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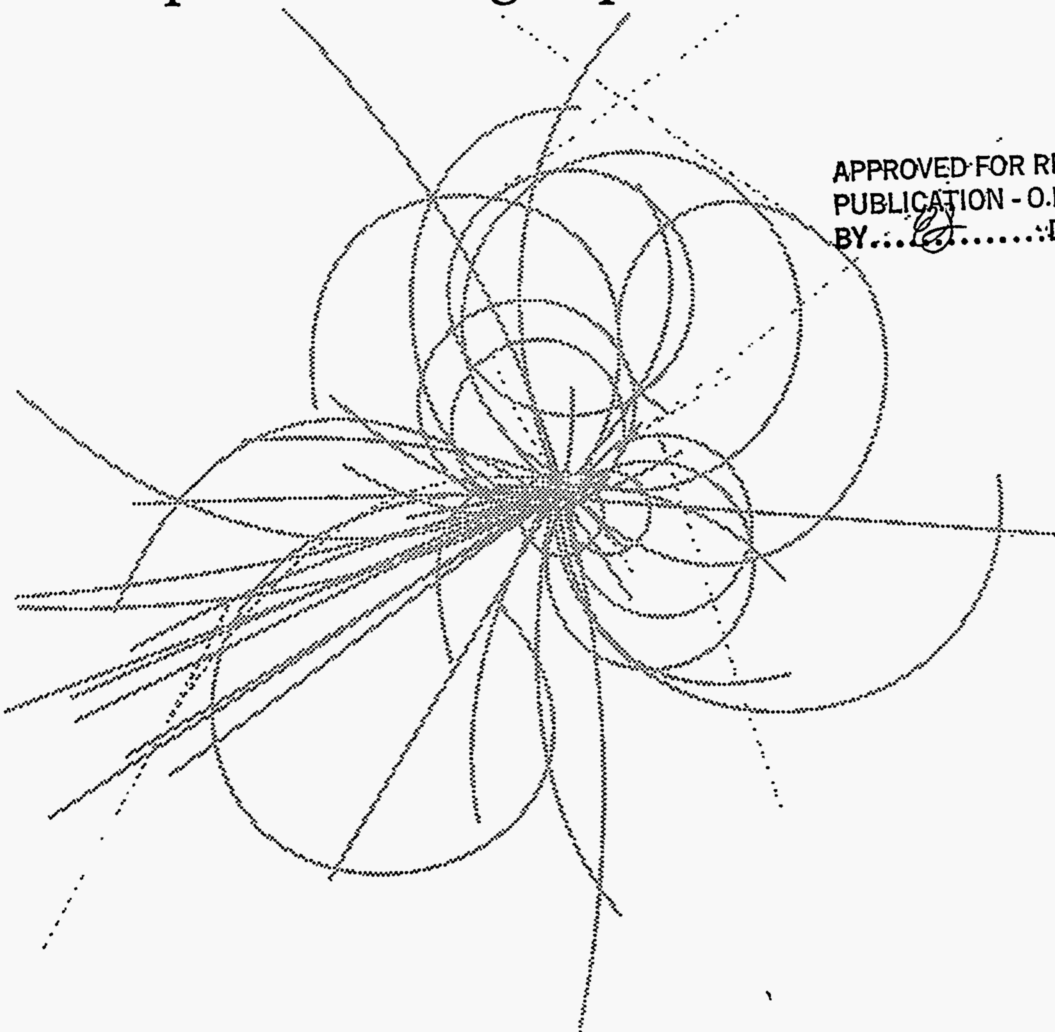

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REFRIGERATION PLANTS FOR THE SSCL

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Abstract: The basic requirements and operating features of the collider cryogenic system have already been described in other publications.[1,2,3] The general arrangement of the refrigeration plant and its subsystems is presented, and the issue of how to provide redundancy in the cryogenic system is addressed, and some of the basic features of the refrigeration plants are described. The collider cryogenic system design is not final yet, and this report only reflects the direction and current status of the cryogenic system design.

