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Superconducting Super Collider Laboratory

Nitrogen System for the SSC

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

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

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1.0 INTRODUCTION

The Superconducting Super Collider (SSC) consists of two parallel magnet rings, each 87,120 m in circumference, constructed in a tunnel 25 m to 74 m below ground level. They are operated at a controlled low helium temperature in order to maintain the magnet windings in the superconducting state. To obtain this condition, the magnet cryostat is designed with a high-quality insulation obtained by a high vacuum chamber, multilayer insulation (MLI), and thermal shields at nominal temperatures of 84 K and 20 K. Thermal radiation and the conduction heat load through the supports are intercepted and absorbed by the 84-K shield. Liquid nitrogen (LN_2) provides the refrigeration for these loads.

The 84-K shield is anchored to two 63.5-mm (2.5 in) stainless-steel tubes. One of the tubes, the "liquid line," serves as a conduit in the distribution system of liquid nitrogen. The other tube, the "vapor line," is used to collect the nitrogen vapor generated in the cooling process and to supply this vapor to the helium refrigerators for precooling. The vapor line may also be used as a continuous cooler by injecting controlled amounts of liquid nitrogen.

The nitrogen system consists of nitrogen supplies (one, two, or more local or remote 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; liquid and vapor transfer lines through the shaft to connect the surface and the tunnel systems; and transfer lines to bypass warm equipment sections of the collider. Recoolers, vapor separators, pumps, control valves, isolation valves, and measuring devices are required to control the temperature, pressure, and mass flow in each circuit of the system.

The nitrogen system is expected to operate at steady state condition except for cooldown, warmup, and system repair, for which transients are expected. (Conditions such as mechanical damage caused to some system may require isolation of a part of the ring in order to warm it up, repair it, cool it down, and bring it back to operation.) During normal operation and standby modes of the collider, temperature, pressure, and mass flow are expected to be constant in all circuits of the nitrogen system.

The conceptual design requirements for various flow schemes and the engineering considerations are presented in this report. Wherever possible, some detailed analysis of the flow schemes and the comparison between them are presented.

2.0 SYSTEM GEOMETRY

2.1 Collider Rings

The main tunnel of the collider is 25 m to 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); 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 surface and the tunnel elevations are given in Table 1.

The center lines of the SSC rings make two parallel planar curves. The vertical distance between the two rings is 900 mm. Figure 2 shows a schematic cross section of the collider tunnel and the relative location of the two rings. In the HEB tunnel only one ring is required.

The difference in altitude between the highest point and the lowest point on one ring of the collider is approximately 81 m. At several points, in the interaction regions, the rings depart from the original plane and return to the original plane a relatively short distance later.

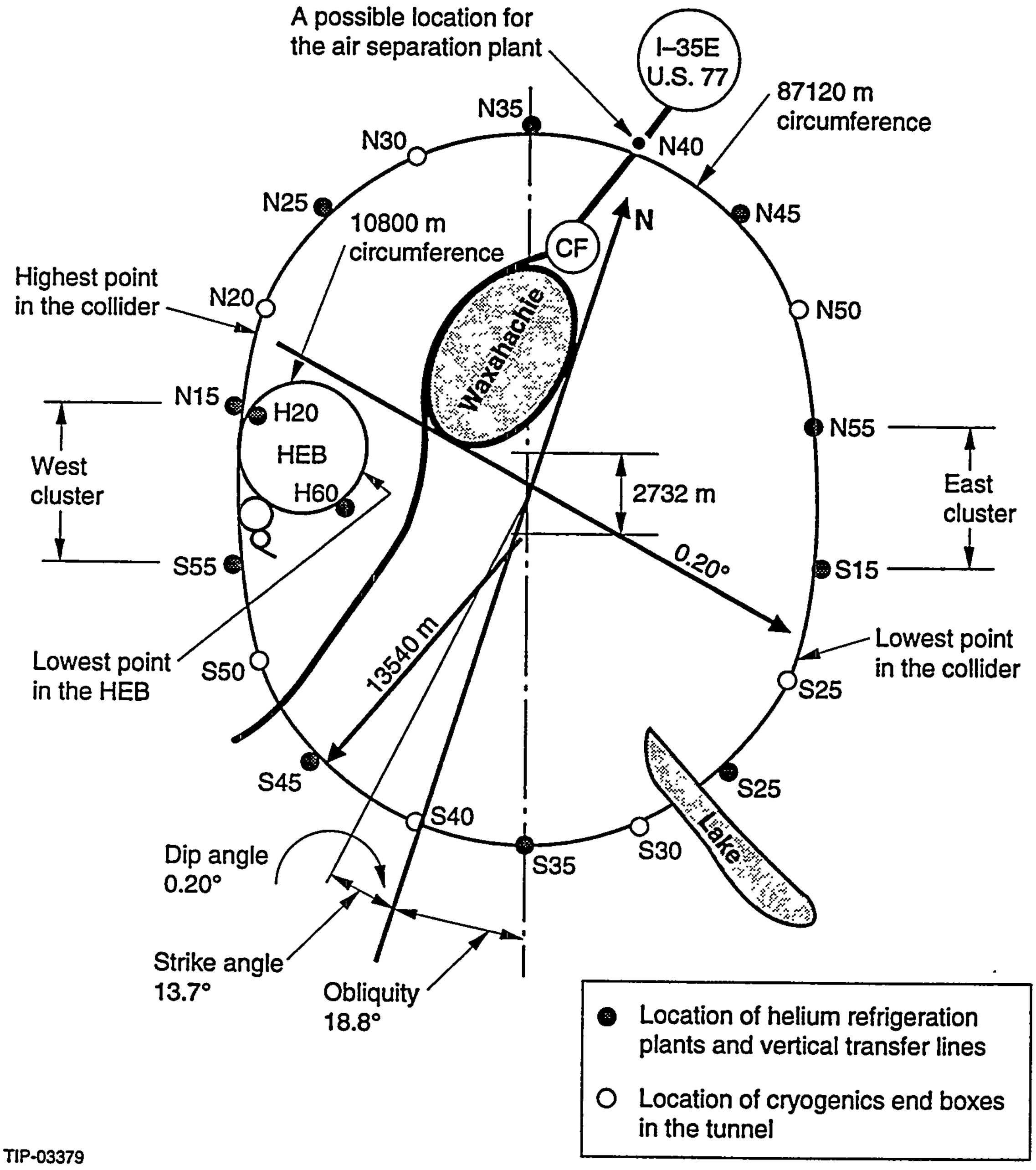

Figure 1(a). Geometry of the Collider Rings and Location of the He Refrigeration Plants.

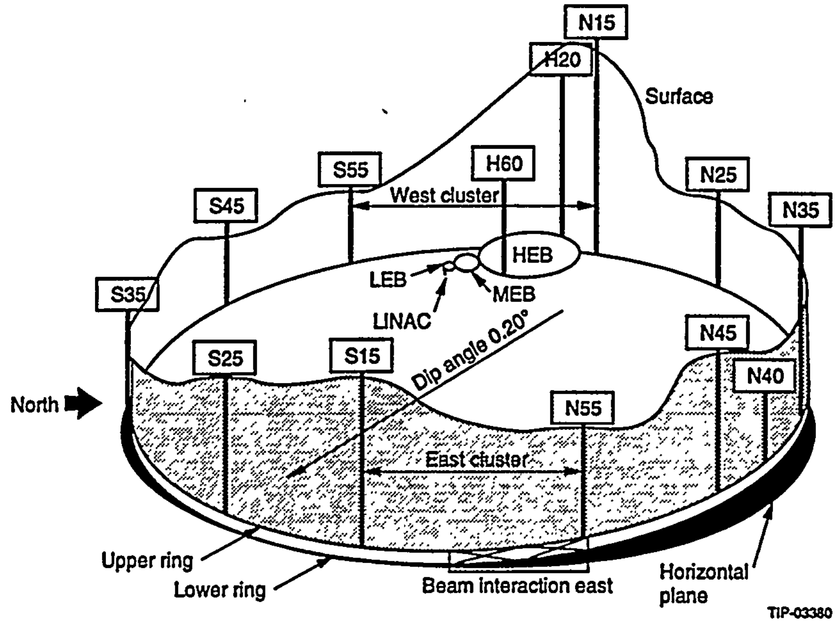

Figure 1(b). The SSC System: Surface Contours as Related to the Ring.

TABLE 1. SURFACE AND BEAM ALTITUDES.

LOCATION	SURFACE ALTITUDE (m)	DEPTH TO BEAMLINE (m)	BEAMLINE ALTITUDE (m)	BEAMLINE REF. ALT. (m)
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 (F3)	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
East Cluster				
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
West Cluster				

The two circular arcs of the rings (north and south) contain almost continuous strings of superconducting magnets, requiring continuous streams of coolants. The cryostats for these regions are designed to enable the handling—including circulation, distribution, and recooling—of the different fluids. They 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 between adjacent shafts and the lengths of the sections vary, as shown in Table 2.

TABLE 2. LENGTH OF STRINGS AND SECTIONS.

STRING	LENGTH (m)	LENGTH OF SECTIONS (m)					
S15 TO S20	3915	1080	1080	675	1080		
S20 TO S25	4815	765	1080	1080	990	900	
S25 TO S30	4050	1080	990	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	990	360	
S50 TO S55	3960	405	1080	1125	1350		
S55 TO N15	9360	*(WEST CLUSTER)*					
N15 TO N20	4320	1080	1080	675	1080	405	
N20 TO N25	3870	360	1080	1080	990	360	
N25 TO N30	4320	540	1080	810	1080	810	
N30 TO N35	4635	1080	540	1080	450	1080	405
N35 TO N40	4455	945	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 S15	9000	*(EAST CLUSTER)*					

The beam injection, the beam abort, and the rf cavities are located in the north part of the west cluster. Two interaction regions are designed south of the west cluster, and two more interaction regions are designed in the east cluster. In the long stretches of straight tunnel, where beam-bending magnets are not required, there are empty cryostats or the specific elements required for the beam physics.

The east and west clusters contain different pieces of warm beam equipment. In all these regions the flow of the cryogens is bypassed through 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.

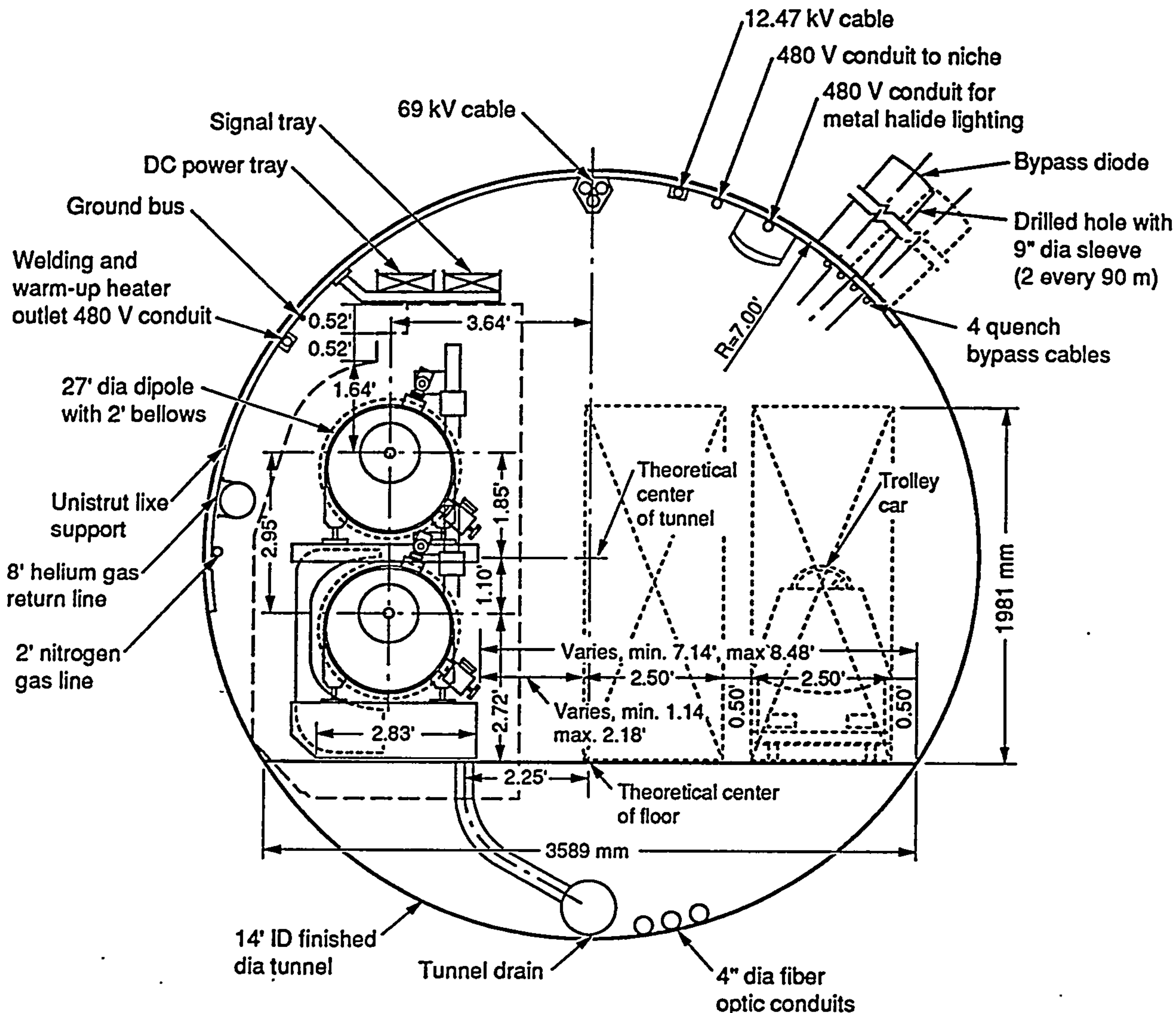

Figure 2. Tunnel Cross Section.

2.2 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 corrector magnets of the HEB are superconducting magnets with a design specific to the HEB. The altitude of the HEB relative to the collider and to the surface is shown in Figure 3.

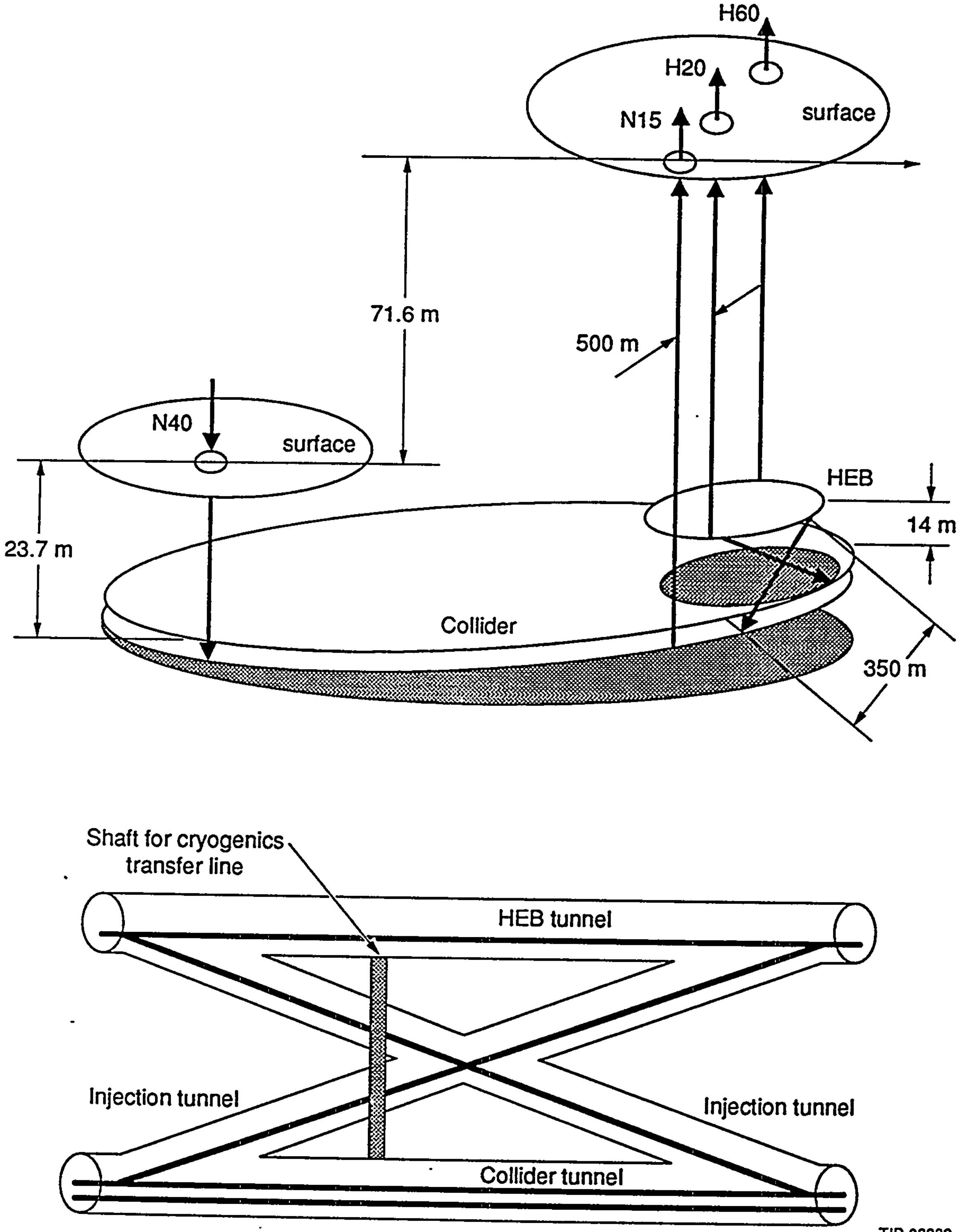

Figure 3. Relative Altitude and Distances. The arrows represent flow directions for one supply at N40.

