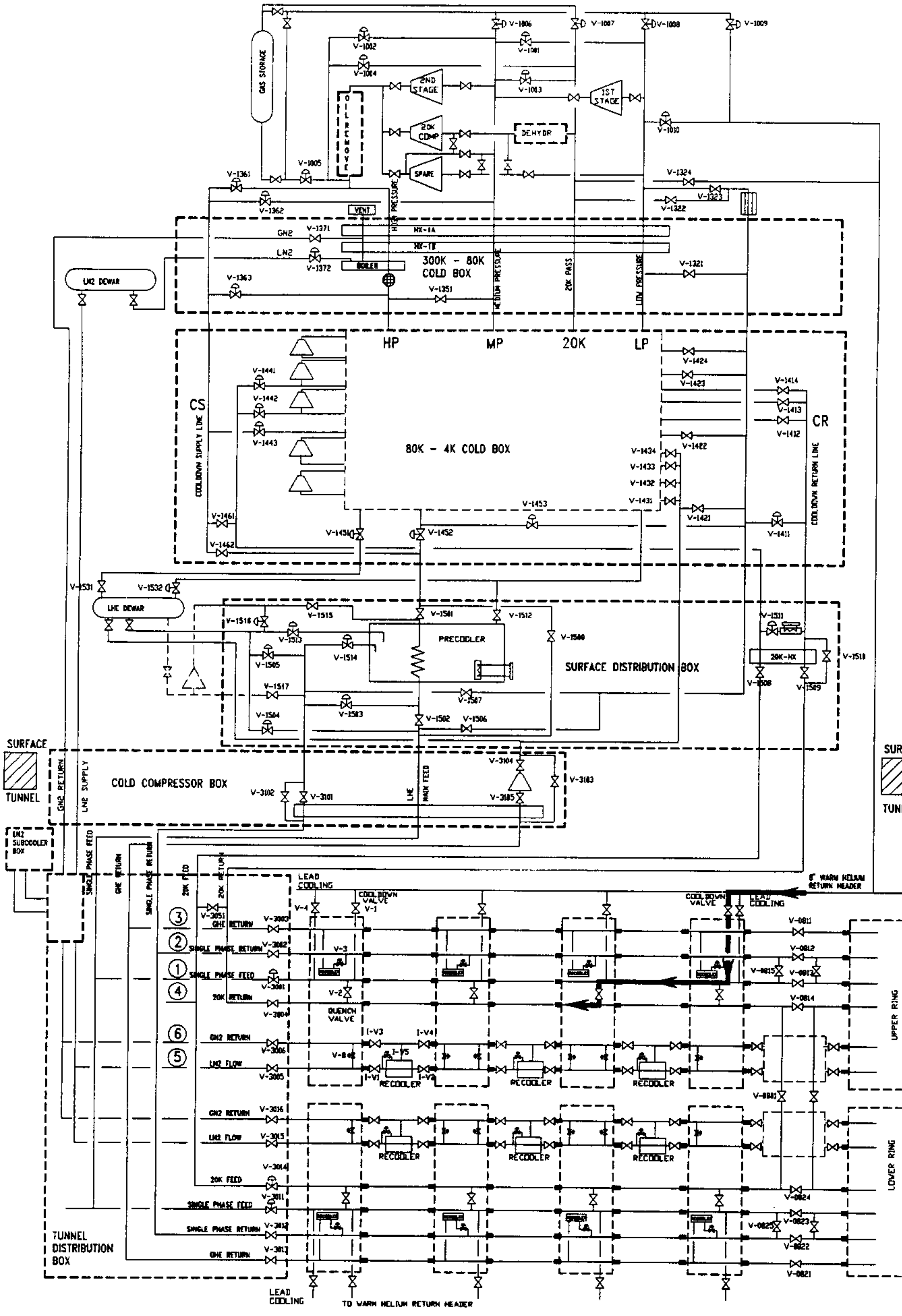


FIGURE 10.6-4 SECTION WARMUP USING HELIUM FROM PRESSURIZED WARM RETURN HEADER

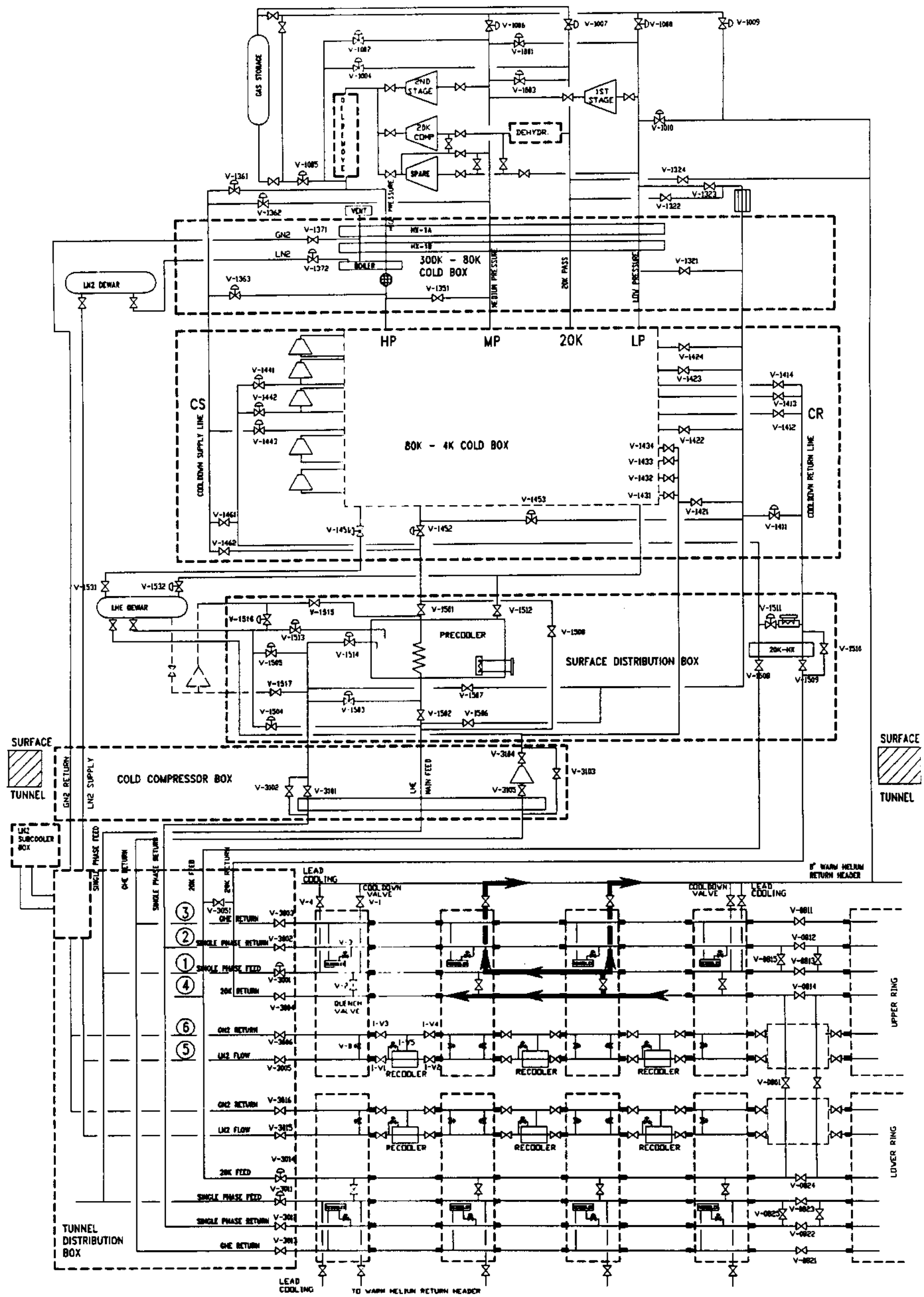


FIGURE 10.6-5 SECTION COOLDOWN AFTER MAINTENANCE

11. CRYOGENIC CONTROL SYSTEM

11.1 SECTOR REFRIGERATOR CONTROL SYSTEM

The control system for the SRS is an integral part of the SSC main cryogenic control system (MCCS). The concept for the SSC cryogenic control system is under development and the current concept for the MCCS in terms of functionalities is described below.

Figures 11.1-1 and 11.1-2 show the various functionalities envisioned for the MCCS. Figure 11.1-1 shows that the MCCS is divided into ten sector refrigeration control systems (SRC). The SRC is located in the sector refrigerator site as shown in Figure-11.1-2. Figure 11.1-2 shows that each SRC is divided into a refrigerator control system (RCS) and a tunnel control system (TCS). The RCS is dedicated to the sector surface refrigerator system, but it is an integral part of the SRC and the MCCS.

The SSC machine will be operated from a main accelerator control room (MACR). The SSC cryogenic systems will normally be remotely operated from a main cryogenics control room (MCCR), and from sector cryogenics control rooms (SRC) for commissioning, maintenance, etc.