INTRODUCTION

The high on-line operating time requirements of the collider system demands an availability of at least 98% on the SSCL cryogenic refrigeration system.[1] To meet this requirement, some redundancy has to be built into the system. There are many different ways to design redundancy into the SSCL cryogenic refrigeration system. To select the configuration that meets redundancy and operational characteristics requires the consideration of many issues: performance flexibility (load adjustment), high system availability, capability to provide and control single phase flow, inventory management, quench handling, contamination, sector cooldown and warm-up, and capability of upgrading to higher refrigeration capacity or lower temperature operation (3 K). Redundancy is provided by designing plants with larger capacities and shifting load from neighboring plants during emergencies. Design pipe sizes for the cryogenic flows in the cryostat make it difficult to shift 4 K refrigeration and 20 K refrigeration to neighboring plants. In contrast, shifting 4 K liquefaction load can be accomplished relatively easily. The goal is to have a cost-effective design that meets the collider operational and redundancy requirements.

BASIC FEATURES OF THE HELIUM REFRIGERATION PLANT

Ten helium refrigeration plants 8.6 km apart are located around the ring. Each plant has to provide cooling for the magnet system, which requires 4 K refrigeration, lead cooling, and 20 K shield cooling. The overall plant arrangement and its subsystems configurations

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play an important role in meeting the operational requirements of the collider helium refrigeration system. Development of the plant arrangement is an important activity at the present time.

The interconnections of the major subsystems of the typical refrigeration system at a site are shown in Figure 1. Redundancy and other requirements will determine the final configuration and interconnections in the plant, and only the major operating points, essential features, and components of the plant are indicated on this figure. The coldboxes operate on a common compressor system with the appropriate interconnecting lines for the 4 K and 20 K loop (13,14,15,16). There is capacity to store 18700 standard m^3 (660,000 SCF) of helium gas inventory in ten tanks and 228 m^3 (60,000 gallons) of liquid helium inventory in two dewars at each site. This will be used for inventory management, emergency situations, and cooldown. A 76 m^3 (20,000 gallons) liquid nitrogen storage dewar, to provide emergency cooling for the shields and refrigerator and enough inventory to keep the collider system cool during shutdown periods of the refrigeration plants, is also necessary. The refrigerator coldboxes are located at ground level for ease of installation and maintenance.

One or more coldboxes in the tunnel house a subcooler with circulating pumps supplying the conditioned 4 K, 4 bar helium to the magnets, a cold compressor, and a heat exchanger in the 20 K loop that will be used during quench conditions to manage refrigeration. Another coldbox circulates and recools the nitrogen flow for the 80 K shield. Nitrogen vapor (12) from this recooler is used for precooling in the helium refrigerator. Liquid helium (1) subcooled to 4 K and subcooled liquid nitrogen (6) supplied from their respective coldboxes go to the valve box where the flows are divided up, supplying the four strings with cooling. Liquid helium is returned to the subcooler via a separate line (2). The saturated vapor from the recoolers is also returned in another line (3) to the subcooler, where the cold compressor maintains the appropriate saturation pressure, depending on the required operating temperature of the magnets. Flow exiting the cold compressor (9) is returned to the refrigerator. The warmest magnet is allowed to operate at 4.35 K, which in turn requires the warmest recooler to be at 4.1 K, and pressure drop in the vapor return line requires an even lower (vapor) pressure (approximately 0.8 bar) at the return to the subcooler. A cold compressor is chosen as part of the system, since this allows the collider system to be operated at the design operating temperature and provide the capability to upgrade to low-temperature operation, while simultaneously providing the head pressure and allowing the coldbox the flexibility to operate at above atmospheric pressure. A vacuum-jacketed transfer line containing the low-temperature lines connects the refrigerator to coldboxes in the tunnel. Helium from the power lead cooling is returned through a warm gas header that runs through the collider ring and is fed back to the refrigerator through a separate line (11). Cooling to the 20 K shield is provided by a separate supply and return line (4 and 5) to the valve box in the tunnel. Quench handling is also done through the 20 K system. In order to supply liquid (10) from the dewars at the desired pressure, a make-up pump is required between the dewars and the subcooler. Table 1 lists the nominal sector loads of the collider cryogenic system. Table 2 lists the basic operating points for a refrigeration plant.