2.3 Cryostat

A cross section of the dipole cryostat is shown in Figure 4. Two nitrogen tubes, 63.5 mm OD (57.15 mm ID) 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 warmed up to 300 K and vented to the atmosphere.

The tubes in the cryostat strings 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 tube.

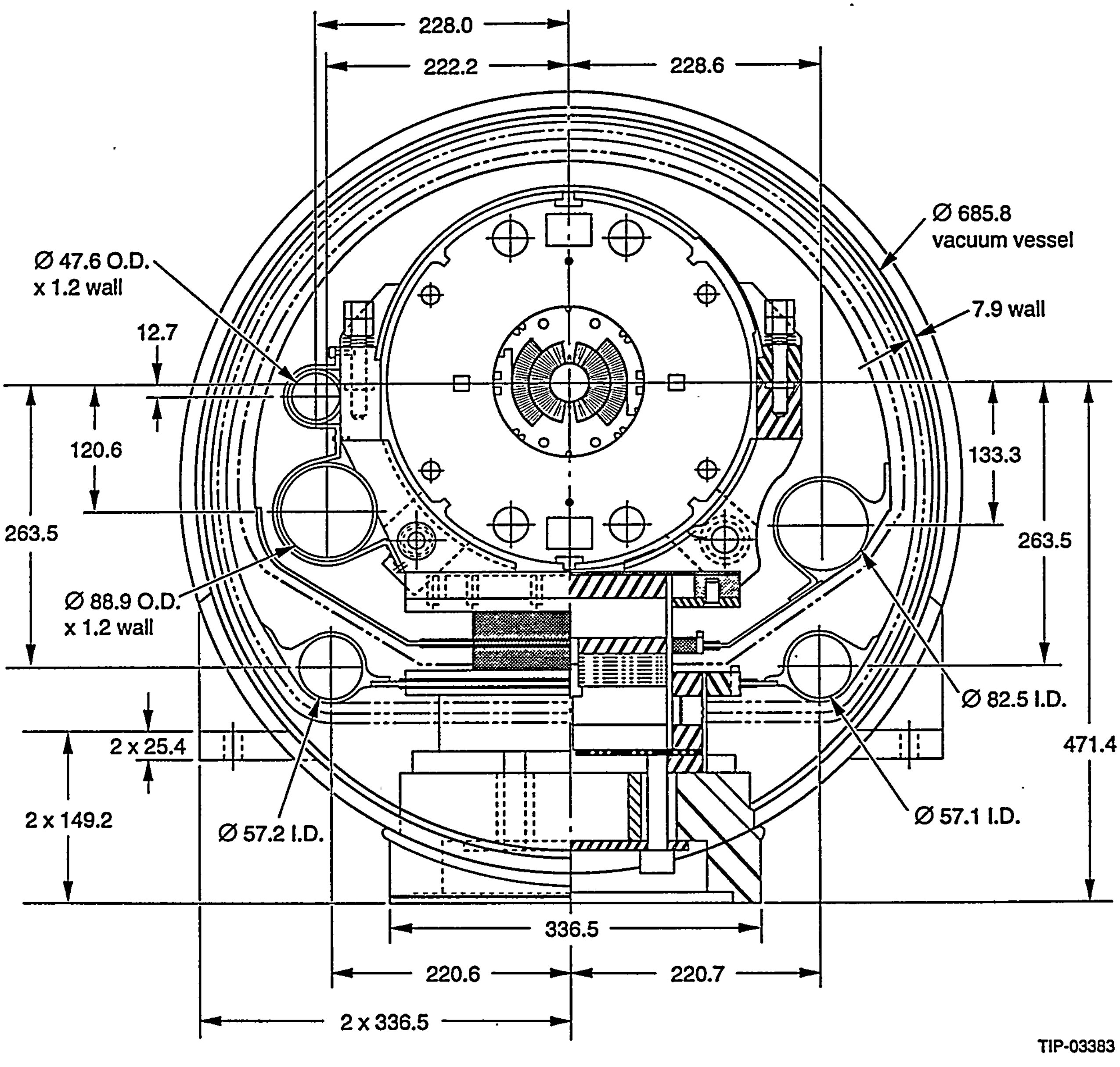

Figure 4. Dipole Cryostat Cross Section.

2.4 Shafts

The depths of the different shafts are given in Table 1. The transfer lines connecting the surface cryogenic equipment to the tunnel will be installed in the main shafts designated by N15, N25, S15, *etc.* On the surface, the cryogenic lines are routed to the helium plant and to the dewars. The length of these lines ranges from 70 m to 100 m.

3.0 SYSTEM REQUIREMENTS

Figure 5 shows the 84-K heat loads and the mass flow rates of liquid and vapor nitrogen in an arc sector. The heat loads of the east and west clusters are assumed to be 50 percent higher than the heat load of a regular arc sector.

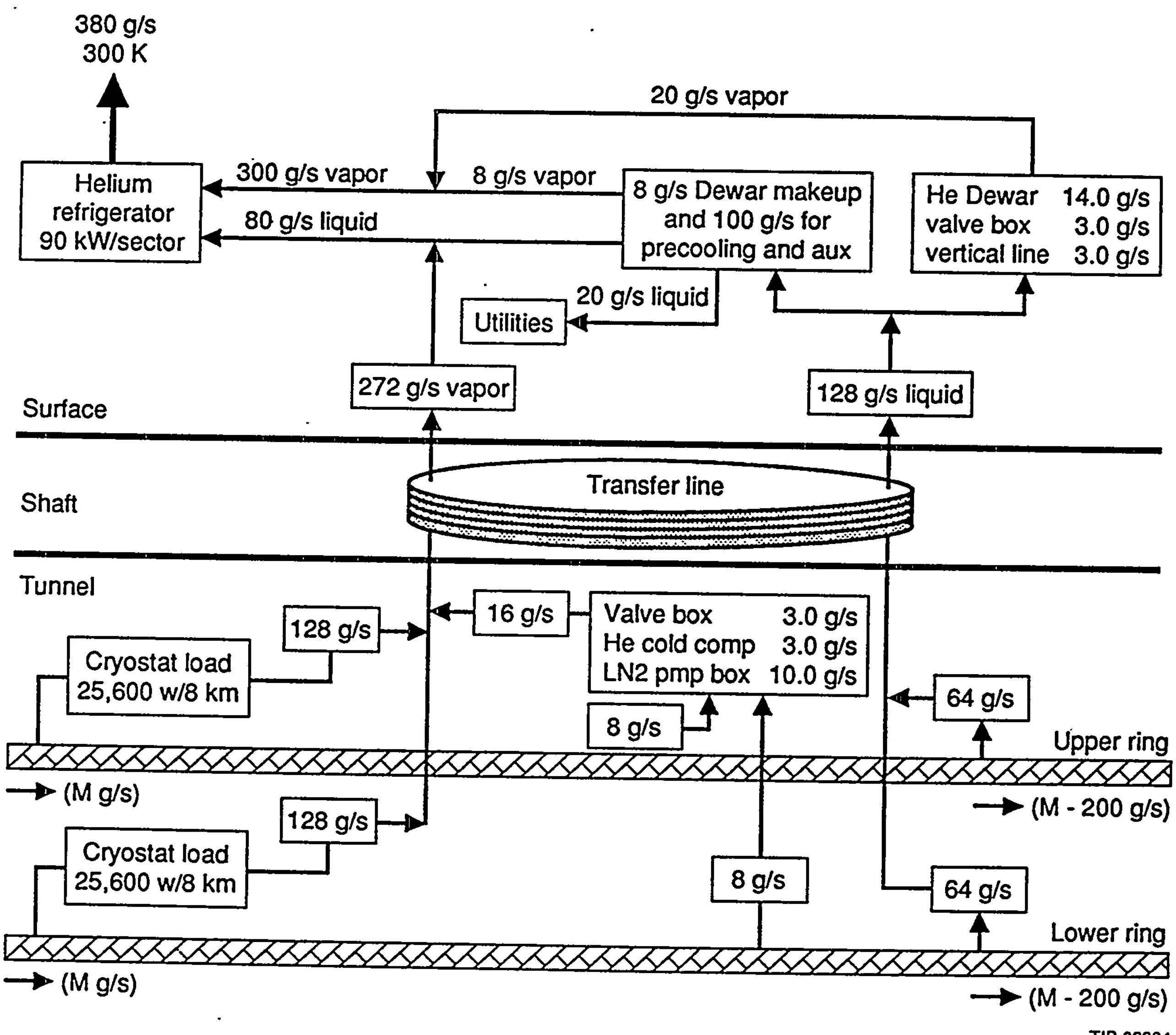

Figure 5. 84-K Heat Loads and Mass Flow Rates in an Arc Sector.

3.1 Nitrogen System Requirements

The nitrogen system is required to provide:

- 84-K shield refrigeration at a nominal temperature of 84 K.
- Heat transport medium for the 84-K shields.
- Distribution system for the nitrogen in the tunnel.
- Ability to make up liquid nitrogen to the reservoirs at the above-ground locations.
- Refrigeration for the cooldown process of the cold mass from 300 K to 80 K.
- Precooling for the helium systems.

3.2 Design Targets for the Nitrogen System

Design targets for the nitrogen system include:

- The lowest possible temperature levels for the 84-K shield.
- The lowest possible operating pressure.
- The smallest possible temperature variation.
- Maximum vapor recovery.
- Simple control and instrumentation requirements.
- Low first cost and operation cost.
- Lowest possible inventory.
- Safe and reliable operation.

4.0 OPERATIONAL REQUIREMENTS

4.1 System Configurations

The 84-K refrigeration to the cryostats and the supply of precooling nitrogen to the helium plants should be continuous and uninterrupted for all possible system configurations and system states, as follows:

- Simultaneous operation of both rings.
- Independent operation of each ring.
- Some combinations of disconnected strings.
- One nitrogen generation plant not operating (in case of two or more LN_2 plants).
- No liquid nitrogen supply for one day.

4.2 Maximal Pressures

The nitrogen tubes in the cryostats are made of stainless steel 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 transient conditions like cooldown, fillup, and warmup, the pressure may rise up to 1.5 MPa.

4.3 Nitrogen Inventory and Generation

The inventory of the nitrogen in the tunnel should be kept to a minimum. The volume of one nitrogen tube in the cryostat is 2.565 m3/km. (Under nominal conditions the liquid nitrogen mass is 2050 kg/km and the vapor mass is 12.5 kg/km for a vapor pipe.) The inventory for different parts of the collider is given in Table 3.

TABLE 3. NITROGEN INVENTORY FOR DIFFERENT PARTS OF THE COLLIDER.

	Liquid (kg)	Vapor (kg)
Nominal section (1080 m)	2,214	13.5
Nominal string (4320 m)	8,856	54
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	—

Ten standby liquid nitrogen dewars for the collider and two for the HEB will be located on the surface near the shaft entrances and helium plants. The design capacity of 75 m^3 per dewar can contain up to 54,200 kg of liquid nitrogen.

The total nitrogen inventory at normal operating conditions is given in Table 4.

TABLE 4. TOTAL NITROGEN INVENTORY.

Collider	359,300 kg
12 reservoirs	650,400 kg
HEB	38,500 kg
Total inventory	1,048,200 kg

The total nitrogen consumption estimate is 4784 g/s. This may be generated in one air separation plant (or one location). A better system availability is achieved by using more nitrogen supplies at different places around the ring. Operation schemes for one and two nitrogen sources, as well as calculated results for different mass flow rates, temperatures, and pressures, will be shown below.

The ideal work of liquefaction for nitrogen is 768 kJ/kg (77.3 K). Assuming 30 percent Carnot efficiency, the total power required is 12 MW.

The LN_2 consumption forecast is shown in Figure 6.

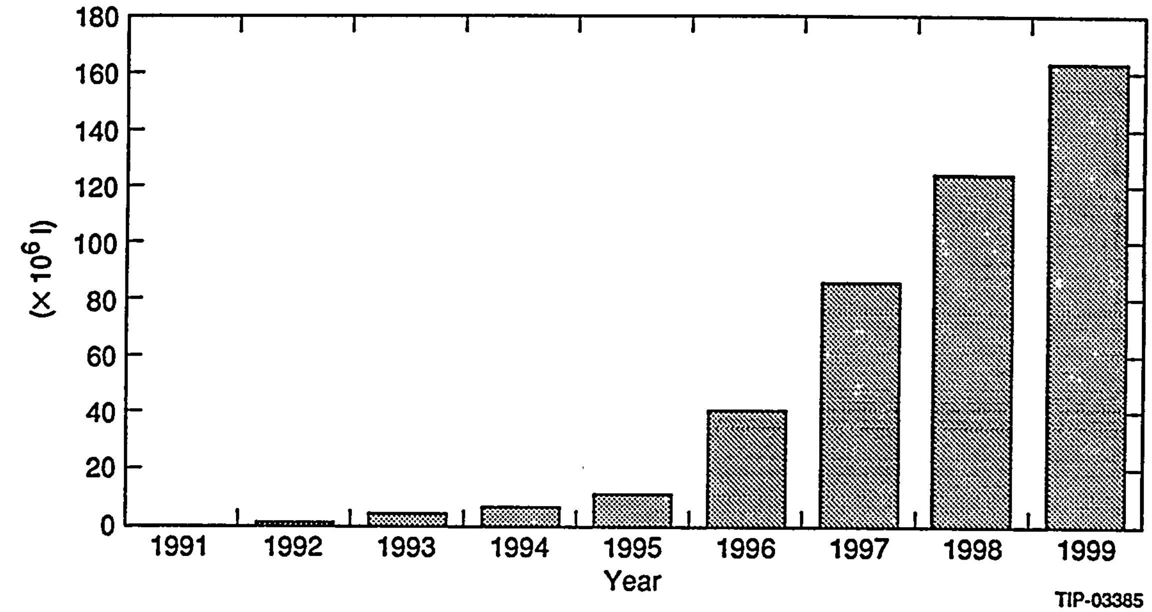

Figure 6. LN_2 Forecast for the SSC.

4.4 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 must be used for recooling. In other parts of the ring, where the tunnel is tilted, the vapor return line may be used as a continuous recooler. As we shall see below, 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. Other parameters, such as pressure and flow rates, are affected by the actual design of the system and the way it is operated.

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. It should be mentioned that every section in the system ends with a U-tube bent upwards. This prevents continuous two-phase flow. The liquid is injected into the U-tube to flow downhill and will evaporate completely before reaching the next (downhill) U-tube. If the heat load is smaller than nominal or if the liquid flow is higher than required, then liquid will concentrate at the lower U-tube and block the vapor flow.

The nitrogen is distributed by pumps in the delivery stations and by cold pumps in the tunnel. The vapor generated by boiling nitrogen in the recoolers is evacuated to the adjacent helium plants where it is heated to 300 K and vented to the atmosphere. It is the purpose of the present work to define the requirements and the dynamic range of the different flow rates, temperatures, and pressures.

5.0 FLOW SCHEMES AND RECOOLING

5.1 Distribution System

The total flow rate of liquid nitrogen required for normal operation of the rings is 4784 g/s. This includes 256 g/s per sector ($256 \times 11 = 2816$ g/s per collider) required solely for refrigerating the 84-K shield. The vapor generated in the tunnel at a nominal temperature of 84 K must be transported to the helium plants for precooling and then vented to the atmosphere at 300 K. (It was assumed that for the cluster regions the load is 50% higher than for an arc sector.)

It is possible to generate the total amount of nitrogen required in one or two plants and to distribute the liquid through the tubes in the cryostats. Another possibility is to build ten smaller plants connected to the helium plants, thus reducing the requirement for distribution of large mass flows in the tunnel.

5.1.1 One Plant

One possible scheme involves only one air separation plant (or one input station) located near the N40 shaft. This location was chosen because of its proximity to main roads I-35E and U.S.77, facilitating surface transportation of other cryogenic liquids or gases generated in the plant and not used in the collider (see Figure 7(a)).

5.1.2 Two Plants

A second possibility is to build two plants (or two supply stations), one near N15 and the other near S15. N15 is the highest point near a shaft, so that using the geodetic head may help in distributing the nitrogen with lower pump work. In addition, N15 is close to the HEB and to the west cluster, both of which are major N_2 consumers (see Figure 7(b)).

5.1.3 Ten Plants

This configuration makes the operation of the different sectors independent from one another and minimizes the distribution of liquid nitrogen in the tunnel. It also improves the total system availability.

A comparison of the mass flows in the cryostats as required for different schemes is given in Figures 7(a), 7(b), and 7(c).

5.2 Recoolers

The number of recoolers in the tunnel depends on the acceptable temperature range for normal operation. A higher number of recoolers will result in smaller temperature variations.

The recoolers may be designed as compact heat exchangers with boiling nitrogen in the shell side, or they may be created by injecting liquid from the LN_2 line into the vapor line, which serves as a distributed boiling medium. The last can be used only for those parts of the tunnel where the inclination of the tunnel is sufficient to keep the liquid flowing downhill. According to available data, the inclinations of the tunnel between N15 and N20, and between S15 and S25, are too small to enable free flow of liquid in a channel, so only compact heat exchangers may be used in these places. In the east and west clusters, the cryogenic lines are routed through bypasses in order to make room for warm equipment. These include many vertical connections preventing the use of continuous recooling.

Figures 8(a) and 8(b) show the compact recoolers installed near the sector feed boxes and end boxes; Figure 8(c) shows the continuous recooling system created by injecting liquid into the vapor line. Figure 8(d) shows a recooler with a circulation pump that may be used if the pressure in the lines must be minimized.

