SSCL-Preprint-87

SSCL-Preprint-87

Superconducting Super Collider Laboratory

84 K Nitrogen System for the SSC

M. McAshan, M. Thirumaleshwar, S. Abramovich, V. Ganni, and A. Scheidemantle

March 1992

To be published in *Supercollider 4*

SSCL-Preprint-87

84 K Nitrogen System for the SSC*

M. McAshan, M. Thirumaleshwar†, S. Abramovich,
V. Ganni, and A. Scheidemantle

Superconducting Super Collider Laboratory‡
2550 Beckleymeade Avenue
Dallas, TX 75237

March 1992

---

*Presented at the International Industrial Symposium on the Super Collider, New Orleans, March 4-6, 1992.

†Guest collaborator from Center for Advanced Technology, Indore, India.

‡Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

84 K NITROGEN SYSTEM FOR THE SSC

M. McAshan, M. Thirumaleshwar*, S. Abramovich, V. Ganni, and A. Scheidemantle

Superconducting Super Collider Laboratory†
2550 Beckleymeade Avenue
Dallas, TX 75237 USA

ABSTRACT

The nitrogen system for the Superconducting Super Collider (SSC) is designed to provide the 84 K (nominal) shield refrigeration for the collider rings. Liquid nitrogen is supplied to the collider tunnel from one, two, or more locations on the surface through the service shafts and is distributed along the 87 km of both rings by the 84 K shield lines. Additional design requirements for the nitrogen distribution system include precooling fluid supply to the helium plants, supplying makeup liquid nitrogen to the reservoirs located at the entrance of the main shafts, and providing an efficient cooldown means for the cold mass from 300 K to 90 K. The operational modes and possible emergency and maintenance conditions of the collider are taken into account for the nitrogen system design. The status of our work, including design considerations that address thermal aspects (heat load, recooling scheme, etc.) and hydraulic aspects (pressures, elevations, distances, etc.) of the nitrogen system will be discussed.

INTRODUCTION

The SSC consists of two parallel magnet rings, each 87,120 m in circumference, constructed in a tunnel 25–74 m under ground. The rings are operated at a controlled low temperature of about 4.2 K, in order to maintain the magnet windings in the superconducting state. The magnet cryostat[1] is designed with a high-quality super insulation—*i.e*, a high vacuum chamber, multilayer insulation (MLI), and thermal shields at 84 K and 20 K nominal temperatures. Thermal radiation and the conduction heat load through the supports are intercepted and absorbed by the 84 K shield. Liquid nitrogen provides the refrigeration for these loads.

The nitrogen system consists of a nitrogen generation plant (one, two, or more air separation plants); ten nitrogen dewars for the collider and two for the High Energy Booster (HEB) located on the ground at the main shaft entrances; and associated piping, heat

---

* Guest collaborator from Center for Advanced Technology, Indore, India.

† Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

The nitrogen system consists of a nitrogen generation plant (one, two, or more air separation plants); ten nitrogen dewars for the collider and two for the High Energy Booster (HEB) located on the ground at the main shaft entrances; and associated piping, heat exchangers, controls, etc. The conceptual design for various flow schemes and the engineering considerations are presented in this paper.

THE SYSTEM GEOMETRY

The Collider Rings

The main tunnel of the collider is 25–74 m deep. Its axis is on a plane with an inclination of approximately 0.2°. The highest point in the tunnel is in the vicinity of N15 (located north of the west cluster), and the lowest point is close to S15 (south of the east cluster). The shape of the tunnel and the relative locations of the shafts are schematically shown in Figure 1.

The circular arcs of the rings contain almost continuous strings of superconducting magnets. The arcs are segmented into sections connected to each other by U-tubes so that the various parts of the system can be isolated for maintenance purposes. For practical reasons, the length of the magnet strings between adjacent shafts varies, ranging from 8.2 km to 9.3 km, and the length of the sections varies from 360 m to 1350 m. These sections are connected to each other through spool pieces in which the instrumentation, controls, and U-tubes are installed.

In the east and west parts of the collider are the "clusters" that contain different pieces of warm beam equipment. In all these regions the flows of the cryogens are bypassed through specific transfer lines. It may be necessary in some places to route the transfer lines through *different tunnels* in order to make room for the warm equipment. The detailed design of the east and west clusters will be defined elsewhere.