REDUNDANCY IN THE SSCL CRYOGENIC SYSTEM

The high operating on-line time requirements of the collider system demand an availability of at least 98% on the SSCL cryogenic refrigeration system. To meet these requirements, redundancy has to be built into the system. There are many different ways to design redundancy into the SSCL cryogenic refrigeration system. To select a configuration that best meets the operating and redundancy requirements, several major issues should be considered: performance flexibility (load adjustment); high system availability; capability to

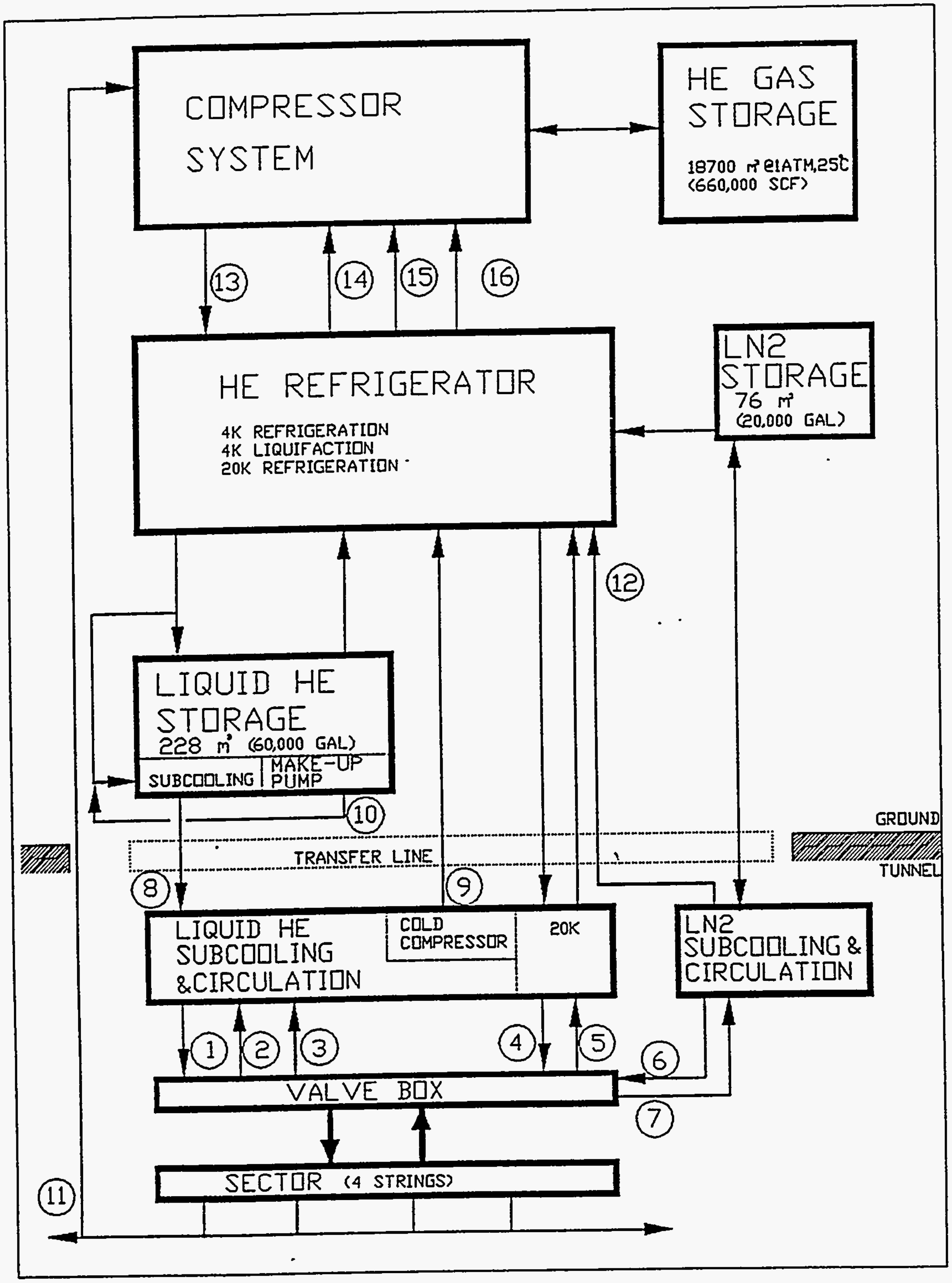


FIGURE 1. BASIC CONFIGURATION FOR THE SSC REFRIGERATION PLANT

provide and control single phase super critical helium flow; inventory management; quench handling; contamination; sector cooldown and warm-up; and capability of upgrading to higher refrigeration capacity or lower temperature operation (3 K).