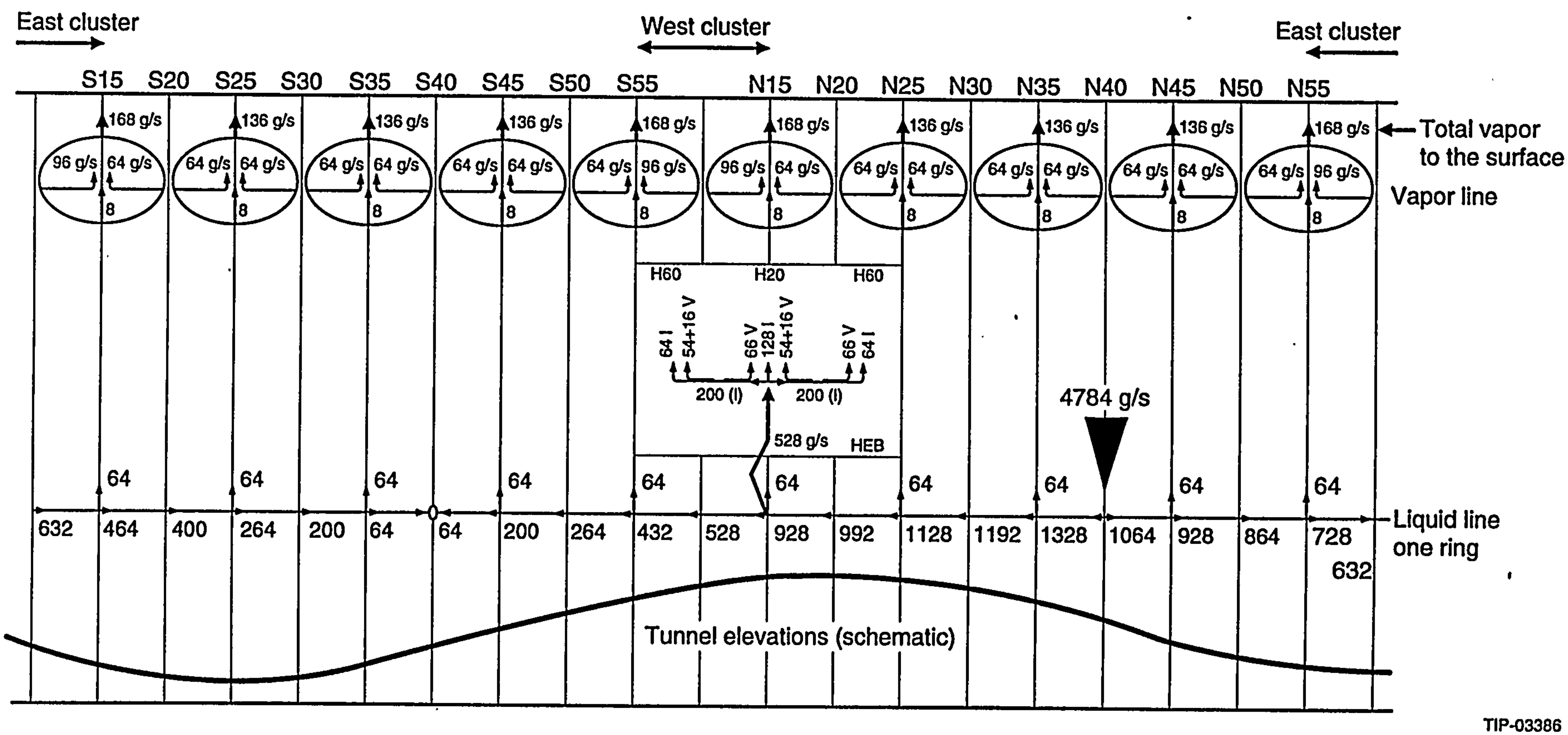

Figure 7(a). Distribution of N_2 in the Collider and the HEB for One Major Input at N40. Mass flow rates are given in g/s for one ring. Recooling: continuous recooler.

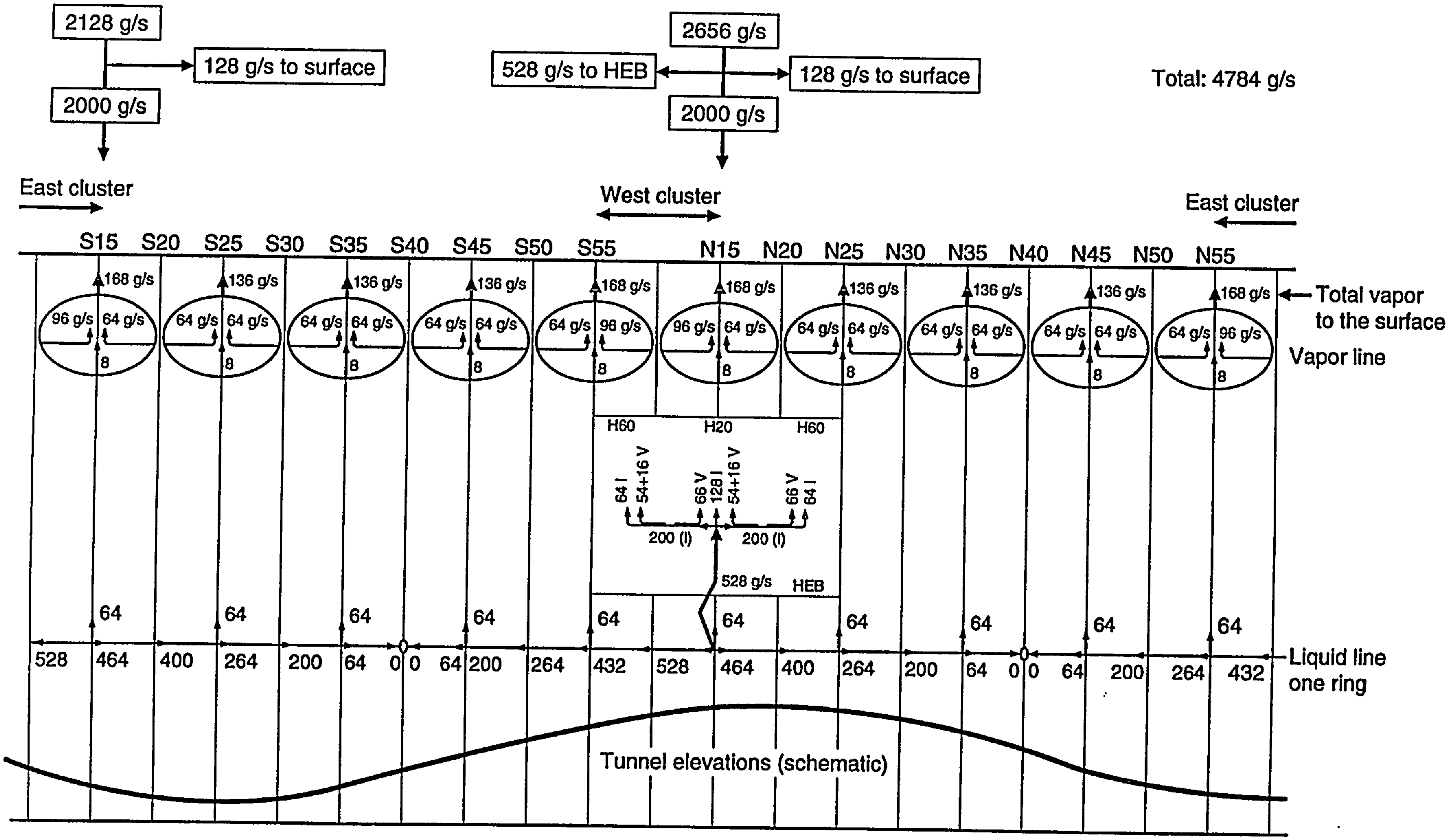

Figure 7(b). Distribution of N_2 in the Collider and the HEB for Two Major Inputs at N15 and S15. Mass flow rates are given in g/s for one ring. Recooling: continuous recooler.

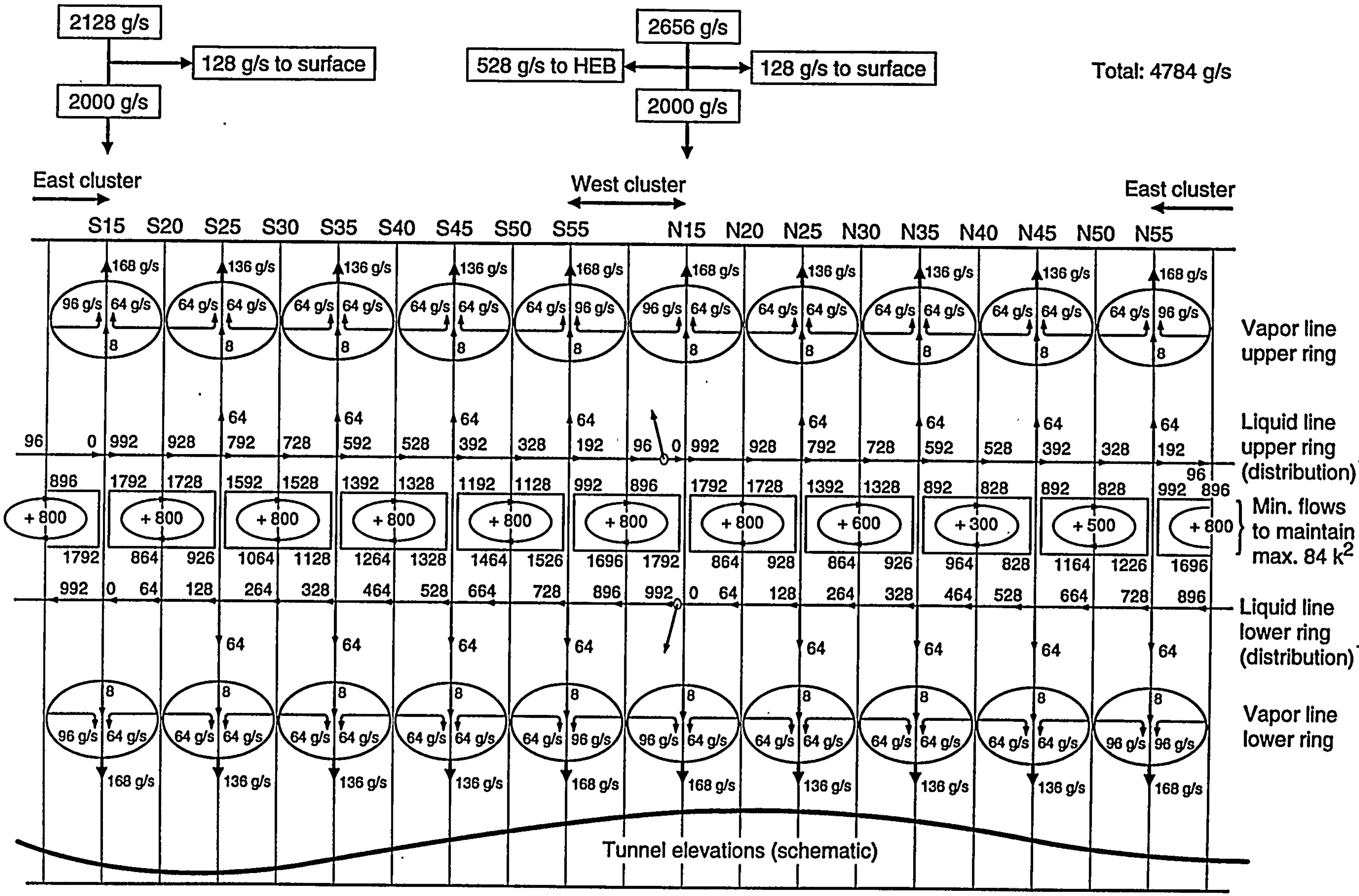

Figure 7(c). Distribution of N_2 in the Collider and the HEB for Two Major Inputs at N15 and S15. To enable internal circulation for compact recooling, the flows in the rings are in opposite directions. Mass flow rates are given in g/s.

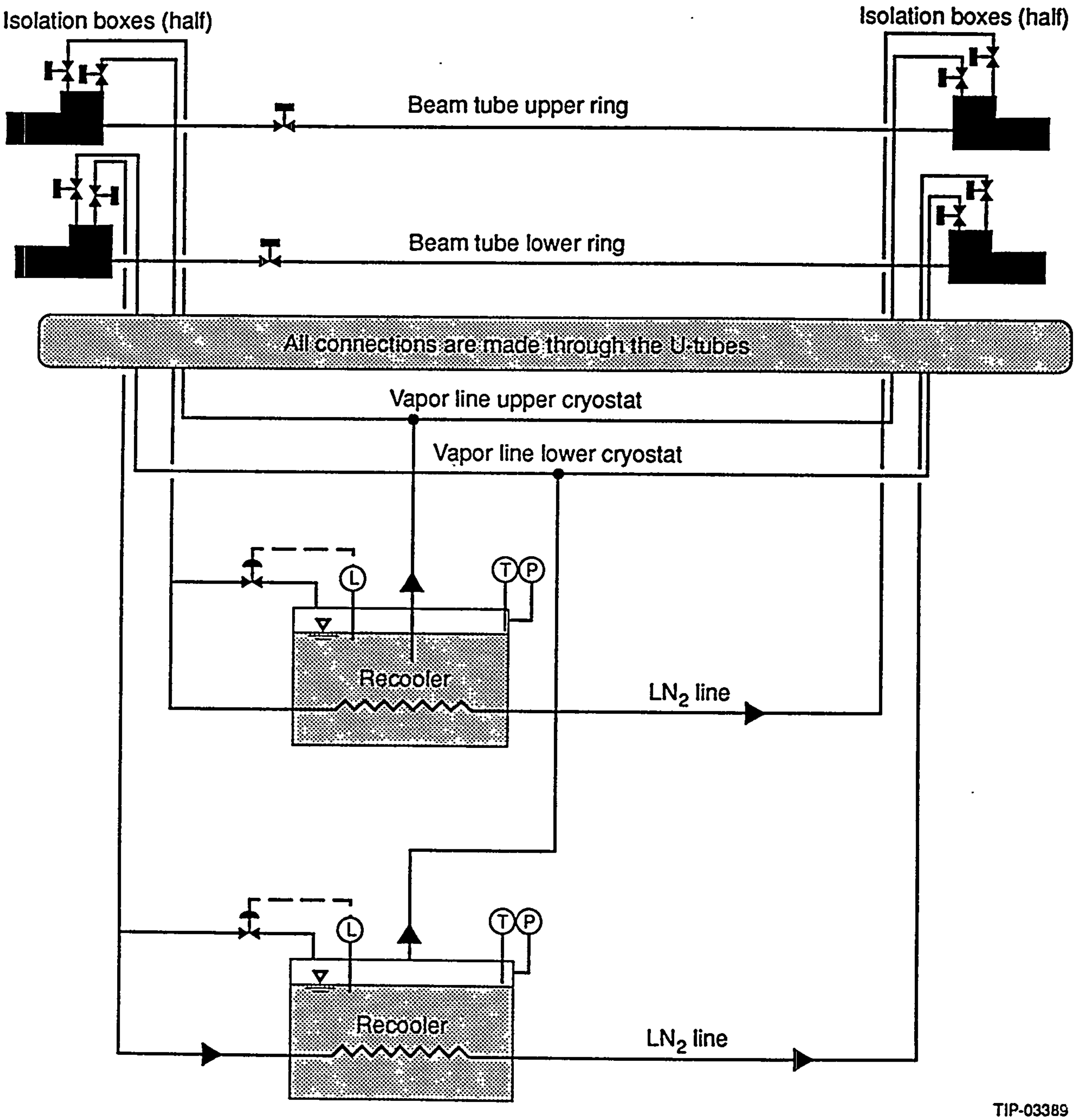

Figure 8(a). Recoolers Near the Isolation Boxes.

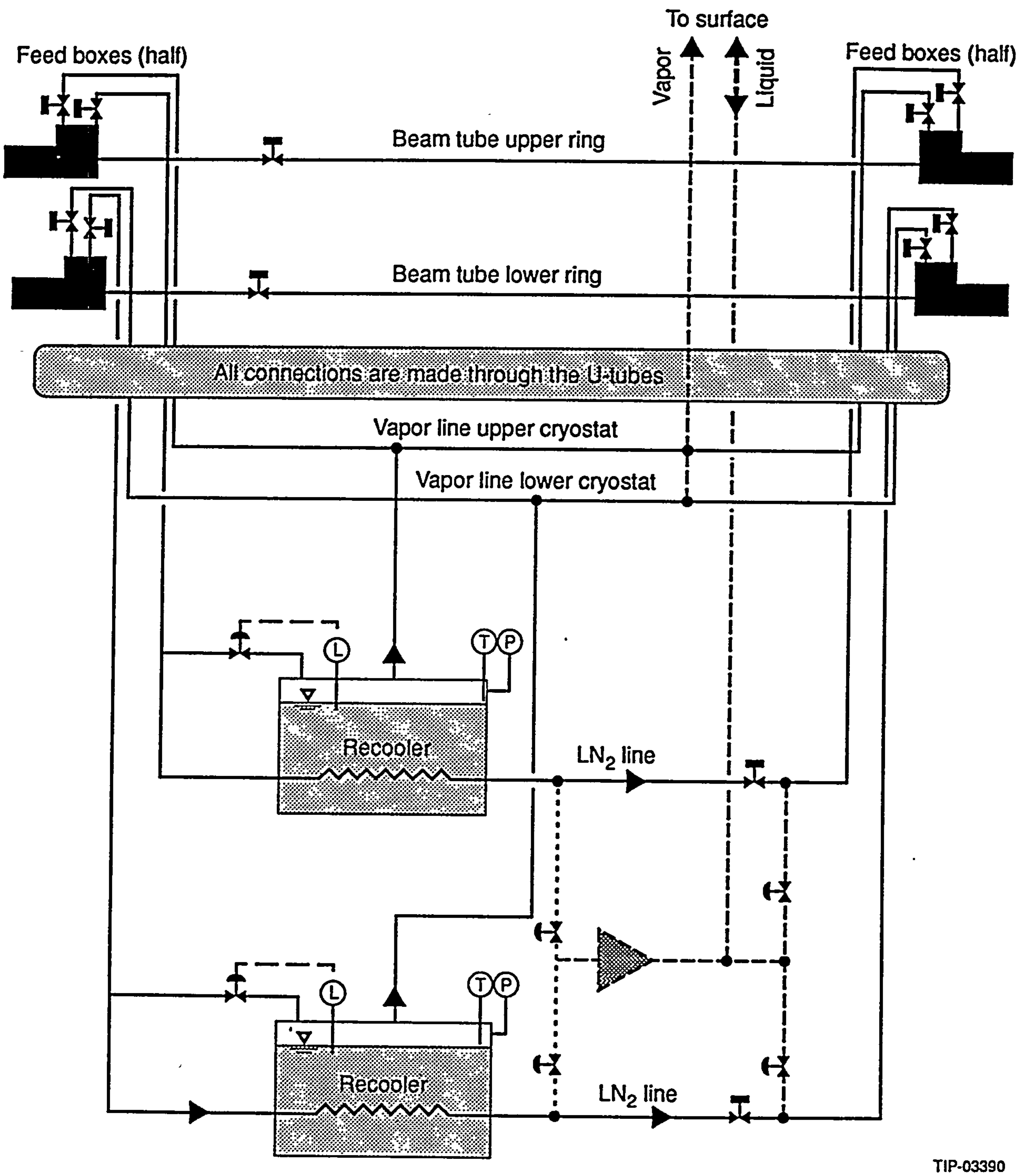

Figure 8(b). Recoolers Near the Feed Boxes and End Boxes.