The actual real-time control of the equipment will be performed at the RCS and TCS levels, with distributed processors (controllers) and communication modules to remote I/O and to the cryogenics peer-to-peer network (Fig. 11.1-2). These controllers will be located above ground at the SCCS location in order to avoid exposure to the tunnel environment. The only control hardware equipment in the tunnel will be remote I/O, which will include analog-to-digital and digital-to-analog conversion modules, special I/O modules (e.g., for diode temperature sensors), and communication modules to remote controllers.

SRC functions such as supervisory control, operator interface, and controller software configuration will be performed in workstations. These workstations contain communication modules to the peer-to-peer network and to the SSC global communication network, as well as a database with all sector tag information.

Global control of the cryogenic system will be performed by the MCCS, which includes the functionality of the SRC workstation and adds global supervisory control and a communication module to the office network (see Figure 11.1-1).

The SSC global communication network provides communication between the different systems (e.g., between the cryogenic system and the vacuum system), and access to a specific set of cryogenic tags and addresses needed for global machine operation from the MACS. This network is being developed by the URA/SSCL controls group and it is based on Time Division Multiplex (TDM) technology.

The cryogenics peer-to-peer network provides: communication among SCCS controllers within a sector and between sectors; access to all cryogenic I/O points; tags for purposes of cryogenic system operation, maintenance, trouble shooting, and modifications; and for upload and download of SCCS controller software.

The field bus provides communication between remote I/O and SCCS controllers (see Figure 11.1-2). In order to guarantee a smooth integration within the SSCL environment, open systems are preferred for the MCCS. The criteria used for judging the openness of a system are:

- The system adheres to a well-defined specification available to the industry.
- The specification is met by products from several independent companies.
- The specification is not controlled by a small group of companies.
- The specification is not tied to a specific machine architecture or technology.

Formal standards are essential as a basis for open systems. URA will adhere to international standards in the following areas:

a. Computer communications (e.g., Manufacturing Automation Protocol [MAP], and Manufacturing Message Specification [MMS])

b. Database management systems (e.g., Structured Query Language [SQL])

c. Operating systems (e.g., UNIX)

d. User interfaces (e.g., X Windows)

e. Controller programming language (e.g., IEC 848)