Table 1
Nominal Sector Loads of the SSC Cryogenic System

	T (supply) (K)	P (supply) (atm)	T (return) (K)	P (return) (atm)	Nominal Load
4 K Refrigeration	4.1	4.0	4.0	0.8	5200 W
4 K Liquefaction	4.1	4.0	303.0	1.1	28 g/s
20 K Refrigeration	16.0	3.0	25.0	2.0	9600 W
80 K Refrigeration	80.0	6.0	90.0	4.6	42,500 W

Table 2
Basic Operating Points for a Refrigeration Plant

Description	T (K)	P (Atm)
1. Liquid helium supply	4.1	4.0
2. Liquid helium return	4.3	3.5
3. Helium vapor return	4.0	0.8
4. 20 K shield supply	16.5	3.0
5. 20 K shield return	25.0	2.0
6. LN shield supply	80.0	6.0
7. LN shield return	90.0	4.6
8. LHe supply from refrig.	4.5	4.0
9. Cold compressor return	5.3	1.2
10. Liquid helium makeup	4.5	4.0
11. Warm helium gas return	300.0	1.2
12. Nitrogen Gas	80.0	1.2
13. High pressure He	308.0	19.0
14. Medium pressure He	303.0	3.0
15. Low pressure He	303.0	1.0
16. Low pressure He (20 K sys.)	303.0	2.0

A major issue in the redundancy scheme for the refrigerators is whether or not to retain 4 K refrigeration capability at a site when a failure occurs in the refrigeration system. The maximum distance that 4 K refrigeration can be transported is limited by the pipe size of the 4 K vapor return line in the magnets. To avoid possible problems in maintaining the desired magnet temperature, it is preferable to transport 4 K refrigeration only over the normal operating length of one string (4.3 km). 4 K liquefaction load can be transported over greater distances by moving liquid from one sector to the other. There is only one line for the 20 K refrigeration in the cryostat: the 20 K loop runs through one string and back to the refrigerator through the string in the other ring. The normal flow length of the 20 K loop is therefore 8.6 km. If no local redundancy is provided for the 20 K refrigeration, in failure mode it will be required to design the 20 K loop with flexibility for higher pressure drop and temperature rise to allow the 20 K flow to travel a distance equivalent to a sector and back (17.2 km). A 20 K shield operating at a higher temperature means that the 4 K load will also increase. Concern about this and the large range of operating conditions that the 20 K loop will impose on the operating plant makes it preferable to have local redundancy for the 20 K load. Hence, local redundancy for 4 K and 20 K refrigeration with inter-sector redundancy for 4 K liquid load is a preferred redundancy scheme. This capability can be accomplished through different plant configurations and backup of individual components in the plant.

With local backup of 4 K and 20 K refrigeration as a choice and 4 K liquefaction to be tapped from the neighboring plants, the issue is how to provide the local redundancy necessary to meet collider availability requirements. One way of accomplishing this is to operate the refrigerator unbalanced -- that is, with the low pressure return flows of the 20 K and 4 K at their normal rates and the high pressure supply at a reduced rate. The excess inventory, after being compressed, is returned to the warm helium return header; from there the neighboring plants make up the extra flow that they are providing to the failed sector. Hence, the sector that has a failed coldbox (in the case of a two coldbox configuration) or has lost capacity (in the case of a single coldbox configuration) will still handle the 4 K and 20 K refrigeration and the neighboring plants will provide the additional liquid to makeup for the reduced capacity. The excess inventory at the failed sector is returned through the warm helium return header to the neighboring plants.

SSCL REFRIGERATION PLANT CONFIGURATIONS

As described earlier, there are many issues to consider in the design of the SSCL refrigeration system. One of the major issues is how to design redundancy into the cryogenic system. A previous plant design concept consists of three different coldboxes,[3] which gives greater flexibility in the control of the collider cryogenic system but faces the same redundancy issues, and it may not be cost effective. Plants with fewer coldboxes should be examined in order to design to cost.