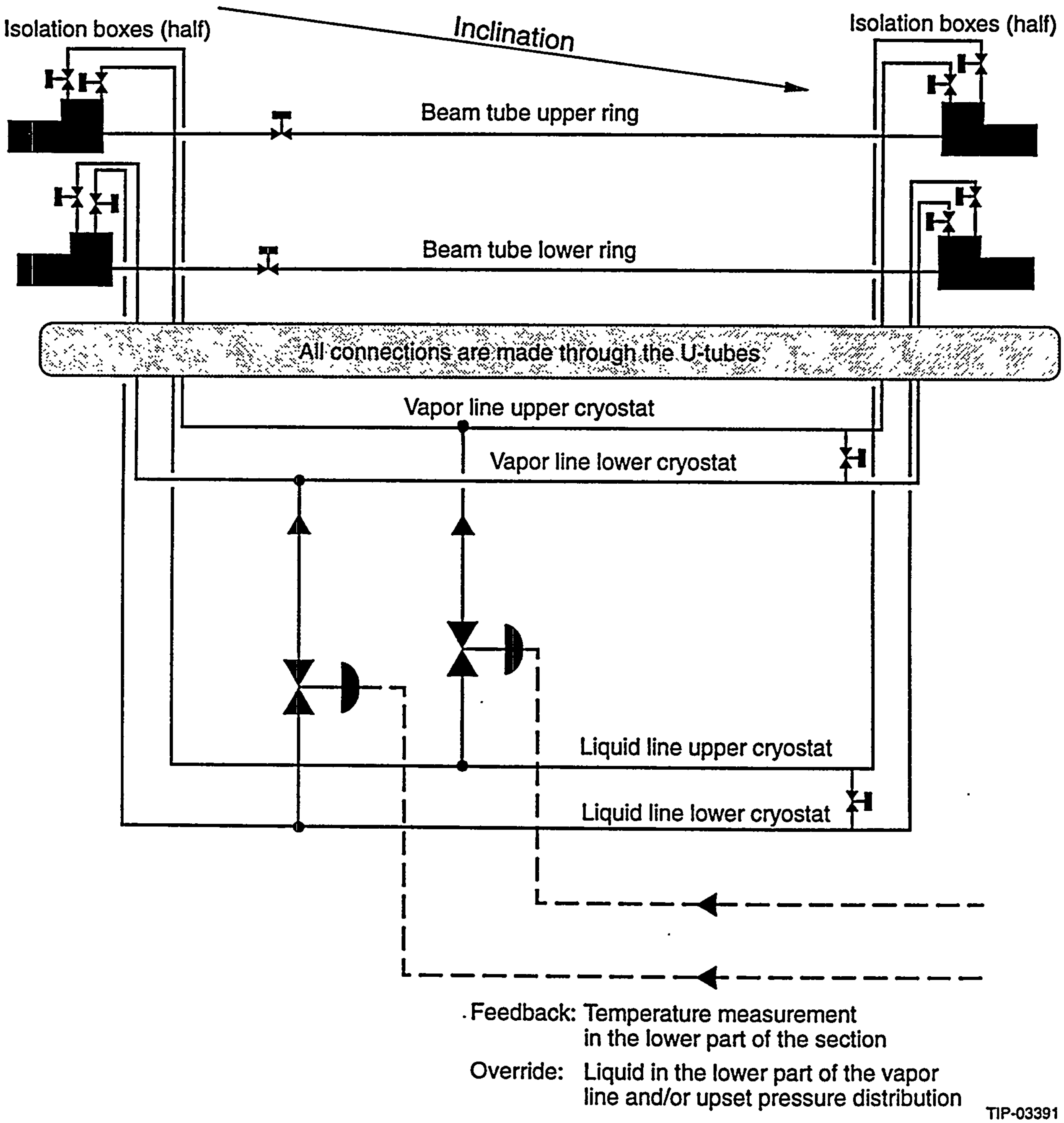

Figure 8(c). Continuous Recooling by Injection of LN_2 Into the Vapor Line.

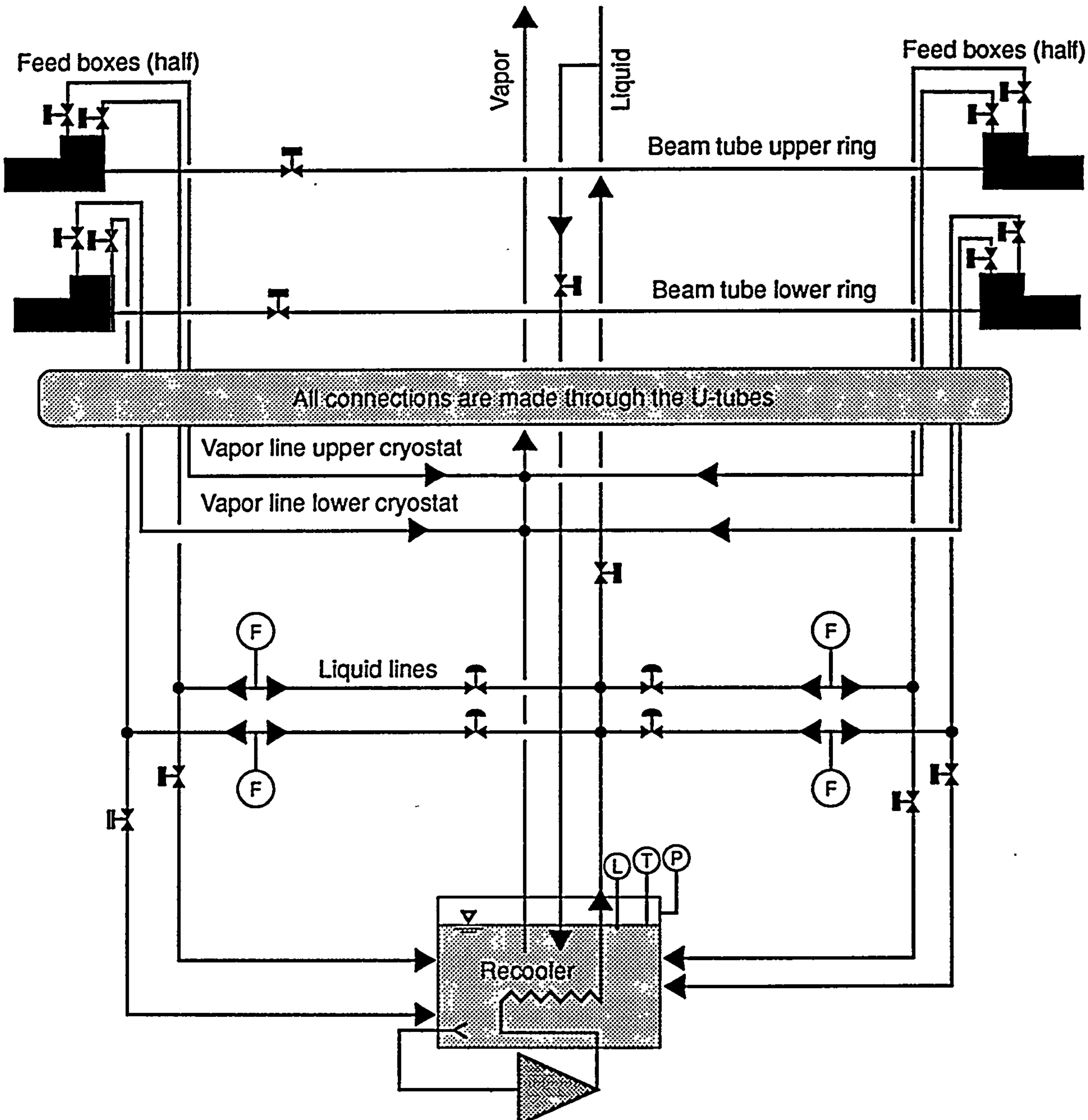

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Figure 8(d). Recooler System for Minimizing the Pressures in the Tunnel.

5.3 Vapor Pressure in the Recoolers

The vapor is extracted from the recooler and removed to the adjacent helium plant through the N_2 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 maximum vapor generation in a nominal string (under normal operating conditions) is 64 g/s. The pressure drop in the vapor line is different for the different recooling schemes. If there are two recoolers per string located at the feed and end boxes, then the flow rate per line is constant at 32 g/s. For the distributed recooling system, the vapor flow changes continuously between 0 and 64 g/s. In the interaction regions of the east and west clusters the heat loads are assumed to be 50 percent higher, so the maximum vapor flow is 96 g/s. These lines are longer than the regular string so that the expected pressure in the vapor lines and the temperature will be higher.

It should be remembered that if there is a two-phase flow in the lower part of the vapor line, then a liquid pocket will be generated and will block the vapor flow. This situation will cause unstable vapor flow conditions leading to pressure oscillations. Liquid pockets in the vapor lines should be prevented.

5.4 Disconnected Strings

In the event that one string is disconnected by isolating one section, and the rest of that ring must 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 upset conditions will be shown below.

5.5 Cooldown of the 84-K Shield

The cooldown process requires reduction of the temperature of the tubes and the shield material from 300 K to 80 K, followed by filling with LN_2 and simultaneous absorption of the heat load.

The heat capacity of the shield and tubes (total mass × averaged specific heat) is approximately

$$16 \text{ kg/m} \times 170{,}546.6 \text{ J/kg} = 2{,}577{,}616 \text{ J/m}.$$

The amount of LN_2 at 80 K (evaporated and warmed to 300 K) required for cooling down the shield is 6.44 kg/m of shield.

The amount of LN_2 required to cool down the shield in a nominal section (1080 m) is shown as in Table 5.

TABLE 5. LN_2 REQUIRED FOR SHIELD COOLDOWN IN A 1080-m SECTION.

Reduce shield temperature	6560 kg
Fill up 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 one section will last 96.7 h (see Appendix C). A more accurate calculation of the cooldown process will take into account the flow limitations, the safety issues, and the change in the heat load during cooldown. All these factors will cause the cooldown process to be much longer.

5.6 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 down the 20-K shield and the magnets to 80 K by circulating cold helium. The helium temperature is obtained by exchanging heat with LN_2, and by the operation of the helium refrigeration plant. A nitrogen mass flow rate of approximately 2000 g/s is required for this process (7.2 tons/h or 172.8 tons/day). The cooldown process of one 4.3-km-long string takes approximately 18 days, requiring more than three refills per day of the local nitrogen reservoirs in order to accomplish the first cooling wave of the cold mass from 300 K to 90 K. It is assumed that this nitrogen is supplied by a separate system (ground transportation).

5.7 Temperature Profile (Cross Section) in the 84-K Shield

A thermal analysis for the 84-K shield shows that the temperature profile in the shield is sensitive to the thermal conduction between the tubes and the shield, the support design, the liquid flow rate, and the heat loads. The integrated emissive heat from the 84-K shield to the 20-K shield may increase by 30–40% if the thermal conduction is reduced by 50%. If the shield is refrigerated by liquid only (flowing in one tube), the integrated emissive power increases by approximately 60%.

6.0 RESULTS

The following is a sample of calculated results of the mass flow rates, pressures, and temperatures for different operating schemes of the nitrogen system.

6.1 Scheme A

Scheme A calls for one nitrogen supply point, located at N40, with the vapor line serving as a continuous recooler.

6.1.1 Vapor Line

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

With these flow rates, the pressure drop along the lines will change, as will the vapor temperatures. Figure 9(a) shows the pressure drop in the vapor line in an arc string and in the cluster region. Figure 9(b) shows the pressure distribution for vapor lines blocked by liquid. Figure 9(c) shows the temperatures in the vapor line of a string (four sections) for flows of 16 g/s per section.

If the liquid injection rate is maintained according to the requirements, the flow in the vapor line is stratified. Figure 10 shows on the "Baker diagram" how the flow pattern changes along one section.

The expected differences between pressures in different strings are in the range of 0 to 2000 Pa. These differences result from the various shapes of shafts and the geometry of each sector, which have not yet been defined.

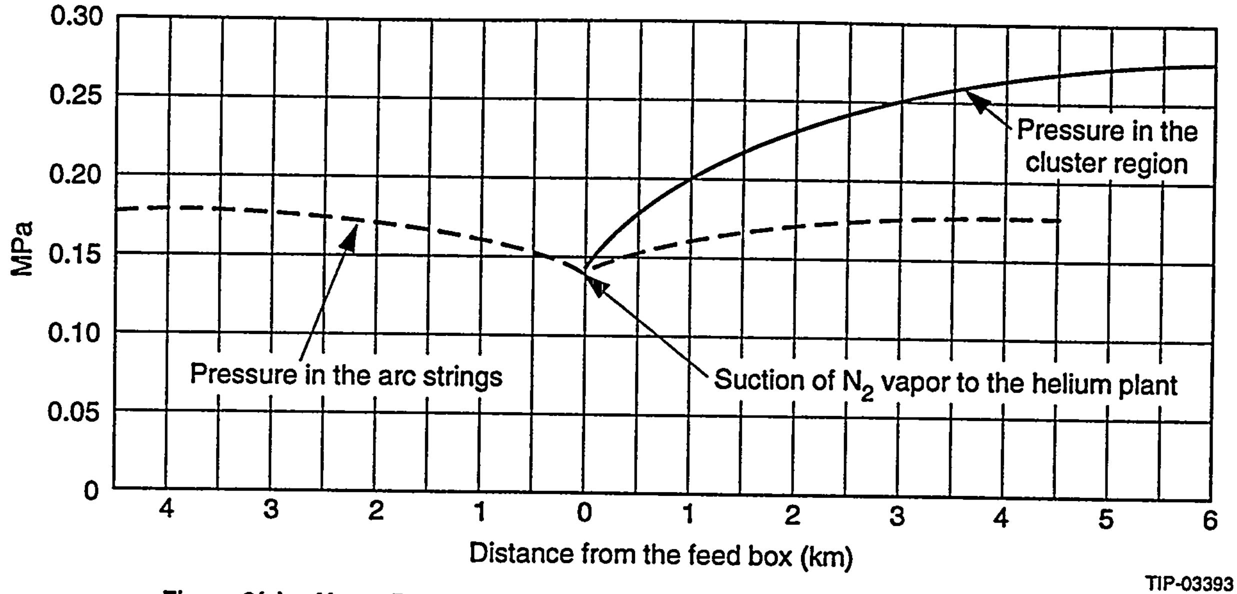


Figure 9(a). Vapor Pressure in the Arc Strings and in the East or West Cluster.

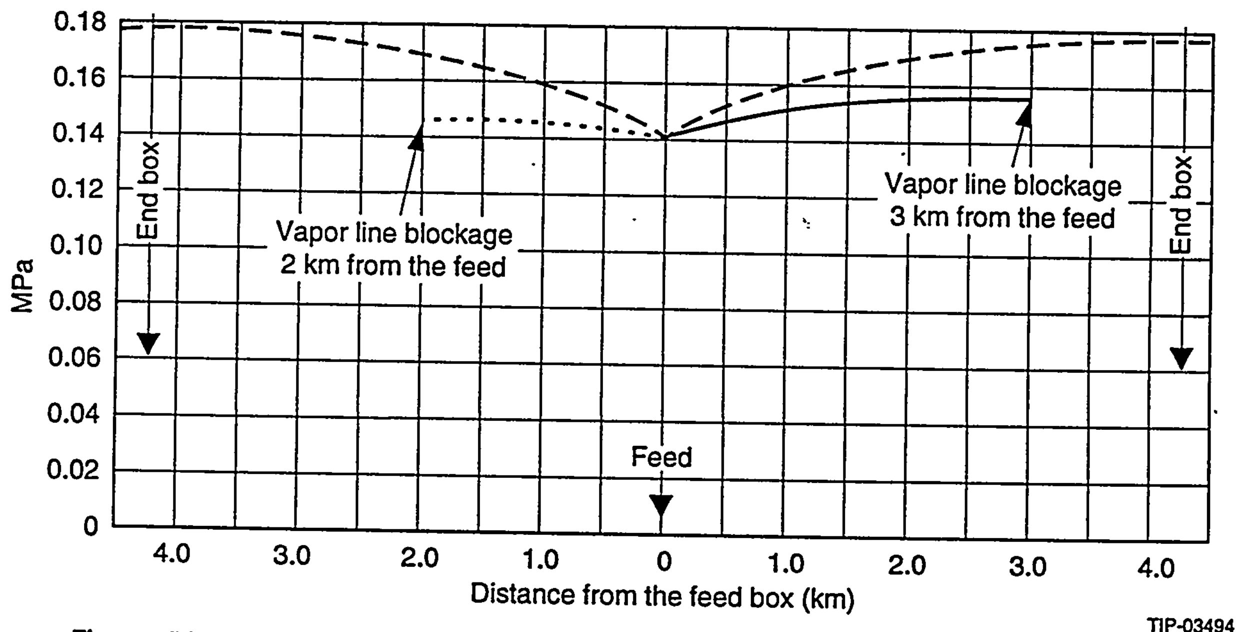


Figure 9(b). Pressure in the Vapor Line for Normal Operation and for Blocked Flow by Liquid.