The HEB Ring

The HEB is 10,800 m in circumference, built in a tilted plane parallel to the collider, 14 m above the collider plane. The main bending dipoles, the quadrupoles, and the correctors of the HEB are superconducting magnets with a design that is specific to the HEB.

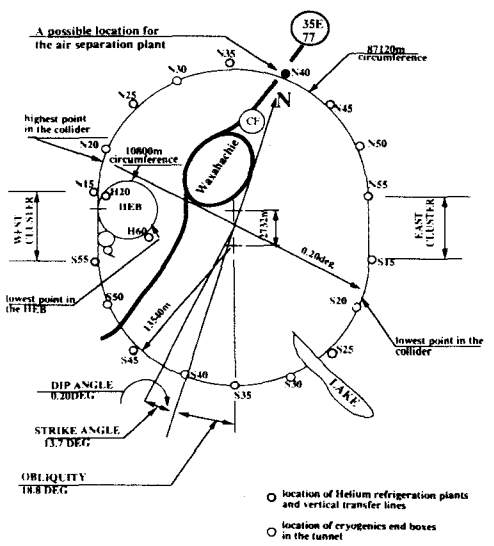

Figure 1. Geometry of the collider rings and the location of refrigeration plants.

The Cryostat

Two nitrogen tubes, 63.5 mm O.D. (57.15 mm I.D.) each, are anchored to the 84 K shield. These two lines can be used for liquid flow, two-phase flow, or nitrogen vapor flow. In normal operation mode, one tube is used as the main distribution conduit for the liquid nitrogen. The other tube serves as the vapor conduit for the cooling system and supplies the vapor to the helium plants, where it is used in the helium refrigeration process and is vented to the atmosphere at 300 K.

The cryostats in the string are connected to each other through flexible bellows connections. In a nominal section of 1080 m there are 84 bellows connectors and four 90° bends per line.

The Shafts

The depths of the different shafts vary from 25 m to 74 m. The transfer lines connecting the surface cryogenic equipment to the tunnel will be installed in the main shafts, designated N15, N25, S15, etc.

THE SYSTEM REQUIREMENTS

Figure 2 shows the 84 K heat loads and the mass flow of liquid and vapor nitrogen. The heat loads of the east and west clusters are assumed to be 50% higher than those of a regular arc sector.

Nitrogen System Requirements

1. Provide the 84 K shield refrigeration at a nominal temperature of 84 K. The shield temperature should not exceed 84.0 K.
2. Heat transport medium for the 84 K shields.
3. Distribution system for the nitrogen in the tunnel.
4. Make up liquid nitrogen to the reservoirs at the above-ground locations.
5. Refrigeration for the cooldown process of the cold mass from 300 K to 90 K.
6. Precooling for the helium system.

Design Targets for the N_2 System

1. Lowest temperature levels of the 84 K shield.
2. Lowest possible operating pressure.
3. Smallest temperature variations.
4. Maximum vapor recovery.
5. Simplest control and instrumentation requirements.
6. Low first cost and operation cost.
7. Lowest possible inventory.
8. Safe and reliable operation.

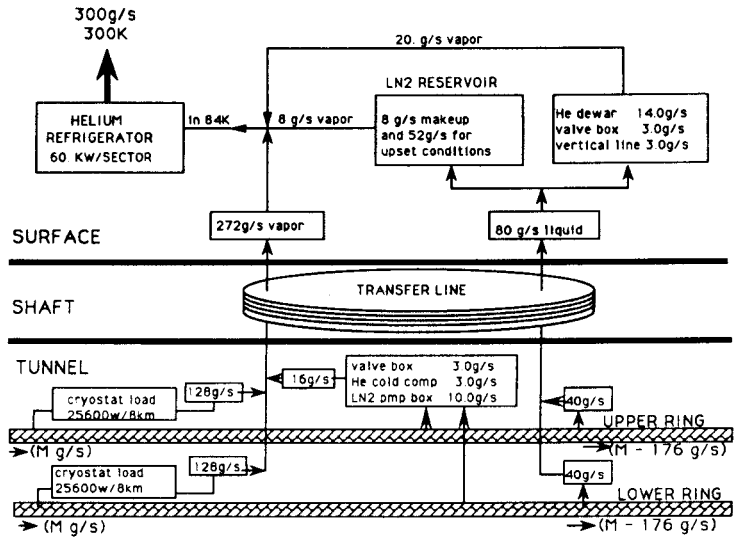

Figure 2. LN_2 load per sector.