In the study by Powell and Quack,[4] various coldbox schemes were examined with regard to cost, availability, and redundancy. One of the solutions provided in their study was a plant with two coldboxes, each providing 67% capacity of the nominal sector 4 K load. However, the 20 K refrigeration load was not considered in any detail. The 67% 4 K coldboxes would meet the redundancy requirements, but the 20 K coldbox must be sized for 150% if no local backup is present for the 20 K load, and refrigeration has to be provided by the neighboring plants.

A separate 4 K and 20 K configuration requires three coldboxes at each site. To provide local redundancy for the 20 K refrigeration, it will be more cost effective and efficient to have an integrated design. With the two coldbox concept the most advantageous configuration would be the one consisting of identical coldboxes. Here the load is evenly split during normal operation, and during failure mode the operating coldbox provides the sector with the 4 K and 20 K refrigeration. For a single coldbox configuration, redundancy is provided by designing the system so that the redundancy requirements are met by backing up the various individual components. In either case the operating coldbox at the site of the failure will run in unbalanced mode.

A helpful tool in studying the redundancy scheme and in approximating the size of the plants is to examine the Carnot work requirements of the system. This will help to examine how the loads can be readjusted in the remaining integrated 20 K / 4 K coldbox. Although it is not possible to exactly interchange the loads (4 K refrigeration, 4 K liquefaction,and 20 K refrigeration) for a given Carnot work, it can be used as a first approximation for sizing the coldboxes and compressor system, recognizing that it will be harder to match fixed-nozzle expanders to follow the different modes of operation.

The SSCL refrigeration system is required to deliver 4 K refrigeration at 4 bar pressure with the vapor returned at 0.8 bar. The proper Carnot work requirements should be calculated from these supply and return conditions. By this method, the losses due to J-T expansion in the collider ring recoolers are essentially being considered as part of the load. Table 3 summarizes the supply-and-return design points of the refrigerator for each load.

Table 3
Refrigerator Supply-and-Return Design Points

	T (supply) (K)	P (supply) (atm)	T (return) (K)	P (return) (atm)	Sector Load	Min. Sector Refrigerator Capacity
4 K Refrig.	4.05	4.0 (Liq.)	4.0	0.80 (vap)	5200 W	6500 W
4 K Liquefact..	4.05	4.0 (Liq.)	303.0	1.05 (gas)	28 g/s	35 g/s
20 K Refrigeration	16.50	3.0	24.5	2.00	9600 W	14400 W

The plant sizing can be better understood by studying the Carnot work requirements for the following operational modes:

1. Nominal Load
2. Peak Load (For adjacent plants providing assistance to the failed plant)
3. Failed Plant (4 K and 20 K refrigeration load by the remaining coldbox)

The sector loads and refrigerator design capacities are tabulated below. The 150% of the 20 K load was initially specified as the margin to provide adequate cooldown capacity and for redundancy. If the loads are integrated into the same coldbox, the margin on the 20 K load also needs to be revisited.

Table 4
Nominal Load and Sector Carnot Work Requirements

	Sector		Refrigerator	
	Load	Carnot Work (kW)	Capacity	Carnot Work(kW)
4 K Refrigeration:	5200 W	442	6500 W	552
4 K Liquefaction:	28 g/s	196	35 g/s	245
20 K Refrigeration:	9600 W	215	4400 W	324
	Total	853		1121

During failure mode (plant loses half its capacity) the extra Carnot work requirements for the neighboring plants is determined by the peak capacity of the plant. The missing capacity (half plant) in the failed sector has to be made up from neighboring plants. For a 133% plant the Carnot work requirements are:

If the remaining coldbox provides 576 kW of Carnot work capacity, the balance (657-576 = 81 kW) would theoretically require a 12 g/s unbalance operation (excess mass flow return) to meet the local redundancy requirements of the plant. Two identical coldboxes -- each with a 67% capacity of the total sector 4 K refrigeration, liquefaction, and 20 K load, would provide a total of 1152 kW of Carnot work (Table 7). If each coldbox is sized for 600 kW of Carnot work, it should be capable of providing 100% of the 4 K and 20K refrigeration