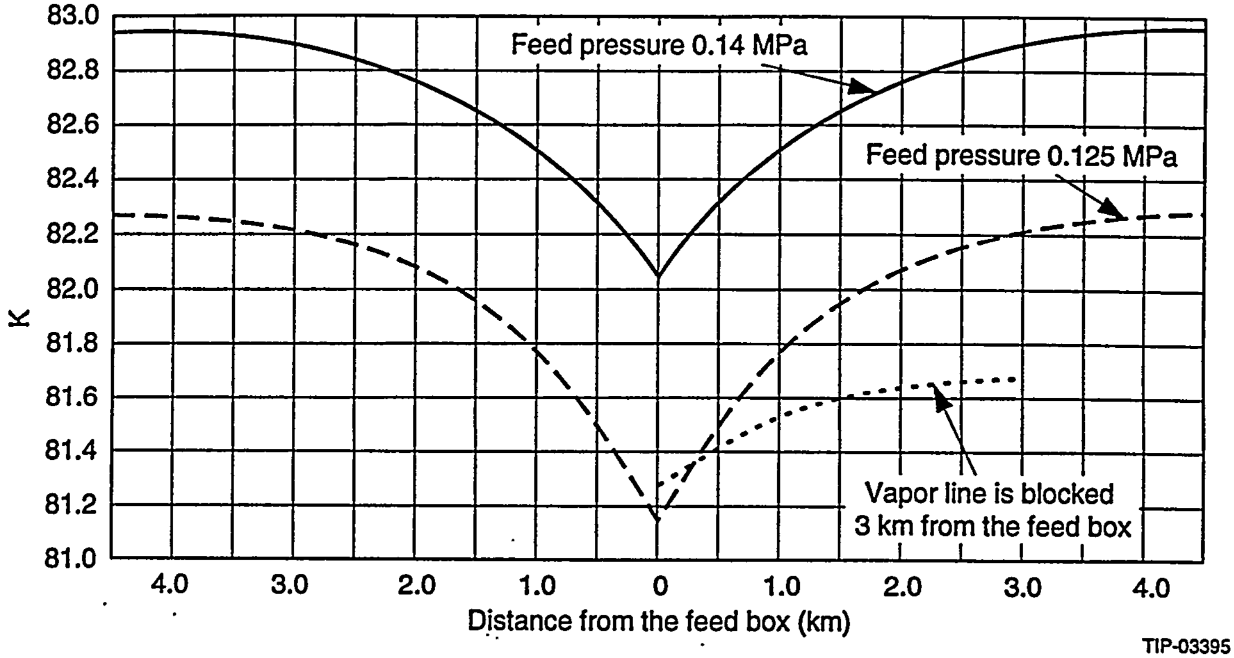
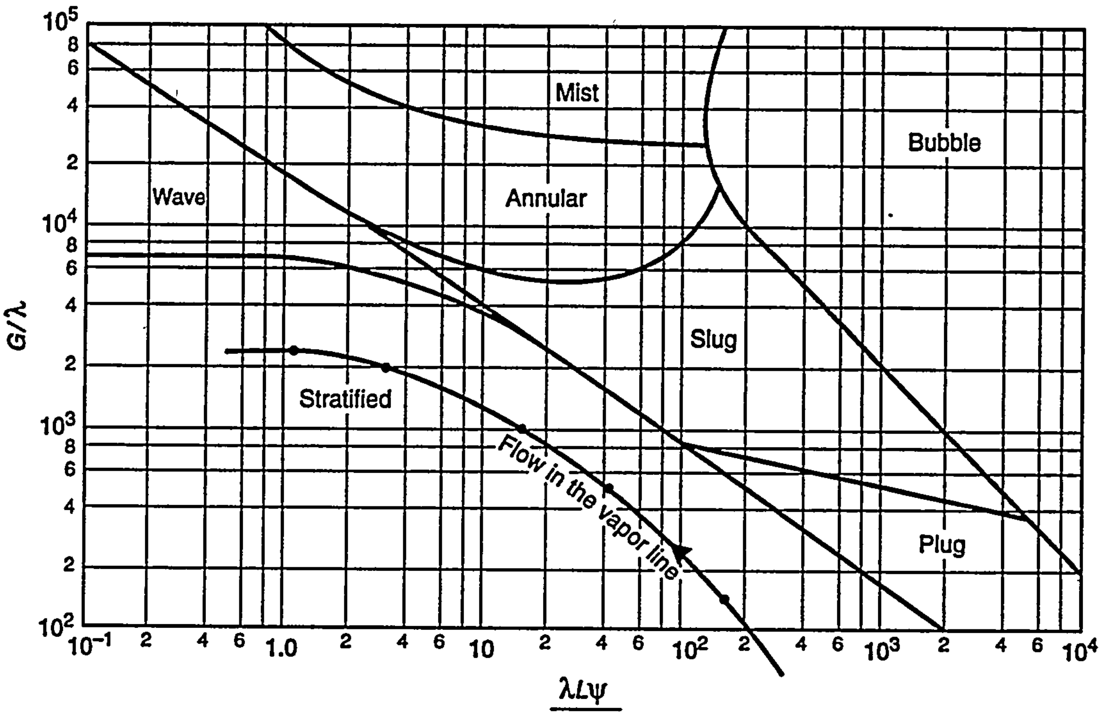


Figure 9(c). Temperature in the Vapor Line for Different Suction Pressures and When the Line is Blocked.



Two-phase flow pattern regions according to Baker (1954).

$\lambda = [(\rho_G/\rho_a)(\rho_L/\rho_w)]^{1/2}$

$\psi = (\sigma_w/\sigma_L)[(\mu_L/\mu_w)(\rho_w/\rho_L)^2]^{1/3}$

L = liquid mass flow rate per unit area, $lb_m/hr\text{-}ft^2$

G = vapor mass flow rate per unit area, $lb_m/hr\text{-}ft^2$

ρ_G = vapor density

ρ_L = liquid density

ρ_a = density of air = 1.20 kg/m^3 = 0.075 lb_m/ft^3

ρ_w = density of water = 998 kg/m^3 = 62.3 lb_m/ft^3

σ_L = surface tension

σ_w = water surface tension = 0.073 N/m

μ_L = liquid viscosity

μ_w = water viscosity = 0.001 Pa-s = 1 centipoise

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Figure 10. Baker's Diagram (taken from Barron, *Cryogenic Systems,* 1985, p. 414).

6.1.2 Liquid Line

For normal operation, the required flow rates are shown in Figure 7(a) (for one major supply point), Figure 7(b) (for two major supply points), and Figure 7(c) (for two supply points if N_2 recoolers are located only near the feed boxes, 8 km apart). For pressures limited to a maximum of 1.25 MPa in the lines, without circulation pumps in the tunnel, the resulting pressure levels are shown in Figure 11.

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 Figure 12).

6.1.3 System Operation When One Critical String Is Disconnected

If there is only one nitrogen supply point, and if 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 0.55–0.60 MPa. To prevent boiling in the first 4.3 km, the feed pressure must be higher than 0.8 MPa, with a back pressure higher than 0.15 MPa. This result indicates that in order to keep the pressure below a reasonable value, circulation pumps installed in the tunnel are needed in all those strings where the nominal flow rate is high.

6.1.4 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 LN_2 must be supplied through the remaining parts of the system — *i.e.*, through lines 87 km long. The whole nitrogen supply of 4784 g/s must go through two lines (see flow rates in Figure 13). The following are two different ways to distribute this flow:

1. Vapor line used for cooling: Without circulation pumps in the tunnel, the required supply pressure is 4.4 MPa (for disconnected string N40–N35) and 5.2MPa (for disconnected string N40–N45). Of course, these pressures are unacceptable and pumps are needed to distribute the nitrogen. Figures 14(a) and 14(b) show the pressure distribution in the tunnel if the strings are disconnected and pumps are used for circulation.

2. The "vapor line" may be 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.

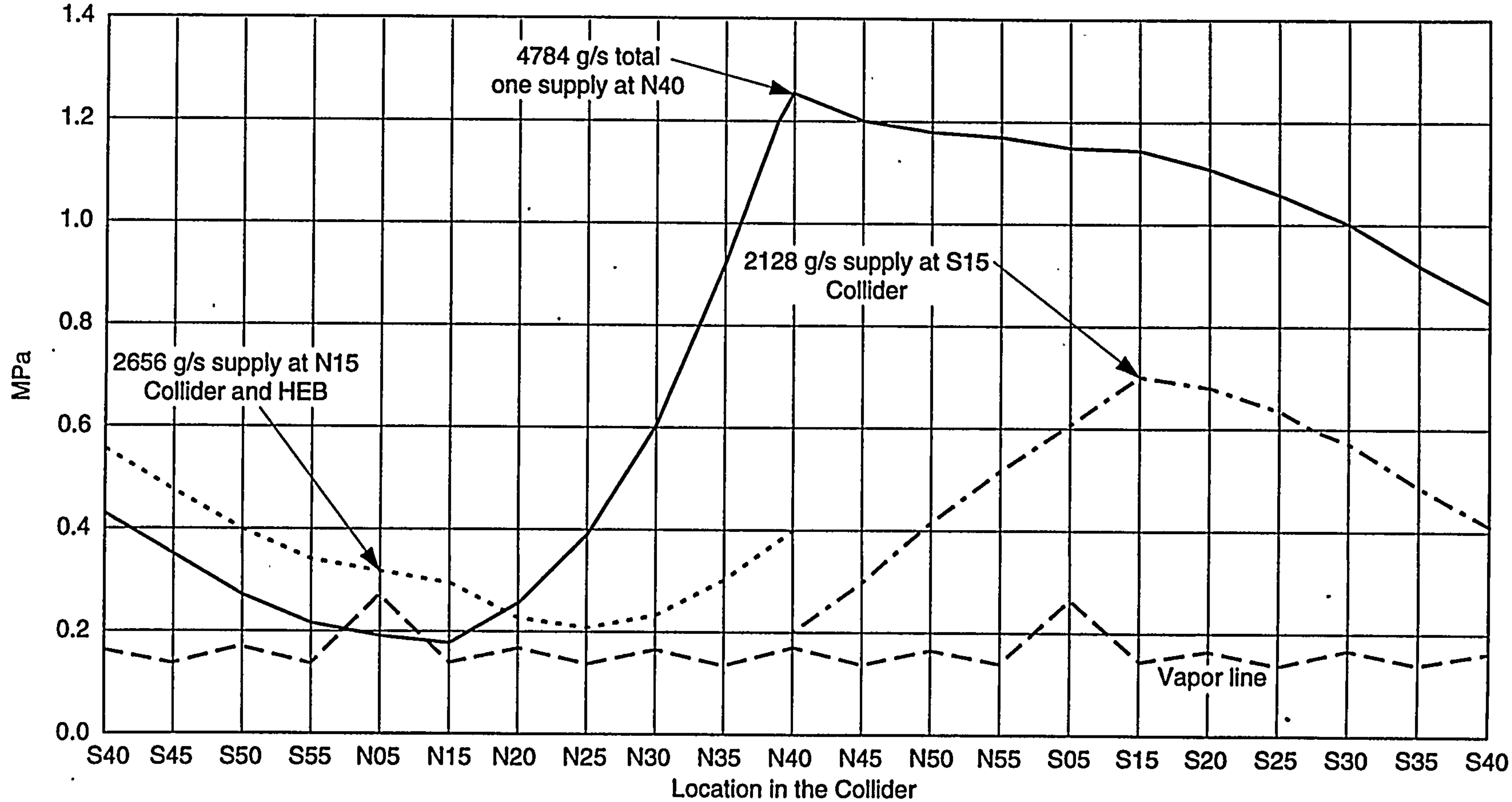

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Figure 11. Pressures in the Nitrogen Lines for Different Configurations.

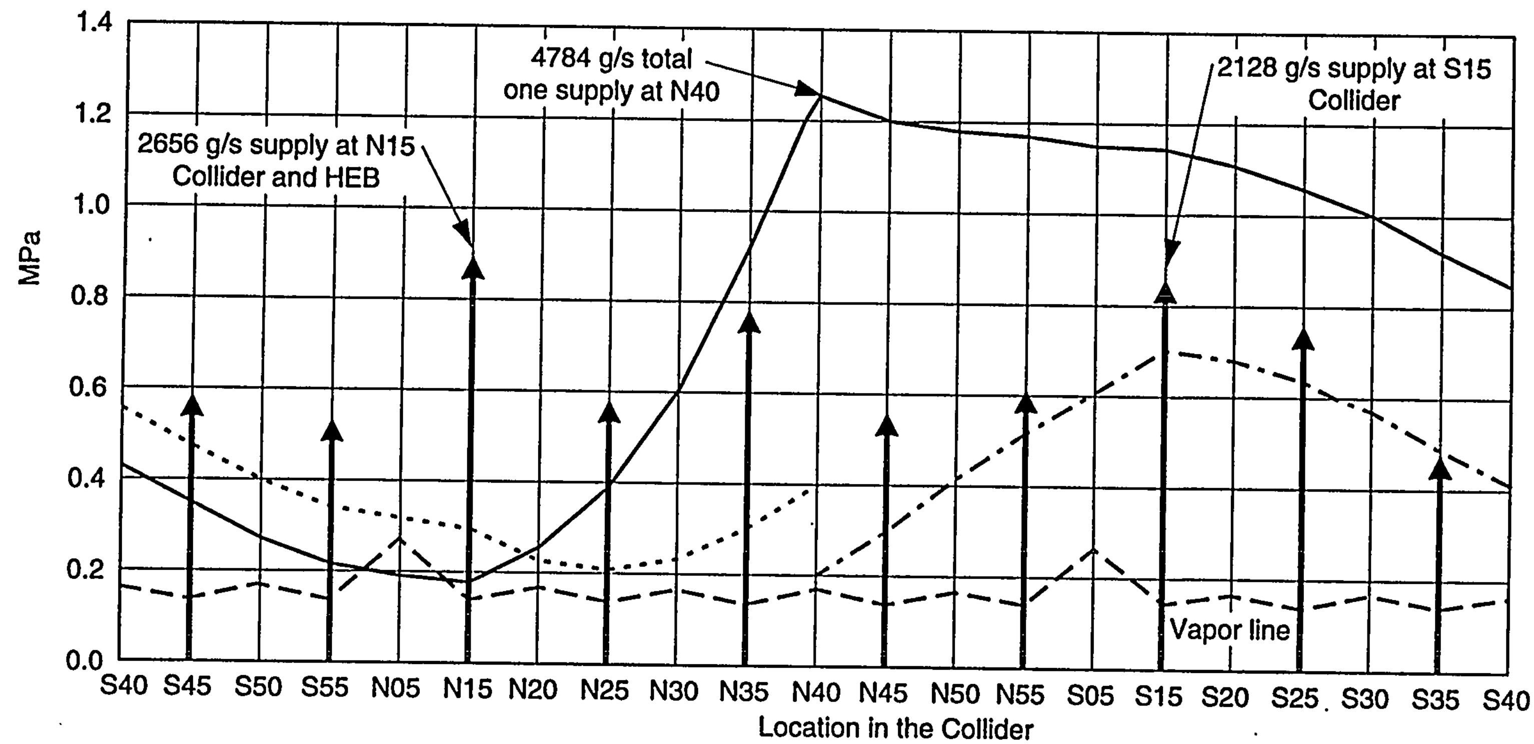

Figure 12. Pressures in the Tunnel Required to Pump Liquid to the Surface (Vertical Arrows).

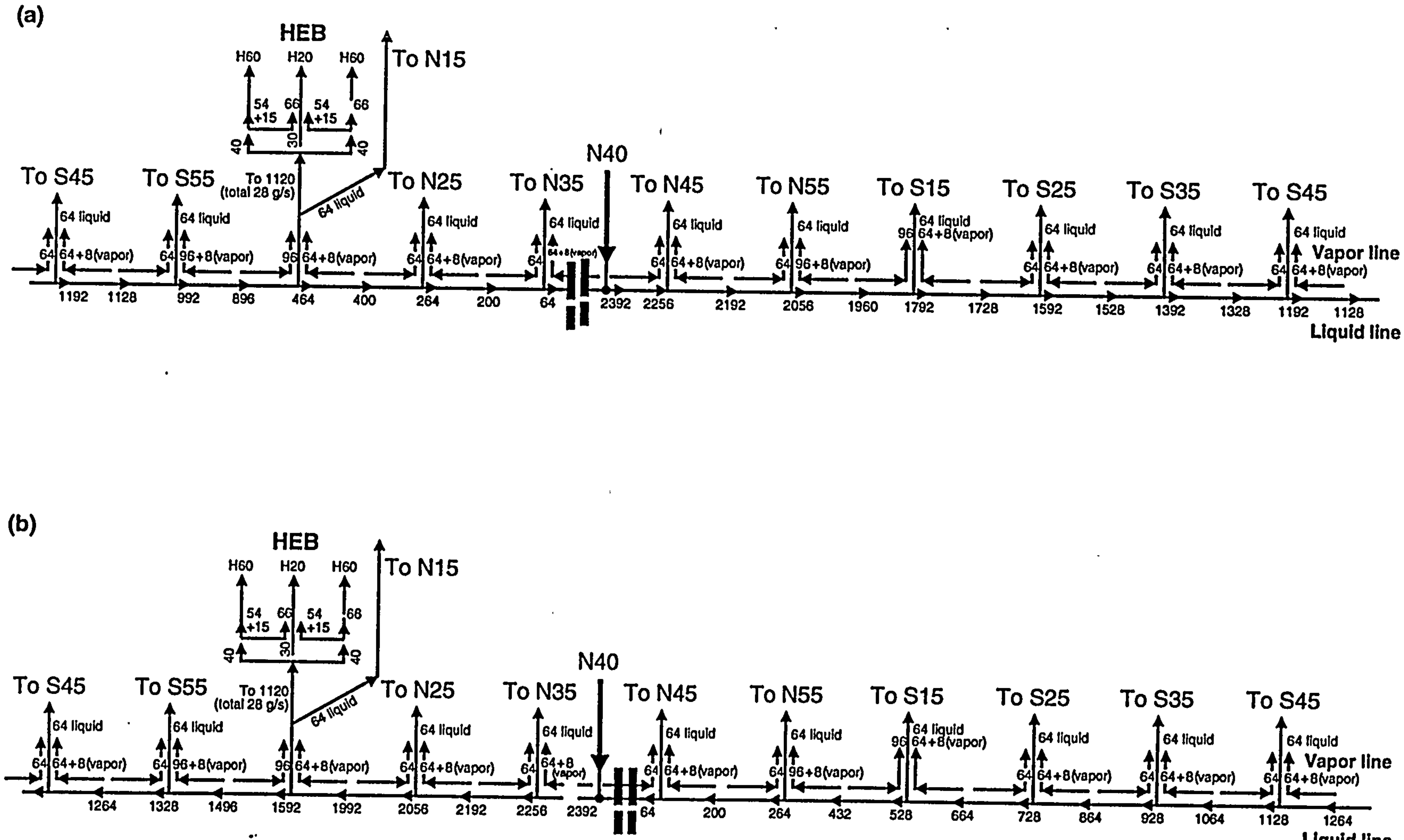

Figure 13. Liquid and Vapor Flow in g/s for Disconnected Strings. Nitrogen supply at N40: total 4784 g/s; (a) for strings west to N40; (b) for strings east to N40.