OPERATIONAL REQUIREMENTS

The 84 K refrigeration to the cryostats and the supply of the precooling nitrogen to the helium plants should be continuous and uninterrupted for all possible system configurations—*e.g.*, operation of one or both rings or any combination of disconnected strings, one or more air separation plants not operating, etc. The flow rates for different configurations are given in Figure 3.

The Maximal Pressures

The nitrogen tubes in the cryostats are made of aluminum and are designed for a maximum pressure of 2.0 MPa. A maximum design pressure in the lines for normal operation will be 1.0 MPa. During cooldown, fill-up, and warm-up, the pressure may rise to 1.5 MPa.

Inventory and Supply

The volume of one nitrogen tube in the cryostat is 2.565 m^3 per km. The inventory for different parts of the collider follows:

	liquid (kg)	vapor (kg)
One sector (4 strings)	35,424	216
One ring	178,596	1,089
Total for the collider	357,192	2,178
Total for the HEB	38,492	
12 LN_2 dewars	650,400	

The total inventory of nitrogen for the SSC is 1,048,200 kg. The total nitrogen consumption for the SSC is 4200 g/s. Assuming 30% Carnot efficiency, the total power required is 11 MW (15,000 hp).

Ten stand-by reservoirs of nitrogen for the collider and two for the HEB will be located on the surface near the helium plants.

The LN_2 consumption forecast is shown in Figure 4.

The Controlled Parameters

The main parameters to be controlled in the nitrogen system are the temperature and the mass flows.

The required range of temperatures is obtained by recooling. In a few locations (between N20 and N25, and between S20 and S25) the tunnel is horizontal; in these places, compact heat exchangers have to be used for recooling. In other parts of the ring, where the tunnel is inclined, the vapor return line may be used as a continuous recooler. The pressure in the vapor return lines and the number of recoolers are the main factors affecting the temperature and the temperature variations in the cryostat.

If compact heat exchangers are used as recoolers, the boiling temperature depends on the local pressure in the vapor return lines. In this case, the only parameter to be controlled is the liquid level in the recooler.

If the vapor line serves as a continuous recooler (liquid nitrogen is injected into the vapor line), then a control loop is required for each section of the ring to control the flow rate of the injected liquid.

Figures 5a and 5b show the compact recoolers installed near the sector feed boxes and end boxes. Figure 5c shows the continuous recooling system by injecting liquid into the vapor line. Figure 5d shows a recooler with a pump that may be used if the pressure in the lines must be reduced to a minimum.