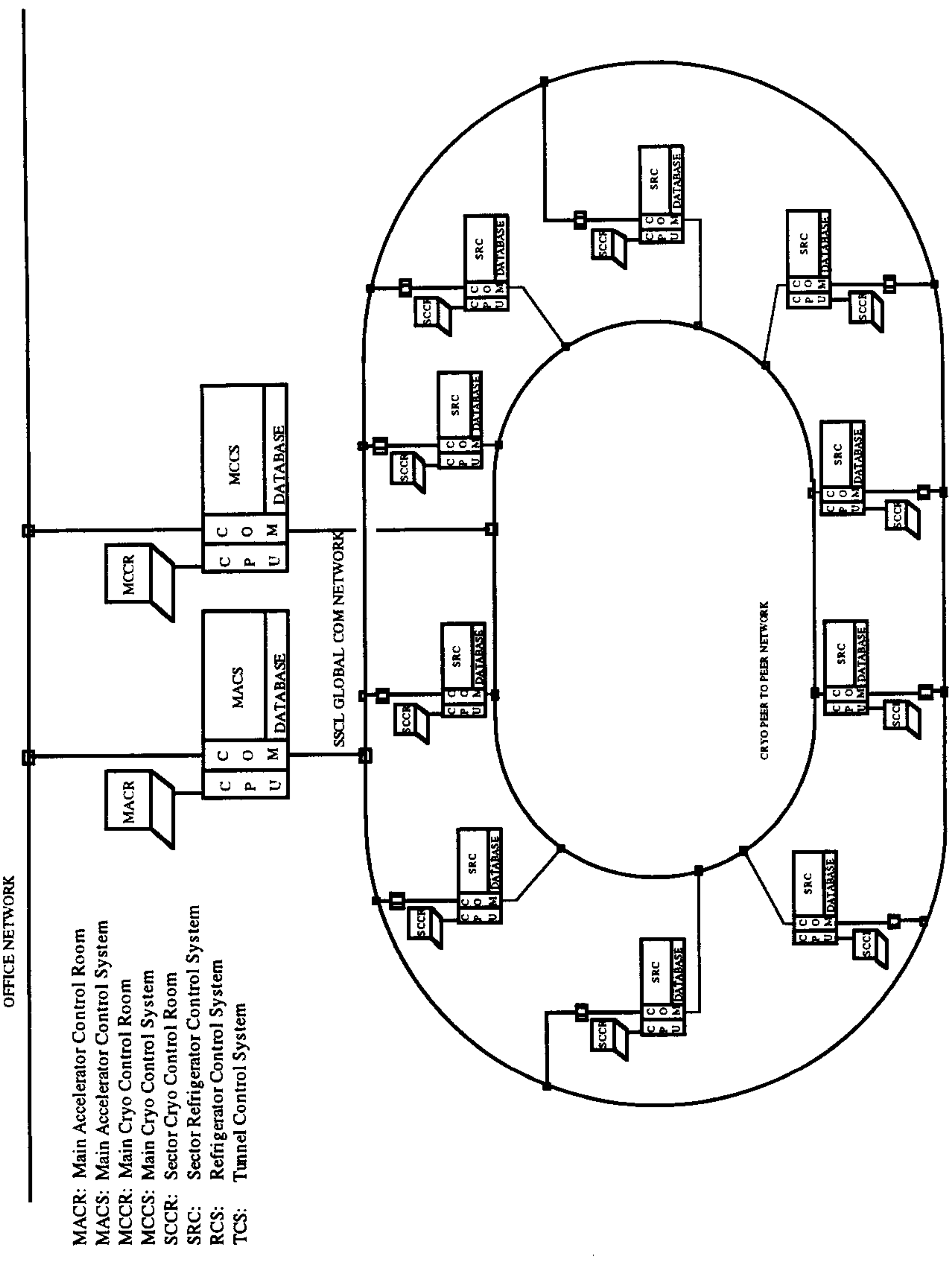


Figure 11.1-1. Main Accelerator Cryogenic Control Scheme

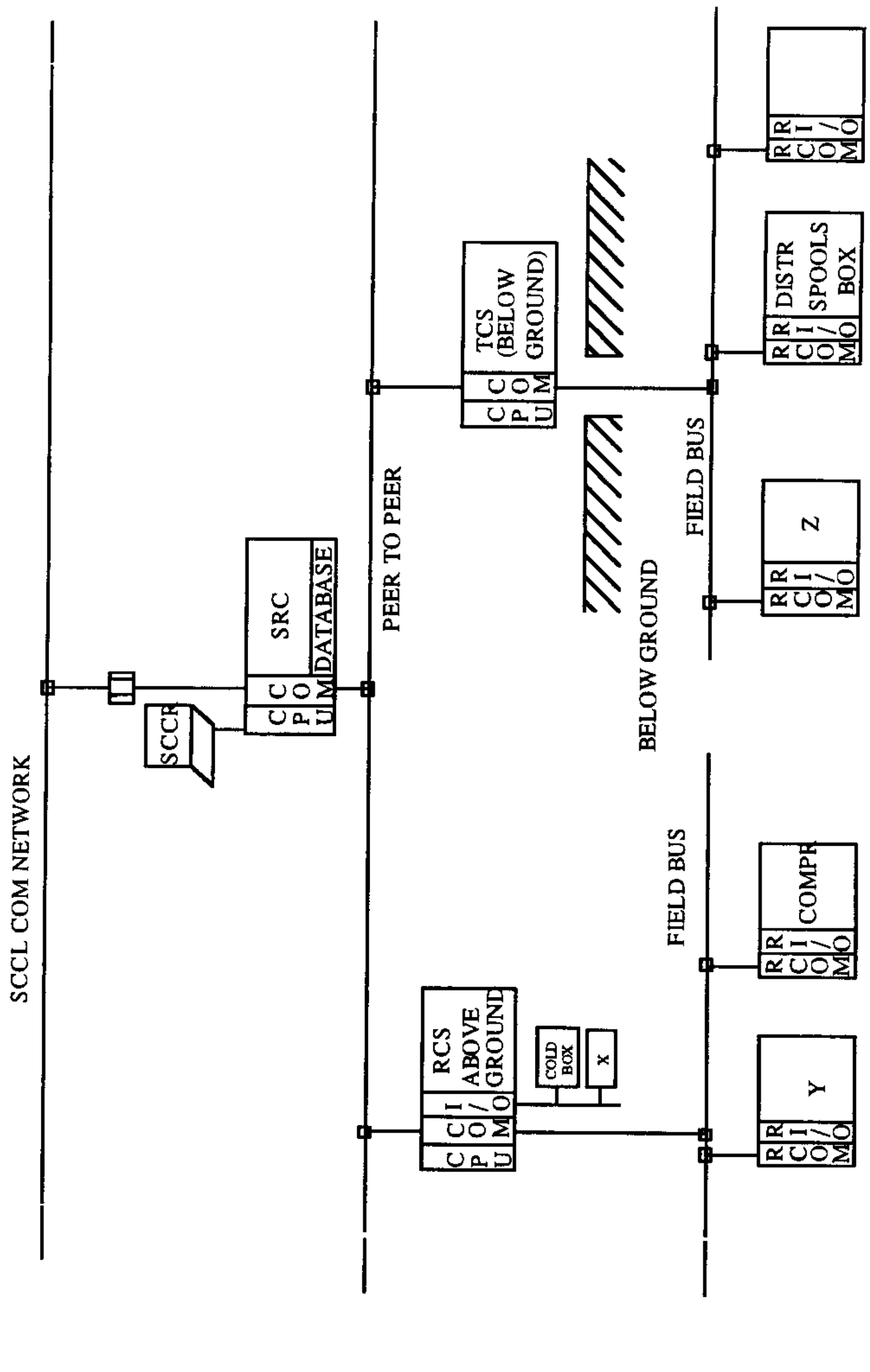


Figure 11.1-2. Sector cryogenic control scheme

INDEX TO TERMINOLOGY

Beam tube –The vacuum tube in which the proton beam travels.

HEB – High Energy Booster

CMS – Compressor system

Conditioning – The process of bringing a superconducting magnet to its maximum current without quenches by operating it at reduced temperature and at currents above the nominal operating current. If the magnet is warmed up, all or part of the conditioning process may need to be repeated.

Corrector – A small low-current superconducting magnet designed for steering corrections (dipole corrector), optical adjustments (quadrupole and sextupole correctors), or compensation of magnet errors in main magents (multipole correctors). Correction magnets reside in spool pieces and other selected locations in the magnet string.

Dipole – A superconducting magnet with one north pole and one south pole, which produces a uniform magnetic field to bend the path of the particle beam.

Dump Resistors – The magnet current must be quickly reduced to zero when a quench is detected, to prevent burnout of the conductor. This is accomplished by connecting the magnet strings to dump resistors which dissipate all or part of their stored energy. These resistors are located at the string ends.

Half-cell – The smallest repetitive unit in the magnet system of the accelerator, consisting of a series combination of five dipoles, one quadrupole, and one spool piece. Each half-cell is 90 m long. It is expected that magnet quenches can be confined to a single half-cell.

MACR – Main accelerator control room

MACS – Main accelerator control system

MCCR – Main cryogenics control room

Quench – The sudden reversion of a section of the conductor in a magnet to the resistive normal conducting state due to an energy input from a disturbance. This zone increases in temperature and size so long as the current is maintained, even after the original disturbance is over.

Quadrupole – A superconducting magnet with two pairs of alternating north and south poles, which focus the particle beam.

RCS – Refrigerator control system