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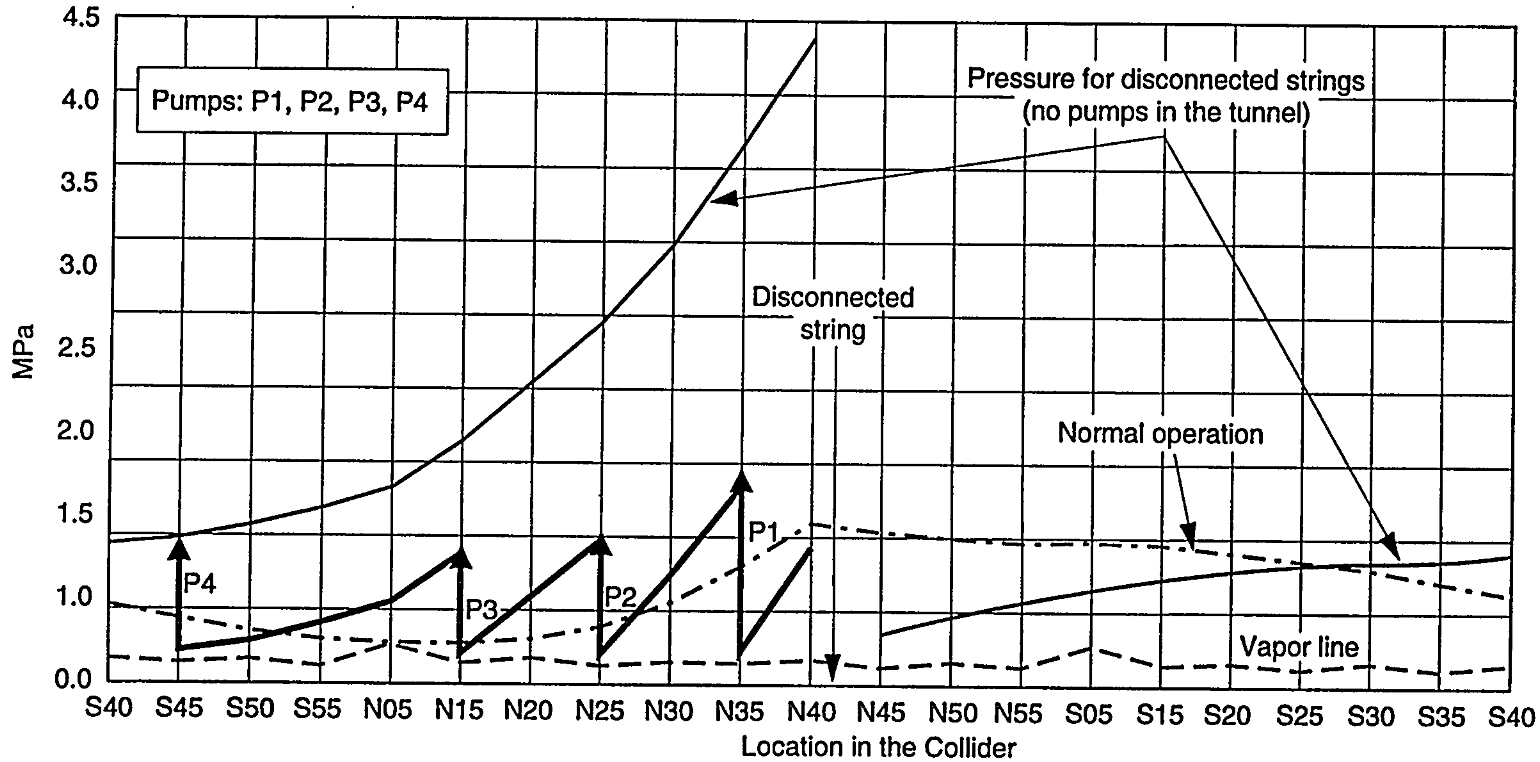


Figure 14(a). **Pressure in the LN_2 Lines for Disconnected Strings With and Without Pumps (string N40–45 disconnected).**

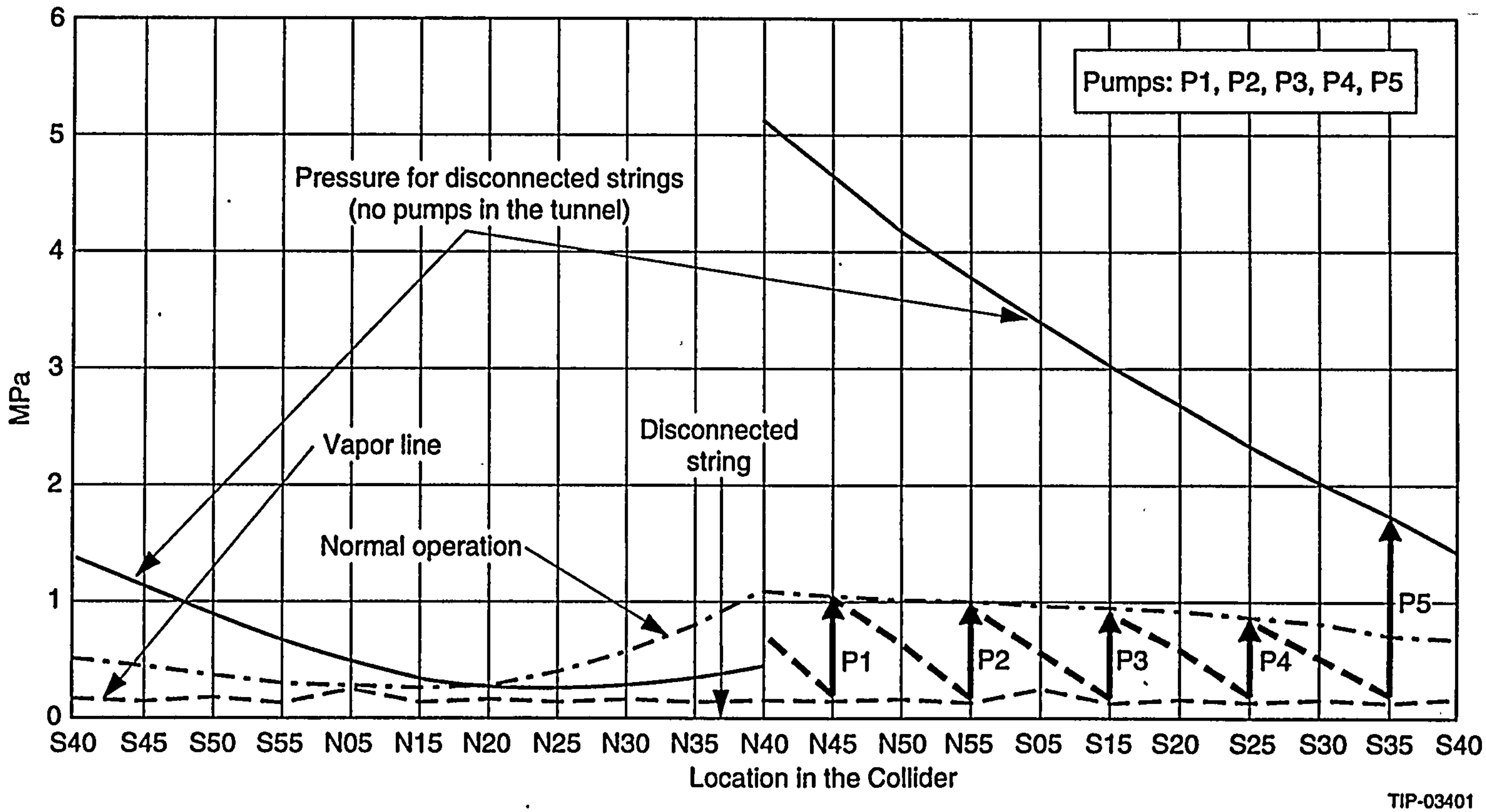


Figure 14(b). Pressure in the LN_2 Lines for Disconnected Strings With and Without Circulation Pumps (string N35–40 disconnected).

6.2 Scheme B

Scheme B calls for nitrogen supply points at N15 and S15, with the vapor line serving as a continuous recooler. The mass flow rates are as shown in Figure 7(b). For this configuration, the pressures and temperatures in the vapor line are the same as for Scheme A (see Figure 9).

Compared with the previous configuration, the mass flow rates 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, there must be liquid pumps in the tunnel. The pressure distribution if no pumps are installed in the tunnel to circulate the flow is shown in Figure 11.

To prevent vapor in the liquid line, the pressures in the liquid line must be kept above the saturation point. Two-phase flow across the U-tubes may block the liquid flow and introduce high disturbances in the system.

If a string is disconnected, then the flow in the parallel string may be doubled, but the pressures are still lower than the resulting pressures in the previous model.

Figure 12 shows the minimum required pressure for pumping liquid to the surface. 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.

6.3 Scheme C

Scheme C calls for nitrogen supply points at N15 and S15, with liquid flow recooled by compact recoolers. As mentioned earlier, the inclination of the tunnel in the regions between N15 and N30 and between the east cluster and S30 is too slight to allow the free flow of boiling liquid in the vapor line, which prevents the use of this line as a distributed recooler. The detail 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, this is true 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, plus a vapor separator every 8 km; Scheme C.3—a recooler every 1 km, plus a vapor separator every 8 km.

6.3.1 Scheme C.1

In this model, all the heat load is absorbed by the liquid, which is recooled every 8 km. To obtain the required temperature range, the liquid mass flow in the cryostat should be sufficiently high to prevent two-phase flow. The minimum flow to keep the temperature at 80–89 K for a heat load of 25,600 W/8 km is 1374 g/s. For the east and west cluster, the load is assumed to be 50 percent higher (38,400 W per cluster), and the minimal flow rate should be at least 2060 g/s. Figure 7(c) shows the mass flows in the ring, including the distribution requirements for this scheme. The resulting mass flow rates will require operating pressures beyond the acceptable levels even if a circulation pump is installed in the tunnel for every sector.

6.3.2 Scheme C.2

This scheme and some of its variations were analyzed earlier (for slightly different flow rates). We found that a compact heat exchanger is sufficient at the end of each sector and that a heat exchanger with a vapor separator and a liquid pump are needed in the feed box of the sector in order to maintain the temperature below 89 K. The availability of the pump in each sector allows reduction of the pressure in the liquid lines. This in turn may lead to two-phase flow in the liquid line. Figure 8(d) shows a schematic diagram of the piping and recooling system for this scheme.

Figure 15(a) is the pressure-temperature (P-T) diagram for a mass flow rate of 731 g/s in string S25-S30 (the flow is uphill). At S30 the LN_2 is recooled and the main flow is reduced by 82 g/s. The remaining 649 g/s flow in string S30-S35 is subcooled liquid as long as the pressure is higher than the boiling pressure. When the pressure drops further, boiling conditions are present, the flow contains both liquid and vapor, and the friction pressure drop becomes much higher. To prevent the two-phase flow, the back pressure must be elevated to a value higher than 0.27 MPa, and the pressure at S25 must be higher than 0.5 MPa.

Figure 15(b) is the P-T diagram for 542 g/s from S45 to S40 and 460 g/s from S40 to S35, with a recooler at S40. The flow is downhill and, as may be expected, the pressure increases downstream. In both strings, the flow begins as liquid and becomes two-phase downstream.

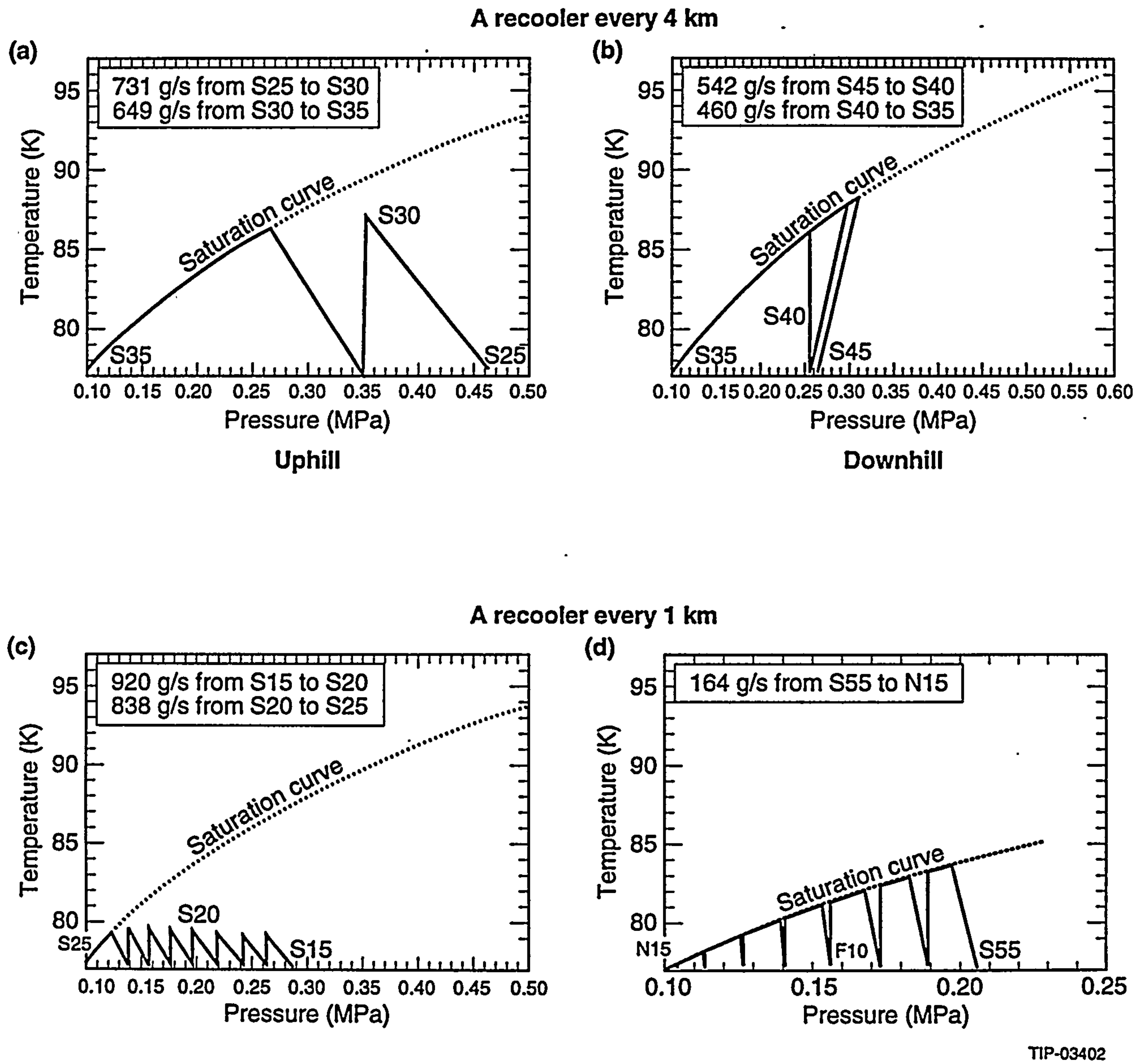


Figure 15. LN_2 Temperature vs. Pressure Profiles. (See recooling scheme, Figure 8(d), main supplies at N15 and S15.)

6.3.3 Scheme C.3

The results of this scheme are similar to those shown for C.2, and will not be discussed in detail. If vapor separators are installed in each section, boiling in the liquid line may be accepted and the pressure levels may be lowered even more.

Figures 15(c) and 15(d) illustrate P-T changes for high flow rates and low flow rates, respectively, with a recooler in every section (approximately every 1 km). In these two cases, the back pressure is maintained at 0.1 MPa.

7.0 CONTROL LOOPS

The design of the control system is directed to meet two major requirements: (1) safe operation of the system, and (2) optimization of operational parameters. The design and analysis of the control loops require the availability of geometric and dynamic data for the system and its interfaces with other systems, the upper and lower limits of the parameters for each operating mode, and basic data in order to compare cost effectiveness of the various solutions.