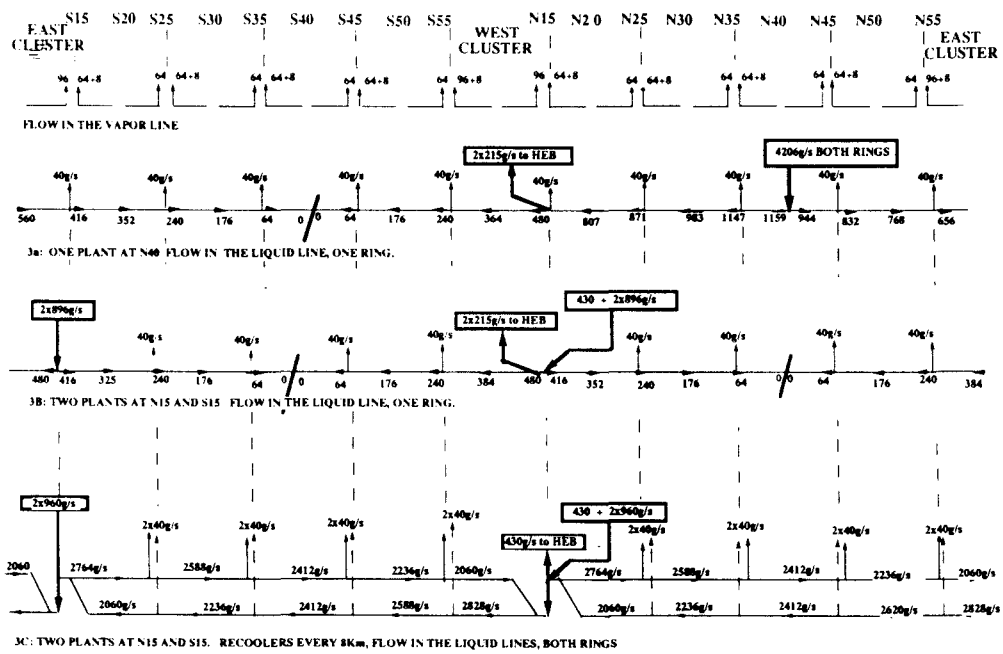

Figure 3. Flow in the collider rings for different configurations, in g/s.

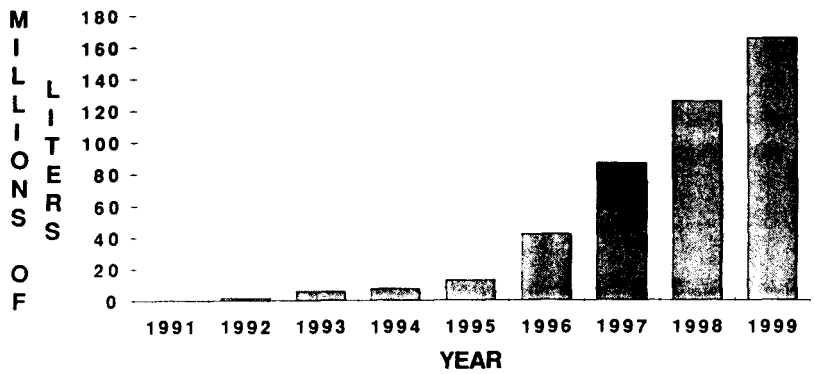

Figure 4. LN_2 forecast for the SSC.

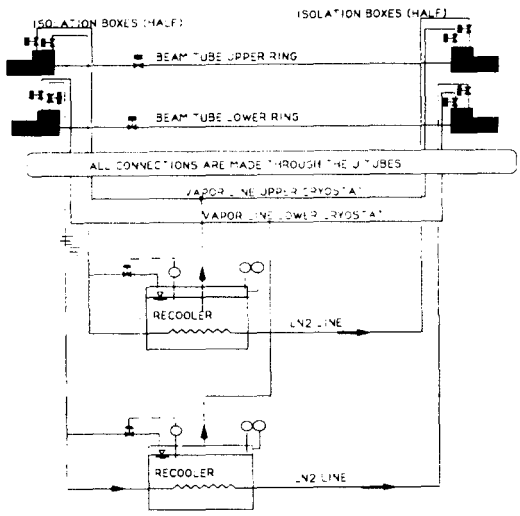

Figure 5a. Recoolers near the isolation boxes.

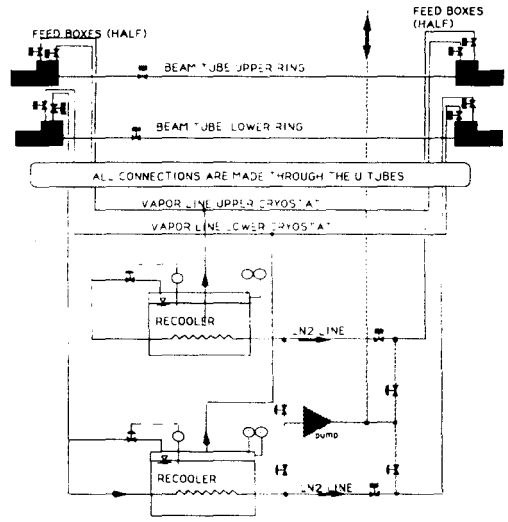

Figure 5b. Recoolers near the feed boxes.