Table 5
Peak Load Carnot Work for 133% plant

	Load	Carnot Work(kW)
4 K Refrigeration:	7000 W	595
4 K Liquefaction:	38 g/s	266
20 K Refrigeration:	13000 W	292
	Total	1152

The operating part of the failed plant shall provide the 4 K and 20 K refrigeration for that sector, as follows:

Table 6
4 K and 20 K Refrigeration Mode Carnot Work

	Load	Carnot Work (kW)
4 K Refrigeration:	5200 W	442
4 K Liquefaction:	0 g/s	0
20 K Refrigeration:	9600 W	215
	Total	657

sector load with some unbalance flow when operating in failure mode. The Carnot work requirements of the neighboring plants providing the additional 4 K liquefaction load are easily met since they are sized for 133%. Sizing the plant with this method is only approximate, and final design capacity depends on the plant's operational characteristics and requirements.

Table 7
67% 4 K load Coldbox Carnot Work

	Each coldbox	Carnot Work (kW) Each Coldbox	Carnot Work (kW) Sector Total
4 K Refrigeration:	3500 W	298	595
4 K Liquefaction:	19 g/s	133	266
20 K Refrigeration:	6500 W	145	291
	Total	576	1152

ADDITIONAL FEATURES

Changes were made to the original design concept during the study of the two-coldbox configuration that would allow the system to remain simple but still incorporate the features necessary for collider operations. Some of the changes and additional features incorporated into the system are listed below.

Compressor system. The low and medium pressure flows of the 4 K load from both coldboxes return to a common compressor system, which has its own backup compressors. The use of a common system with the appropriate interconnections allows for greater flexibility and more efficient use of the operating and backup compressors. The coldbox has a separate compressor suction return line for the 20 K system. This makes the 20 K system more flexible by allowing the suction pressure to vary somewhat to follow the 20 K load requirements. This in turn will accommodate the transient operating modes, in particular quenches, and minimize the disturbance to the 4 K refrigeration.

Refrigeration supply. It will be advantageous to supply the make-up helium to the subcooler at 4 bar and 4.5 K directly from the refrigerator and to use the make-up pump only as a backup.

Liquid dewar pressure. The dewar pressure will be allowed to increase to 2 bar, without affecting the refrigerator operation, thus increasing the flexibility for quench handling and inventory management.

Use of quench return line. The quench return line to the dewar can be used for the following applications:

1. Liquid helium inventory can be transported back to the dewar if the pressure in the 4 K, 4 bar loop exceeds maximum operating conditions due to quenches.
2. Will also serve as pump by-pass for both make-up and circulating pumps.
3. During cooldown from 20 K to 4 K and during the ring filling sequence, large quantities of make-up helium will be required. The quench return line can be used to transport liquid helium from the dewar to the magnets. Since the magnet string will be at 1 bar nominal pressure, the liquid helium can be transported from the dewar and the return vapor can be recovered by the refrigerator.

SELECTION OF PLANT CONFIGURATION

With two coldboxes and the 20 K system integrated into both coldboxes it is possible to design a system that meets the redundancy requirements of the collider. The single coldbox may be a cost-effective option if redundancy requirements can be satisfied with the proper design configuration. Further study needs to be done to explore the single coldbox option. Selection of the final configuration also requires further examination of other issues such as cooldown/warm-up, contamination, quench and inventory handling, upgradability, load adjustment, and cost.

Process Cycle Design

A process cycle with the combined 4 K and 20 K refrigerator has been modeled and an exergy analysis has been carried out on the model to aid in optimization. Current studies indicate that nominal coldbox Carnot efficiencies of 50-55% are achievable with a 4-turbine configuration using liquid nitrogen pre-cooling, assuming the load is located at ground level. Since tunnel depth varies from site to site, ground level was used as the baseline design depth. With compressors of 55% isothermal efficiency, an overall plant efficiency of 25-30% could be achieved. A more detailed explanation will follow on how the coldbox and plant efficiency are defined here. Figure 2 gives a flow diagram of a refrigeration plant. It should be emphasized that a coldbox design was used here for illustrative purposes and to obtain performance and capacity results. The process cycle configuration could be different and will be left open for design by the manufacturer of the refrigerator. In addition, the cycle design needs to be further examined and modified to handle the upgrade to 3 K refrigeration. For operation at 3 K, a case study is made with the assumption that approximately the same amount of Carnot work is required as that of the 4 K load. The nominal 3 K refrigeration load is therefore approximately 3400 W. This is accomplished by intercepting the synchrotron radiation with a special 20 K liner in the beam tube, and results in an increase of the 20 K load. Table 8 lists the case study loads for the 3 K operation of the collider ring.