RFS – Refrigeration system

SCS – Sector Station Cryogenic System.

SCCR – Sector cryo control room.

Section – A series combination of twelve half-cells. At the end of each section are cold valves which can isolate all of its cryogenic lines from those of the next section.

Sector – A parallel combination of four strings arranged as shown in Figure 2.2-1. All connections to the SRS are made at this level. The main power connections from the magnets to the sector power supplies and dump resistors are made at the feed can and end can of each string in the sector.

Spool Piece – A can containing beam optics correctors, instrument lead feedthroughs, and quench protection equipment for all magnets in its associated half-cell. Each spool piece also contains a cryostat vacuum barrier between two adjacent half-cells. Every second spool piece contains a recooler.

SPRA – Standard spool with recooler.

SPRB – Spool with recooler to connect a string of magnets to a bypass.

SPRC – Spool with recooler to connect an isolated magnet string to a bypass.

SPRE – End spool with a recooler on the right side. The two parts of the spools are part of different cryogenic sectors.

SPRF – Feed spool with recoolers on both sides.

SPRI – Isolation spool with a recooler on the right side.

SPRS – Standard spool with recooler and 2.5 meter extension.

SPRT – Spool with recooler to connect an isolated magnet to a bypass.

SPXA – Standard spool with no recooler.

SPXR – Return box.

SPXS – Standard spool with no recooler and a 2.5 meter empty cryostat extension.

SPXU – Spool with no recooler and no vacuum barrier (standard length, used in the utility-straight).

SRS – Sector Refrigerator Surface System.

SRC – Sector surface refrigerator control system.

SSC – Superconducting Super Collider

String – A series combination of four sections starting with the sector feed spool and ending with the end spool.

Training – The process of bringing a superconducting magnet to its maximum current by a series of quenches and dumps at successively higher currents. This current capability is generally maintained as long as the magnet is kept cold. If the magnet is warmed up, all or part of the training process may need to be repeated.

TCS – Tunnel control system