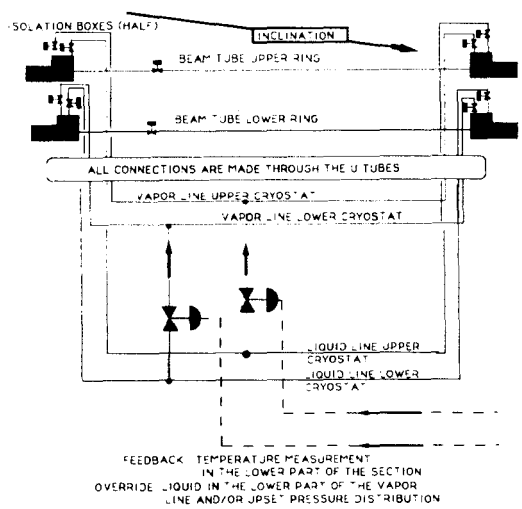

Figure 5c. Continuous recooling.

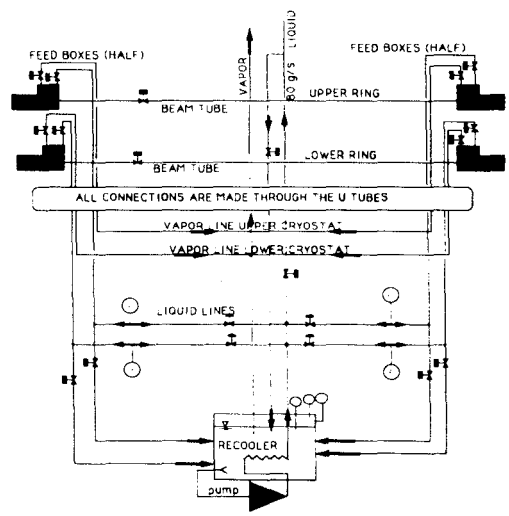

Figure 5d. Recooler system with vapor separator.

The vapor is extracted from the recooler and removed to the adjacent helium plant through the vapor line. Based on the helium plant design, the suction pressure of nitrogen to the plant is 0.13 MPa. The vapor flow is directed from the four strings of each sector of the collider into the vertical conduit (transfer line) to the helium plant.

The liquid nitrogen is distributed by pumps at the air separation plants and by cold pumps in the tunnel. The vapor generated by boiling nitrogen in the recoolers is transported to the adjacent helium plants, where it is warmed to 300 K and vented to the atmosphere.

OPERATION AT OFF-DESIGN CONDITIONS

Disconnected Strings

If one string is disconnected by isolating one section and the rest of that ring has to be kept cold, then the nitrogen flow must be supplied through the parallel section (the other ring) and/or, if possible, through the other direction of the ring. Solutions for such conditions are shown below.

Cooldown and Warm-up of the 84 K Shield

The amount of liquid nitrogen required to cool the shield in a nominal section (1080 m) is shown as:

To reduce shield temperature to 84 K	6560 kg
To fill the lines (liquid and vapor)	2220 kg
Heat load during cooldown	3600 kg
TOTAL	12,380 kg

With an initial flow rate of 27 g/s, increased gradually to 43 g/s, the cooldown time of the first section will be 97 h.

Cooldown Process of the Cold Mass

After cooling down the 84 K shield and maintaining the nitrogen flow required to absorb the 84 K heat load, the next step is to cool the 20 K shield and the magnets to 90 K by circulating cold helium. The 90 K helium is obtained by exchanging heat with liquid nitrogen at the helium refrigeration plant. A nitrogen mass flow rate of approximately 2000 g/s is required for this process (7.2 tons/hour or 172.8 tons/day). The cooldown process takes approximately 21 days, so that more than three refills per day of the local nitrogen reservoirs are needed to accomplish the first cooling wave of one string 4.3 km long.

RESULTS

Scheme A: One plant located at N-40, the vapor line serving as a continuous recooler

The vapor line. For nominal sections 1080 m long and constant heat load per unit length, the required injection of liquid in the vapor line is 16 g/s per section.

Figure 6a shows the pressure drop in the vapor line of a string (four sections), for a flow of 16 g/s per section. If this liquid injection rate is maintained, the flow in the vapor line is stratified.