7.1 Inventory Control

The amount of liquid and vapor nitrogen in the tubes in normal operation mode is approximately 2240 kg for a nominal section of 1080 m, and 2800 kg for a section 1350 m long. The fillup of the nitrogen lines is one of the first steps in putting the ring into operation, and emptying the nitrogen lines is one of the last steps when stopping the system. The inventory of nitrogen should not change by more than 6 percent during the operation of the ring. (Assume that the temperature of the nitrogen changes from 80 to 90 K without changing phase; because of the change in the specific weight, the expected change in the inventory is 100 kg per section.)

If a line is ruptured, there will be a spill into the cryostat. This may be detected by a pressure drop in the nitrogen line as well as by a change in the vacuum level in the cryostat. Both measurements are designed to initiate alarms and procedures to isolate the damaged sections.

A software program will serve as on-line inventory supervisor and controller. This will include local inventory calculation by measurement of temperatures and pressures in the tubes and by central measurements of input and output mass flow rates.

7.2 Pressure and Temperature Monitoring and Control

As shown in the previous paragraphs, the operational pressure levels and temperature levels in the lines depend on the design of the system and on the location in the ring. For normal operation, the pressure is expected to change by less than 3 percent and the temperature by less than 0.5 K. A higher rate of change will require a correction action. For any given operating scheme the monitoring and control system (the computer) will be loaded with the nominal local pressure and temperature as well as with high and low operating limits defined by the expected ranges and the accuracy of the instrumentation. The high alarm limit for liquid pressure measurement of 1.8 MPa is defined by the piping design. The low alarm limit for liquid pressure equals the local vapor pressure (to prevent two-phase flow in the liquid line). The nominal local vapor pressure is in the range of 1.3–1.8 MPa for an arc string. Without special venting equipment (cold vents or cold blowers), the vapor pressure in the clusters is higher. If a helium plant is out of service, the nitrogen vapor should be vented at low temperature in order to prevent temperature rise in the 80-K shield,.

For safety reasons, the pressure should be scanned at least once per second. Whenever the pressure limits or the pressure rate of change are violated, a software program will alert the operator to the need for intervention, or will automatically begin isolation of the damaged part of the ring.

Whenever saturation conditions are detected (calculated) for the nitrogen in the liquid line, a message will be output and corrective action will be initiated by increasing the pressure in the line.

7.3 Controls for Compact Recoolers

Because of the big differences in flow rates in different parts of the system, the heat exchangers serving as recoolers should be individually designed. The main output from the recooling control is the temperature of the liquid nitrogen at the exit port. This will result from a central control (sector control) of the pressure in the vapor line, which in turn defines the boiling temperature in the recooler. A second control loop is the liquid level in the recooler required to prevent overflow.

7.4 Continuous Recooling by Injection of Liquid into the Vapor Line

As above, the temperature is controlled by maintaining the vapor pressure at the lowest possible level so that liquid injected into this line will meet saturation or boiling conditions. The liquid injection rate should be controlled to provide liquid everywhere in the line while preventing flooding of the lower part of the tube.

7.5 Flow Monitoring and Control

The streams of liquid nitrogen to the collider and to the HEB and the vapor vented from the helium plants define the heat loads. Flow measurements are slow and should be scanned at a rate of once every 10–20 s. Table 6 gives a first evaluation of expected process times and velocities.

TABLE 6. PROCESS TIMES AND VELOCITIES (A FIRST EVALUATION).

Cooldown of the 80-K shield of 1 km	5 days
Cold mass cooldown to 80 K	18 days
Change the pressure in the system by 0.01 MPa	3 (or more) hours
Liquid flow in the cryostat (1000 g/s)	0.51 m/s
Vapor flow in the cryostat (64 g/s)	4.2 m/s

8.0 CONCLUSIONS

The following conclusions were reached with regard to the nitrogen system for the SSC:

1. 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.
2. 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, because N15 is close to the HEB and has the highest elevation, it is preferred from the point of view of operation of the HEB and the LN_2 distribution.
3. Recooling schemes: Providing a compact recooler every 4 km results in a temperature rise of up to 89 K in the 80-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.
4. Pumps: Pumps are required in every sector to supply liquid to the surface and to distribute the liquid in case of subnormal operating conditions. The flow rates and the pumping pressure are reduced if two air-separation plants are installed.

5. The major upset conditions: Disconnection of the two rings close to the air separation plant will require operation of circulation pumps in order to operate the system. 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 lower pressure value 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 in every string.
6. 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-gal truck may carry 22 tons of LN_2).

9.0 EQUIPMENT

9.1 Pumps

Table 7 summarizes the required pumps for liquid nitrogen in the tunnel. The optimal pumping scheme will be defined later.

TABLE 7. PUMPS FOR LN_2 IN THE TUNNEL.

			NUMBER OF PUMPS	
FUNCTION	RATING	FLOW RATE	COLLIDER	HEB
Pumping liquid to the surface	1 MPa	80 g/s	10	2
Distribution in case of disconnected strings	15 MPa	Various (max. 2000 g/s)	10 per ring	1

9.2 Recoolers/Subcoolers

To reduce the vapor pressure in the tunnel, a set of compact recoolers will be installed at every sector feed spool. Compact rercoolers will also be required in the following locations: N20, N30, S20, S30, and H20, and in the two clusters. In the other locations of the end boxes, compact recoolers or continuous recoolers may be used.

The optimal recooling system will be a combination of the different types of recooling systems.

9.3 Temperature and Pressure Sensors

For maintenance purposes, at least one pressure sensor and one temperature sensor are needed for each section. These sensors will also be used for monitoring and control.

9.4 Minimum Equipment for the N_2 System

Table 8 is a list of the minimum equipment required for the nitrogen system.

TABLE 8. MINIMUM EQUIPMENT FOR THE N_2 SYSTEM.

RECOOLING SCHEME	COMPACT RECOOLERS (FIGURE 5 (a), (b))	CONTINUOUS RECOOLERS (FIGURE 5 (a), (b), (c))	SPECIAL RECOOLERS (FIGURE 5 (a), (b), (d))
Recoolers/subcoolers	43	23	23
Special recoolers			10
Pumps for LN_2 to surface			12
Circulation pumps	12[1]	12[1]	
Level sensor	43	23	33
Recooler control valve	43	23	33
LN_2 injection valve		396	
Flow distribution valves	72[2]	72[2]	120
Isolation valves, vapor line	784	784	784
Isolation valves, liquid line	784	784	784
Pressure sensors ,vapor line	202	202	202
Pressure sensors, liquid line	202	202	202
Thermometers, vapor line	202	202	202
Thermometers, liquid line	202	202	202
Flowmeters	22[3]	22[3]	42

1 Require additional switching valves or additional pumps.
2 Additional valves are needed in order to combine circulation pumps and pumps to the surface.
3 Switching valves may be needed or double the number of flowmeters.

APPENDIX A
RECOOLER DESIGN

The purpose of the recooler is to remove the heat absorbed by the LN_2 from the cryostat. Liquid nitrogen flows in the heat exchanger in the tube side. The shell side contains boiling nitrogen at a pressure controlled by systems in the helium plants on the surface. The level of the boiling nitrogen is controlled by injection of liquid from the liquid line (see Figure 8(a)).

Design procedure is as follows: The resistance to heat transfer has three components: inside resistance, wall resistance, and resistance due to film boiling outside the tubes. The wall resistance is small and may be ignored. The internal film resistance is calculated using the Dittus-Boelter equation in the usual way (see McAdams, *Heat Transmission,* 1954, p. 219). To calculate boiling film resistance outside the horizontal tubes, we use the Kutateladze correlation (see Table A.1 for nomenclature) for nucleate pool boiling (see NBS Tech. Note No. 317):

$$\frac{h_{\text{boil}}}{k_l}\left(\frac{\sigma}{g\varrho_l}\right)^{1/2} = 3.25 \cdot 10^{-4}\left\{\frac{(q/A)C_{p,l}\,\varrho_l}{h_{fg}\,\varrho_v k_l}\left(\frac{\sigma}{g\varrho_l}\right)^{1/2}\right\}^{0.6} \cdot$$

$$\left\{g\left(\frac{\varrho_l}{\mu_l}\right)^2\left(\frac{\sigma}{\varrho_l g}\right)^{3/2}\right\}^{0.125} \cdot \left\{\frac{P}{(\sigma g\varrho_l)^{1/2}}\right\}^{0.7} .$$

The procedure is to assume a small temperature drop for the flowing liquid nitrogen and to calculate the length of the heat exchanger required for known inside and outside coefficients. The next step is to calculate the subsequent temperature drop, compare to the first assumption, and repeat the process until the desired temperature is reached. Summation of the different lengths thus computed gives the total length of the coil required. Obviously, the exit temperature is higher than the temperature of the boiling nitrogen in the bath. The temperature difference at the exit defines the heat exchanger effectiveness.

The computer program designed for the recooler computation also gives the pressure drop and the total overall heat transfer coefficient, UA.

An approximate value of UA may be calculated from the Effectiveness-NTU relationship (assuming an average value of specific heat for the overall temperature range considered) for a heat exchanger with boiling liquid on one side, *viz.*:

$$\varepsilon = 1 - e^{-NTU}$$

$$NTU = UA/C_{\min} .$$

It may be noted that to calculate the boiling heat transfer coefficient using the Kutateladze correlation, one should know the value of Q/A. Q is known for the assumed temperature drop; A can be known after the length is calculated. Therefore, the procedure is to first assume a value of Q/A, then calculate the outside heat transfer coefficient, then find out the overall heat transfer coefficient, then again find the area for this small section knowing the heat transferred and the logarithmic mean temperature difference, hence the new value of Q/A; iterate until the two values of Q/A converge to a specified tolerance.

TABLE A.1. NOMENCLATURE FOR THE KUTATELADZE CORRELATION.

h_{boil}	nucleate pool boiling heat transfer coefficient (W/cm^2-K)
k_l	thermal conductivity of the liquid (W/(cm-K))
$C_{p,l}$	specific heat at constant pressure for the liquid (J/(g-K)
ρ_l	density of the liquid (g/cm^3)
ρ_v	density of the vapor (g/cm^3)
μ_l	Newtonian coefficient of viscosity for the liquid (g/(cm-sec))
h_{fg}	latent heat of vaporization (J/g)
σ	surface tension between the liquid and its own vapor evaluated at the temperature of boiling liquid (dynes/cm)
g	acceleration of gravity (cm/sec^2)
q/A	rate of heat transfer per unit area (W/cm^2)
P	pressure of the boiling system (dynes/cm^2)
NTU	number of transfer units (dimensionless)
ε	heat exchanger effectiveness (dimensionless)
U	overall heat transfer coefficient (W/(cm^2-K))
A	heat transfer area (cm^2)
C_{min}	minimum capacity rate (W/K)

APPENDIX B

LIQUID FLOW IN THE VAPOR LINE; FREE SURFACE FLOW IN A ROUND TILTED TUBE (FLOW IN OPEN CHANNELS)*

Following Manning correlation, the flow in an open channel is calculated by

$$Q = A \times V = Rh^{2/3} \times Sb^{1/2} \times A/n,$$

where

A is the flow cross section,
V is the average flow velocity,
Q is the volumetric flow,
Rh is the hydraulic radius,
Sb = tg (alfa),
(alfa) is the inclination of the channel, and
n is the Manning roughness coefficient.

Table B.1 gives calculated results for a round tube 63.5 mm in diameter.

TABLE B.1. CALCULATED RESULTS FOR A ROUND TUBE 63.5 mm IN DIAMETER.

WETTED ANGLE (deg)	FLOW CROSS SECTION (cm²)	WETTED AREA (cm *m)	VOLUMETRIC FLOW (cc/s)				VELOCITY (cm/s)			
			(channel inclination—deg)							
			0.05	*0.10*	*0.15*	*0.20*	*0.05*	*0.10*	*0.15*	*0.20*
180	12.88	8.99	132	187	229	264	10.2	14.5	17.5	20.5
150	8.69	7.50	77.4	109	134	154	8.9	12.6	15.4	17.8
120	5.04	6.02	36.2	51.2	62.7	72.5	7.2	10.2	12.5	14.4
90	2.34	4.51	12.2	17.3	21.2	24.4	5.2	7.4	9.0	10.5
60	0.44	3.01	2.37	3.3	4.1	4.7	3.2	4.5	5.5	6.4
30	0.10	1.50	0.12	0.18	0.22	0.25	1.3	1.8	2.2	2.6

The liquid flow in the vapor line is injected at a nominal rate of 16 g/s, or approximately 20 cc/s. In the upper part of a section the wetted angle (see Figures B.1–B.4) is 62° for an inclination of 1.0° and 92° for an inclination of 0.1°. In the lower part of the section no liquid flow is accepted.

*See R. W. Fox and A. T. McDonald, *Introduction to Fluid Mechanics*, John Wiley and Sons, Chapter 10.

The wetted area per meter of length changes between a minimum value of 0.03 m2/m to zero. Taking the boiling heat transfer coefficient as 2000 W/m2/K, we obtain for the 3.0 W/m and 0.03 m2/m a temperature difference between the boiling liquid to the wall of 50 mK. In the lower part of the tube for a flow rate of only 0.05 cc/s, 0.1° inclination, the wetted area is 0.015 m2/m. Assuming the boiling heat transfer coefficient of 2000, the resulting temperature difference grows to 100 mK.

These results indicate that for all regions between S20 and N15, and between N20 and S15, the flow conditions and the boiling conditions in the vapor line are adequate. For the highest and lowest part of the rings—*i.e.*, between N20 and N25 and between S15 and S20, the tilt angle of the lines is too small to enable reliable conditions of free flow necessary for reliable conditions of heat transfer. In these places compact heat exchangers will be used for recooling.

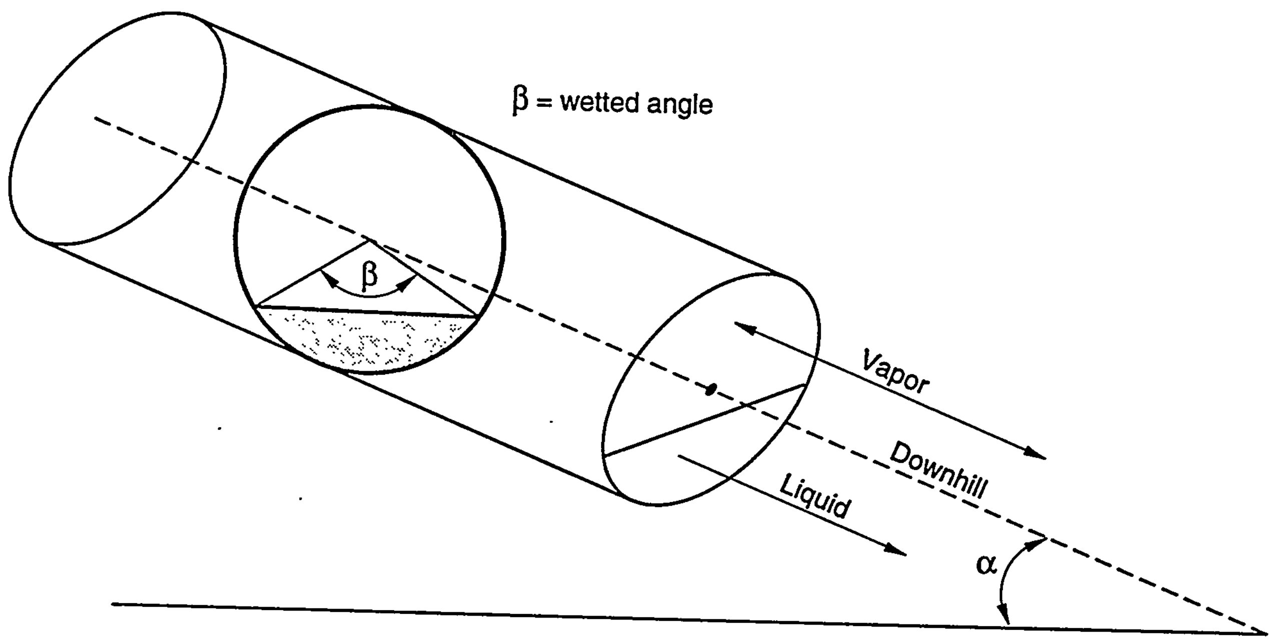


Figure B.1. Two-Phase Flow in an Inclined Round Tube. For an angle = 0.1°, D = 63.5 mm, the flow rate is 18.5 cc/s, the wetted angle is 90°, and the liquid velocity is ≈8 cm/s.

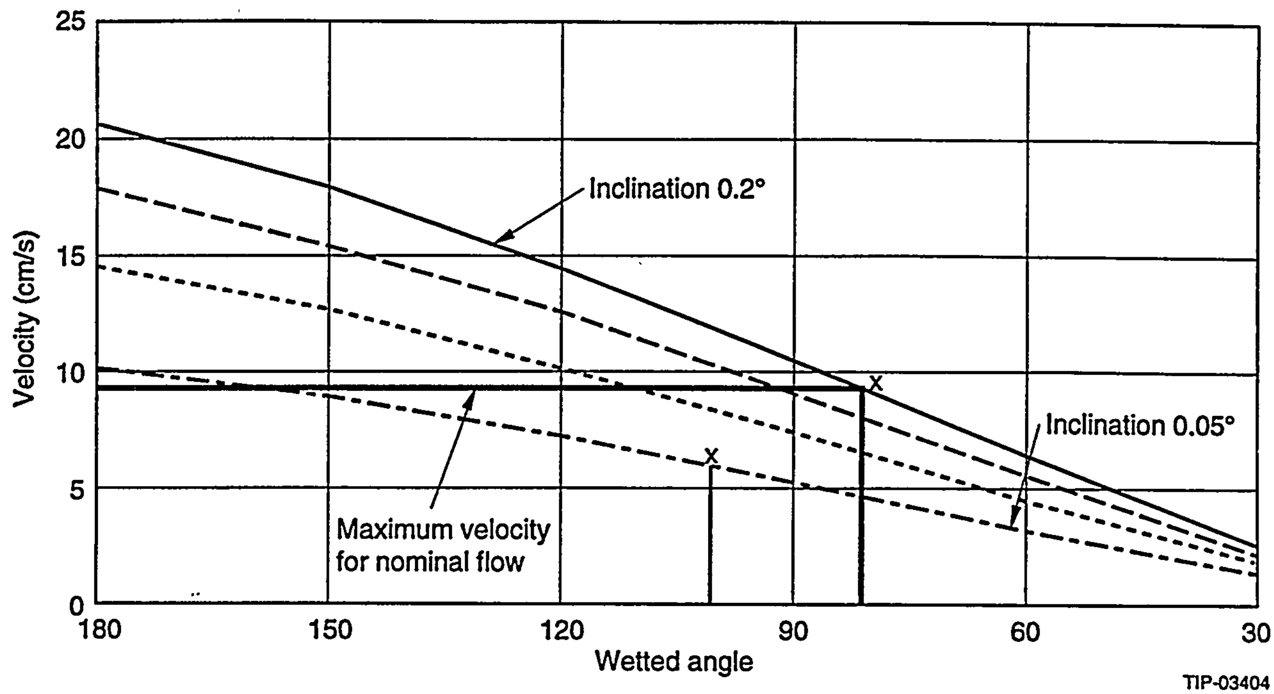


Figure B.2. Fluid Velocity for Different Angles of Inclination.