Table 8
Load Estimates of A Collider Sector at 3 K

	Load	Carnot Work
3 K Refrigeration:	3400 W	391 kW
3 K Liquefaction:	28 g/s	202 kW
20 K Refrigeration :	11600 W	260 kW

	Total	853 kW

Definition of Coldbox and Plant Efficiency:

As described earlier, the required Carnot work is computed based on the supply and return conditions to the magnet string and not on the saturated conditions in the recoolers, where liquid is vaporized. Coldbox efficiency is defined here as the Carnot work required for the load over the total isothermal compressor work plus the Carnot work required for the nitrogen pre-cooling. The compressor work required for the nitrogen pre-cooling is based on a nitrogen plant Carnot efficiency of 35% in calculating the overall plant efficiency. Following are results from a process simulation of a coldbox design with a capacity of approximately 67% of each nominal load to illustrate the definition of the efficiencies.

Table 9
Results of Process Simulation of a 67% Nominal Load Coldbox

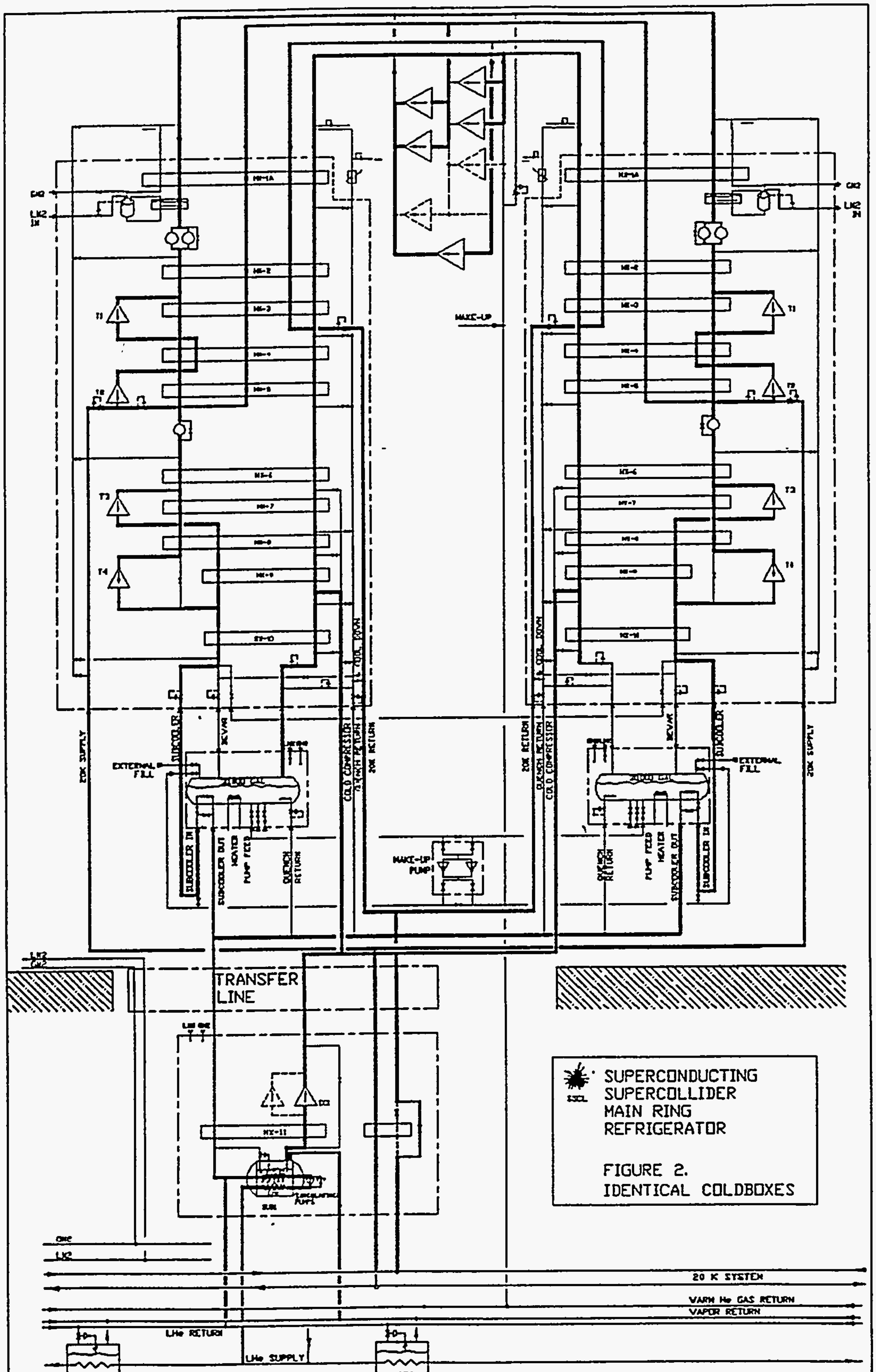
	T (supply) (K)	P (supply) (atm)	T (return) (K)	P (return) (atm)	Load	Carnot Work (kW)
4 K Refrig.	4.05	4.0	4.00	0.80	3500 W	297
4 K Liquefact.	4.05	4.0	303.0	1.05	20 g/s	141
20 K Refrig.	16.4	3.0	25.2	2.00	6500 W	127