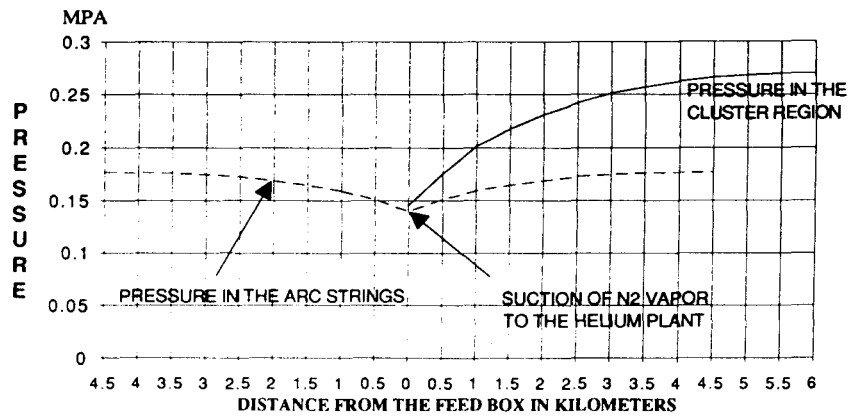

Figure 6. Vapor pressure in the arc strings and in the east or west cluster.

The liquid line. For normal operation, the required flow rates are shown above, in Figure 3 (see 3a for one air separation plant, 3b for two air separation plants, and 3c for two air separation plants with N_2 recoolers located 8 km apart). For pressures limited to a maximum of 1.1 MPa in the lines, and without circulation pumps in the tunnel, the resulting pressure levels are shown in Figure 7.

In order to pump liquid out to the LN_2 dewars on the surface or to the helium plants, the pressure at the lower leg of each vertical transfer line should be at least equal to the static head plus the pressure in the dewar (see vertical arrows in Figure 7). If there is only one nitrogen plant, pumps will be needed at least at S45, S55, N15, N25, and N35. If there are two plants, then pumps will be necessary at every main shaft.

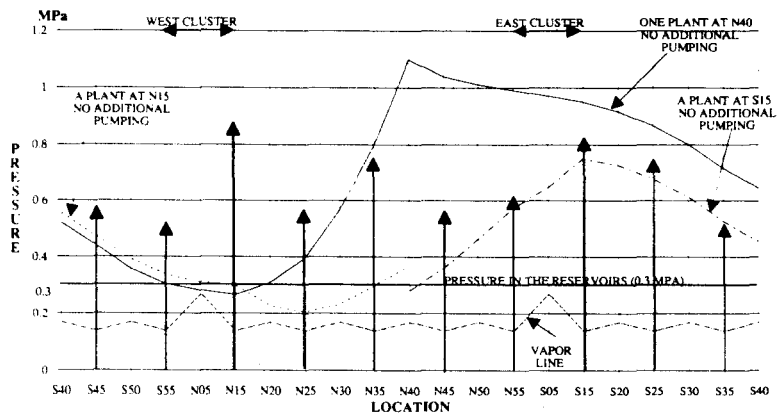

Figure 7. Pressure in the nitrogen system for different configurations. Vertical arrows are the required LN_2 pressure in the tunnel for pumping liquid to the surface.

System operation when one critical string is disconnected. If there is only one air separation plant, and one string between N40 and N35 (or between N40 and N45) is disconnected, then the flow in the parallel line must be doubled in order to supply the nitrogen to the rest of the disconnected line. The pressure drop in a 4.3-km line carrying 2000 g/s is 0.55–0.6 MPa. To prevent boiling in the first 4.3 km, the feed pressure must be higher than 0.8 MPa, and the back pressure higher than 0.15 MPa.

System operation when two critical strings are disconnected. Assume that both rings are disconnected between N40 and N45. The other parts of the system are cold at normal operating temperatures. In this case, the liquid nitrogen must be supplied through the

remaining parts of the system—*i.e.*, through lines 87 km long. The whole nitrogen supply of 4200 g/s must go through two lines (see flow rates in Figure 8a), as follows:

a. *If the vapor line is used for cooling:* Without circulation pumps in the tunnel, the required supply pressure is 4.4 MPa (for disconnected string N40–N35) and 5.2 MPa (for disconnected string N40–N45). Of course, these pressures are unacceptable, and pumps are needed to distribute the nitrogen. Figure 8b shows the pressure distribution in the tunnel if the strings are disconnected and pumps are used for circulation.

b. *If the vapor line is used for liquid flow:* This solution may be used only in a small part of the system where the flow rates are higher than 1800–2000 g/s. Lower flow rates will result in an unacceptable temperature rise in the cryostat.