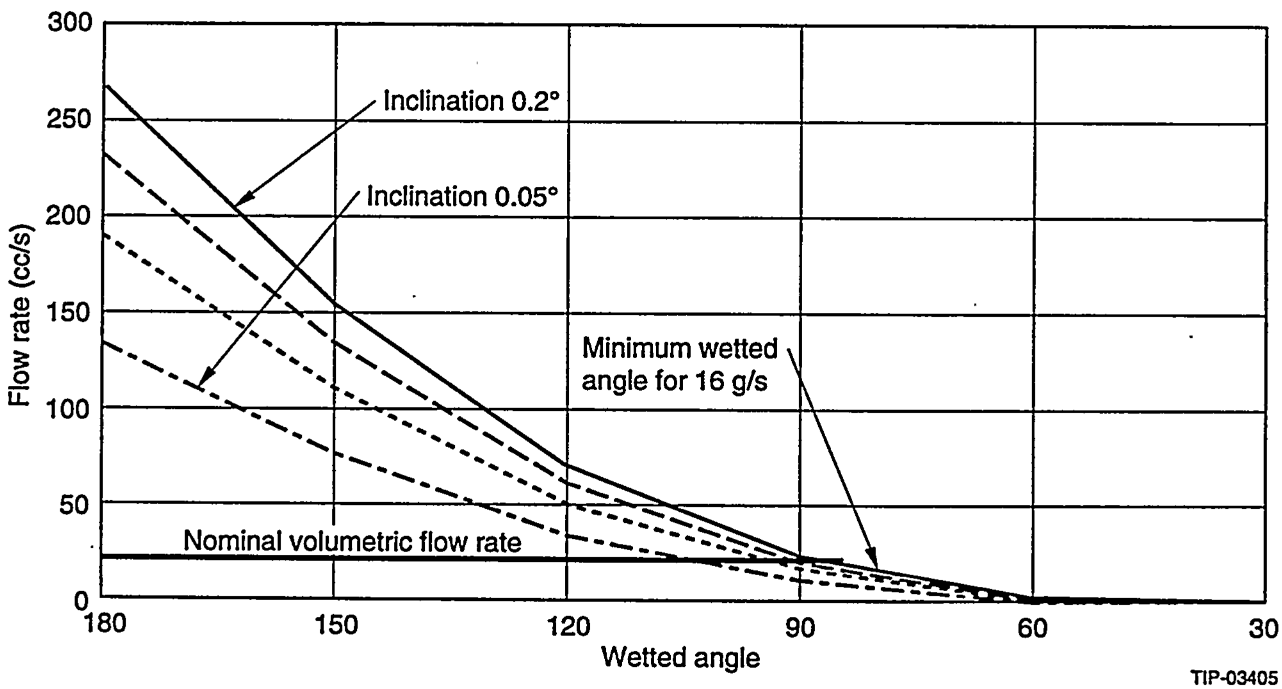
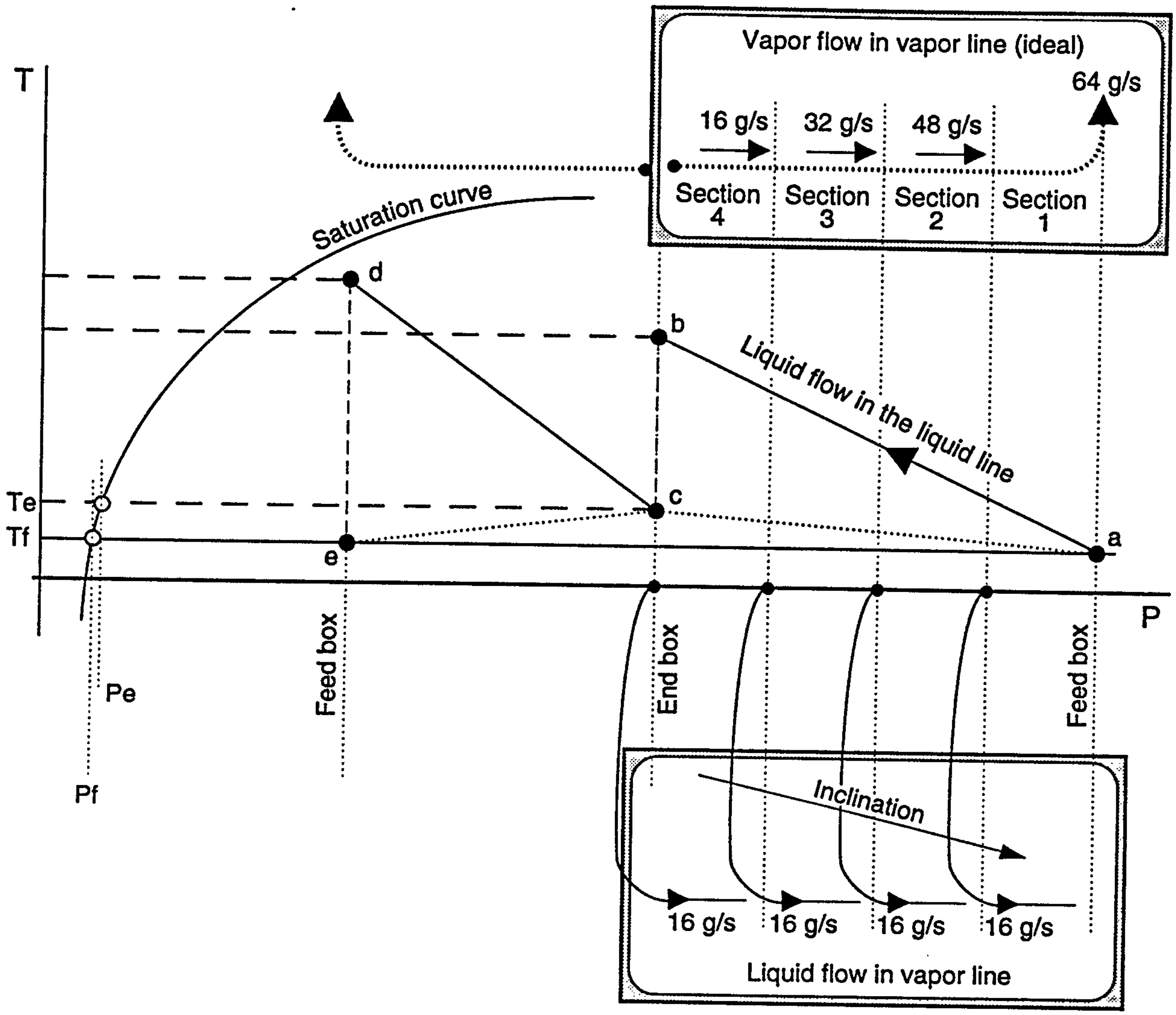


Figure B.3. Flow Rate for Different Angles of Inclination.



Te, Pe	vapor temperature and pressure in the end box recooler
Tf,Pf	vapor temperature and pressure in the feed box recooler
ab	liquid flow in the first string (recooler every 4.3 km)
cd	liquid flow in the second string (recooler every 4.3 km)
bc	feed box recooler
de	end box recooler
ac, ce	continuous recooling

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Figure B.4. Schematic Pressure/Temperature Diagram for the Liquid Line.

APPENDIX C
84-K SHIELD COOLDOWN

Characteristics of the 84-K shield are given in Table C.1.

TABLE C.1. CHARACTERISTICS OF THE 84-K SHIELD.

Total shield volume	= p × 602 × 1.5	= 2.8 e–3 m^3/m
Shield mass	= 2.8 × 2.7	= 7.6 kg/m
Total mass including tubes		≈ 16 kg/m
$H_{(300\ K)}$	= 170,547.6 J/kg	
$H_{(80\ K)}$	= 9,466 J/kg	
Total heat to be removed for shield cooldown	= (16 kg) × (170,547–9,466)J = 2,577,616 J/m	
LN_2 warmed up from 80 K to 300 K	≈400 J/g	

The following requirements have been determined for the 84-K shield cooldown:

1. The mass of nitrogen required for cooldown $=2,577,616/400\ =\ 6,444 g_{(LN_2)}/m_{(shield)}$

   For a flow rate of 20 g/s, the cooldown time of 1 km (single string) = 6,444 × 1000/20 = 89.5 h = 3 days and 18 hours.

   For a nominal section 1080 m long the total amount of LN_2 is 6,560 kg and the cooldown time is 96.7 h (≈4 days).

2. To fill up the lines an additional amount of 2220 kg is required.

3. The heat load during cooldown increases gradually from 0 to a value higher than the heat load for normal operation (the cold mass is warm).

The additional flow rate needed during cooldown to absorb this heat load will be 0.0 growing to 16 g/s as long as the end of the string is warm and the nitrogen is warmed to 300 K. The last stages of cooldown will require an increase in the flow since the nitrogen is output at a lower temperature.

After the cooldown process is finished, 32 g/s is required to absorb the heat load because at that point the nitrogen output temperature is 85 K, not 300 K.

A cross section of the 84-K shield is shown in Figure C.1. Cooldown timing and flow rate characteristics are shown in Figures C.2 and C.3.

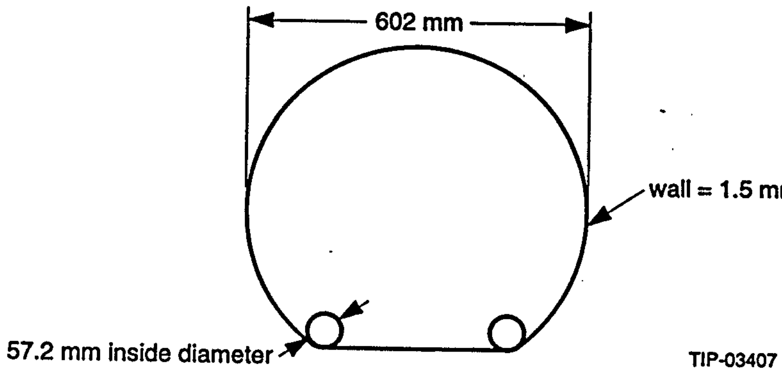

Figure C.1. Cross Section of the 84-K Shield.

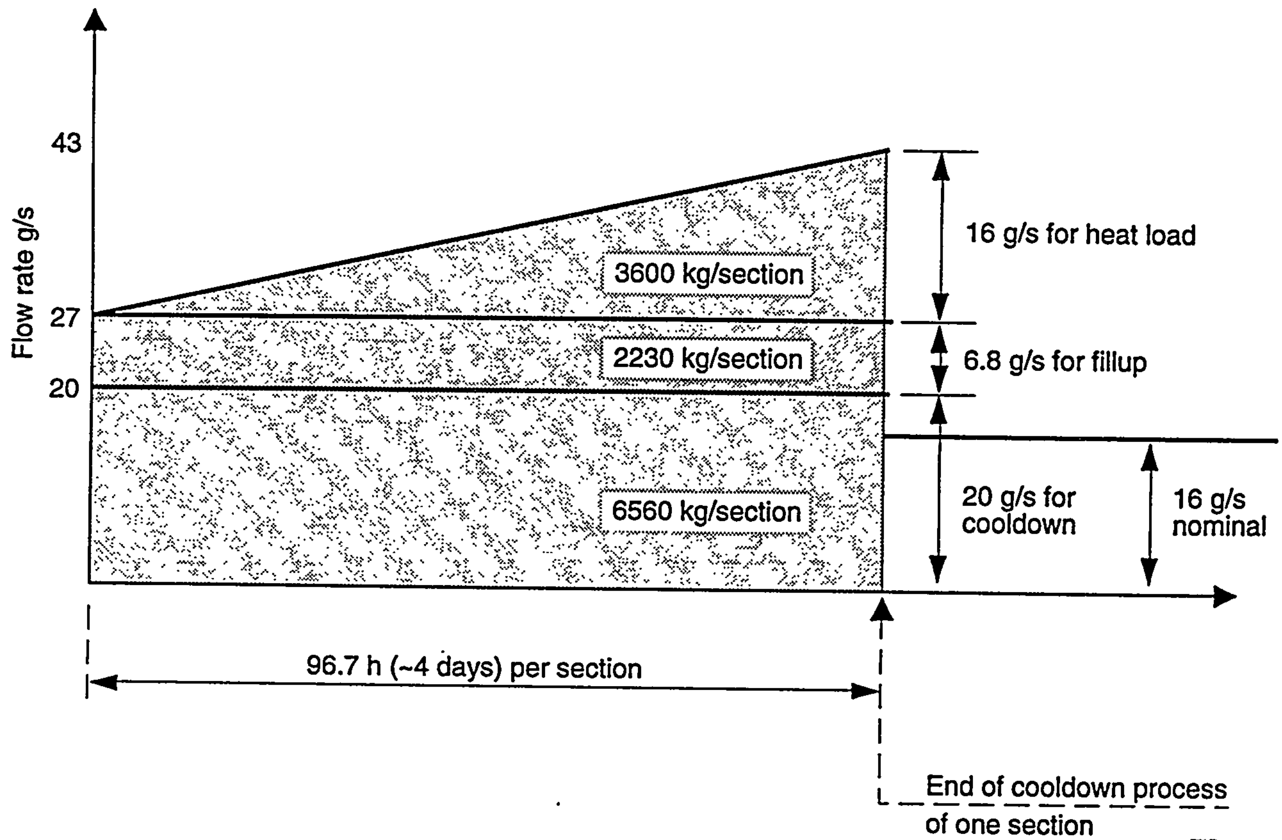

Figure C.2. Shield Cooldown: Constant Cooldown Wave Process (96.7 h, 12,390 kg LN_2).

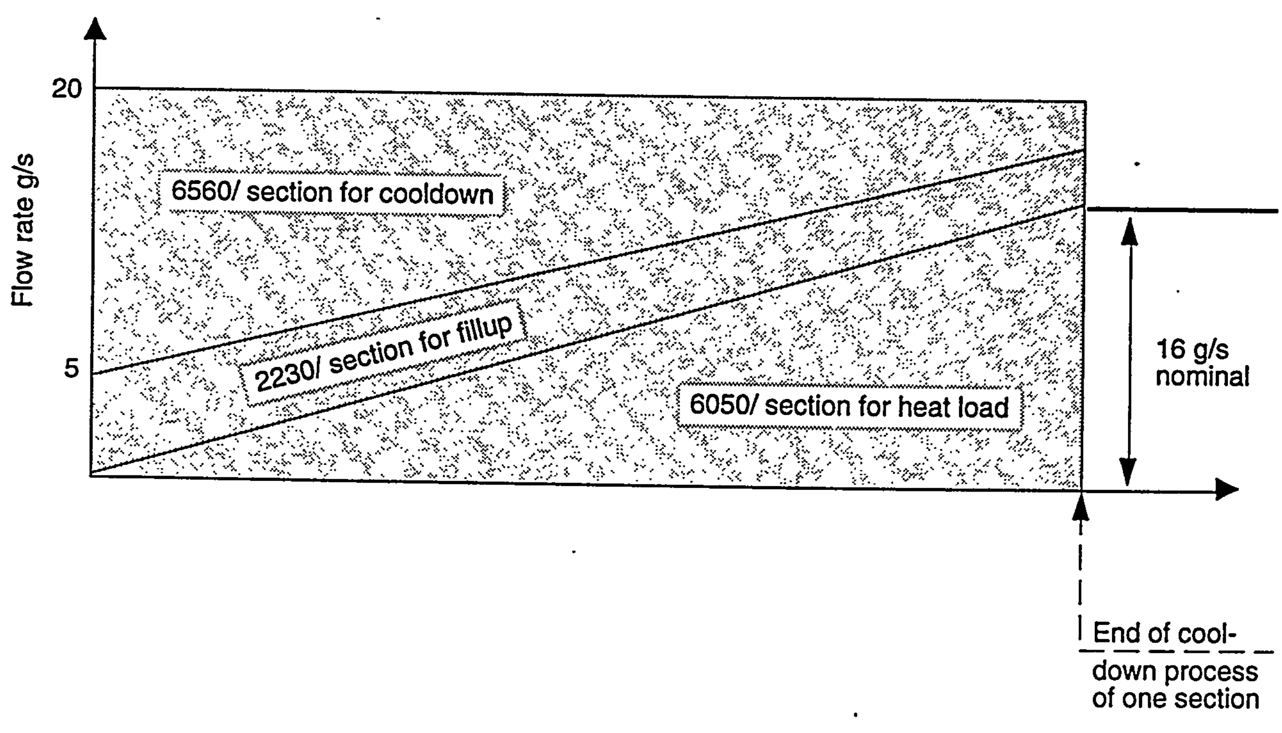

Figure C.3. Shield Cooldown: Constant Flow Process (210 h).