					Total	565

	Isothermal Compressor Work *	Actual Compressor Work
First-Stage He Compressors:	212 kW	386 kW (55% isotherm. eff.)
Second-Stage He Compressors	606 kW	1102 kW (55% isotherm. eff.)
20 K System He Compressors:	211 kW	423 kW (50% isotherm. eff.)
Nitrogen Carnot Work:	65 kW**	184 kW (35% Carnot eff.)
	-------	--------
Total	1095 kW	2096 kW

Coldbox efficiency: 565/1095=51.7% (of Carnot)
Plant efficiency: 565/2096=27.0% (of Carnot)

* 100% isothermal efficiency
** Carnot work for nitrogen pre-cooling (100% Carnot efficiency)



SSCL SUPERCONDUCTING SUPERCOLLIDER MAIN RING REFRIGERATOR

FIGURE 2. IDENTICAL COLDBOXES

NOTE: THE COLDBOX (PROCESS CYCLE) DESIGN SHOWN IS USED FOR ILLUSTRATIVE PURPOSES AND PROCESS DESIGN STUDIES, AND CAN VARY DEPENDING ON MANUFACTURER'S DESIGN AND COLLIDER OPERATING REQUIREMENTS.

CONCLUSION

Since there are many different process cycles possible, the arrangement in the current model might not be as desirable as others with regard to actual components, failure mode operation, upgradability, and other transient modes, and further changes are likely when a better understanding is obtained of the related issues. Detailed process design studies need to be carried out on how to handle quenches, liquid and gas inventory, and cooldown and warm-up operations. This may require results from dynamic simulations of a sector string. Work is currently being done in this area by others and should give us a better understanding in designing the refrigeration system.

This has been an overview of the major issues of the SSCL cryogenic system. Plant configurations that incorporate the use of one and two coldboxes are being considered, as a further attempt to reduce the cost and complexities of the refrigeration plants. Current preliminary process simulation results indicate that plants with two coldboxes can be designed that are efficient and able to meet the collider's load, redundancy, and flexibility requirements. The ideas and issues presented here reflect the current status and direction of the cryogenic system design. However, further studies and modeling of the transient operating modes and upgradability of the collider cryogenic system are needed before a suitable and final design can be selected.

Procurement of Plants

The goal of the SSCL is to issue a first RFI in the fall of '91 and the first RFP during the summer of '92. Ordering of the refrigeration plants will start in '93 and will continue through to '99 with the first plant being commissioned sometime in '95. An outline of the Collider Cryogenic System Milestones follows.

Collider Cryogenic System Outline of Procurement Milestones

Issuance of First RFI	9/91
Remarks from Vendors	12/91
Issuance of First RFP	6/92
Issuance of Last RFP	3/93
E2 Refrigeration Plant Complete Commissioning	9/95

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