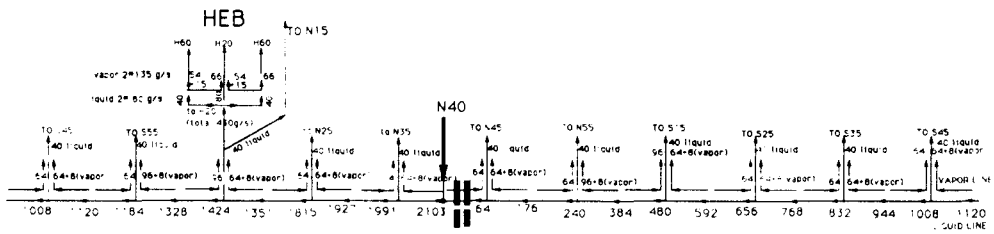

Figure 8a. Liquid and vapor N_2 flow in one ring in g/s for disconnected strings east to N40. One air separation plant (total N_2 generation 4206 g/s).

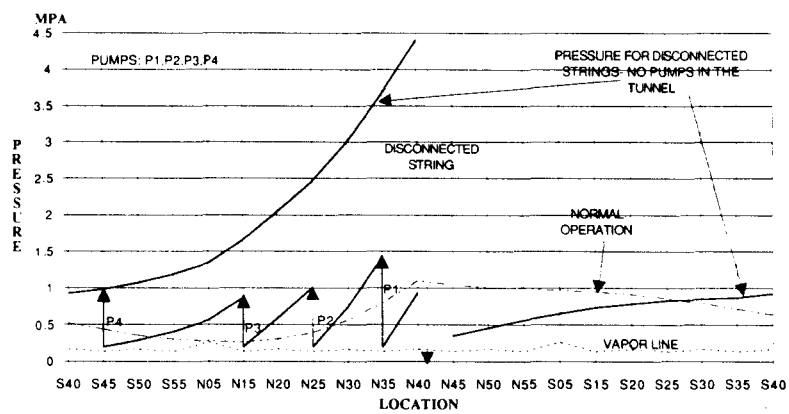

Figure 8b. Pressure in the LN_2 lines for disconnected strings with and without circulation pumps (one plant, string N35–N40 disconnected).

Scheme B: Plants at N15 and S15, the vapor line serving as a continuous recooler

For this configuration, the pressures and temperatures in the vapor line are the same as for Scheme A (see Figure 6). The mass flow rates are as shown in Figure 3b.

Compared with the previous configuration, the mass flows in the liquid lines are only 50 percent, and the lines are shorter by 50 percent. These two factors reduce the pressure drop in the lines. Still, in order to pump the liquid to the surface, to the helium plants, it is required to have liquid pumps in the tunnel. If no such pumps are installed, the pressure distribution is as shown in Figure 8. To prevent vapor in the liquid line, the pressures in the liquid line should be above the saturation point. Two-phase flow across the U tubes may block the liquid flow and introduce disturbances in the system.

Refrigeration if one string is disconnected: If a string is disconnected, then the flow in the parallel string may be doubled, and the resulting pressures for two plants are much lower than the resulting pressures for one plant.

Scheme C: Plants at N15 and S15, liquid flow recooled by compact recoolers

As mentioned earlier, in the regions between N15 and N30 and between the east cluster and S30, the inclination of the tunnel is too small to allow the free flow of boiling liquid in the vapor line, thereby preventing the use of this line as a distributed recooler. The detailed design of some other parts of the ring may raise problems that prevent the use of the vapor line as a continuous recooler—in particular in the east and west clusters. In all these parts of the ring, the installation of compact recoolers may be necessary.

Assuming that the nitrogen recooling is based only on compact heat exchangers, the following schemes were analyzed:

Scheme C.1	only one recooler every 8 km (vapor line not in use)
Scheme C.2	a recooler every 4 km + a vapor separator every 8 km
Scheme C.3	a recooler every 1 km + a vapor separator every 8 km

Scheme C.1. In this model, all the heat load is absorbed by the liquid, which is recooled every 8 km. The minimum flow to keep the temperature between 80 K and 89 K for a heat load of 25,600 W/s per 8 km is 1374 g/s. For the east and west cluster, the load is assumed to be 50% higher (38,400 W/s per cluster) and the minimal flow rate should be at least 2060 g/s. Figure 3c shows the mass flows in the ring, including the flow distribution requirements for this scheme. The resulting mass flow rates require operating pressures above acceptable levels, even with circulation pumps installed in the tunnel every 8 km.

Scheme C.2. This scheme and some of its variations were also analyzed. It was found that a compact heat exchanger is sufficient at the end of each sector and that a heat exchanger, a vapor separator, and a liquid pump are needed in the feed box of the sector in order to maintain the temperature lower than 89 K. This arrangement allows the reduction of the pressure in the liquid lines to a level enabling two-phase flow. Figure 5d shows a schematic diagram of the piping and recooling system for this scheme.

Figure 9 shows the pressure-temperature (P-T) diagram for a mass flow of 920 g/s in the line between S15 and S20 and a mass flow of 838 g/s in the line between S20 and S25. The discharge pressures were reduced to a minimum of 0.1 MPa. An initial pressure of 0.4 MPa at S15 is sufficient to maintain these flows. In other parts of the system where the flow rates are smaller, the required operating pressures are even smaller.

Figure 9 also shows the P-T diagram for different locations in the tunnel (uphill flow and downhill flow) and a comparison of schemes C.2 and C.3.

Scheme C.3. The results of this scheme are similar to those shown for continuous recooling.

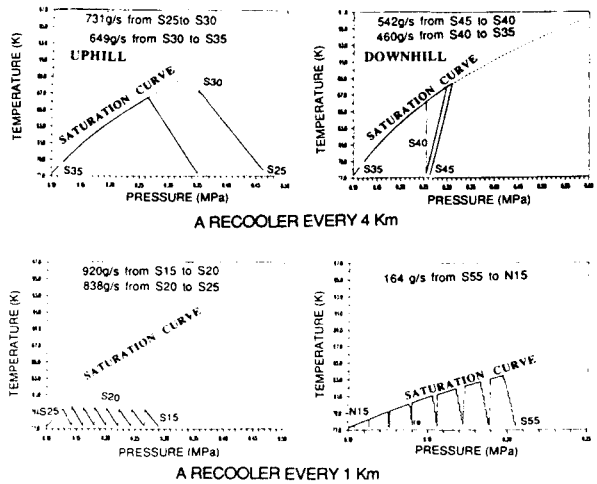

Figure 9. LN_2 temperature vs. pressure profiles.

CONCLUSIONS

Number of air separation plants. While one air separation plant may be more economical, two plants are preferred if availability is an important criterion for selection. Twelve LN_2 refrigerators may be preferred if the venting of large quantities of LN_2 from every helium plant is not acceptable.

Location of air separation plants. N40 is the preferred location from a transportation point of view, because of its proximity to main highways I-35E and U.S. 77. However, N15—which is close to the HEB and has the highest elevation—is preferred from the point of view of operation of the HEB and the LN_2 distribution.

Recooling schemes. Providing a compact recooler every 4 km results in a temperature rise of up to 89 K in the 84 K shield. If continuous recooling is implemented by injection of liquid into the vapor line, the temperature rise in the arc strings may be limited to 84 K.

Pumps. Pumps are required in every sector to supply liquid to the surface, and also to distribute the liquid in case of abnormal operating conditions. The flow rates and the pumping pressures are smaller if two air separation plants are installed.

The major upset conditions. The disconnection of the two rings close to the air separation plant will require operation of circulation pumps in order to operate the system.

The disconnection of a helium plant will cause an increase in the vapor return line pressure and an increase in vapor temperature to 92–94 K. The pressure in the liquid line will have to be increased to 0.4 MPa in order to operate the continuous recooling. To avoid all these changes in temperature and pressure, cold vents of the nitrogen vapor may be used.

Supply LN_2 by surface transportation (trucks) from a remote air separation plant. After the year 1999, demand is expected to be 4200 g/s (363 ton/day). This solution will require more than 17 trucks per day. (One 8000 gallon truck may carry 22 tons LN_2.)

REFERENCES

1. T.H. Nicol, "Cryostat Design for the Superconducting Super Collider," Winter Annual Meeting, ASME, November 1990.