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Planning the SSC Cryogenic System for Future Expansion

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INTRODUCTION

There are two primary connections between the basic parameters of the SSC collider and the cryogenic system requirements. The first of these operates through the dominance of synchrotron radiation heating in the overall heat load budgets of the cryogenic system. The synchrotron radiation heating is dependent linearly on the beam current as the fourth power of the ring energy. The second connection is through the linear temperature dependence of the dipole magnet critical current. In a ring of magnets limited by the critical current the maximum attainable energy is dependent on the operating temperature of the cryogenic system. Thus the operating parameters of the cryogenic system are tied directly to the operation of the collider as a whole, and the design of the cryogenic system can limit in very severe ways the operation of the collider.

The conceptual design of the collider endeavors to balance cost, technological factors, and risk against the somewhat arbitrary performance requirements for the facility in a self consistent way. It is obvious that because this balance will continue to be adjusted both as the design of the collider progresses and on through its operating life, it is important to keep a degree of flexibility in planning and designing the various subsystems even at some cost. In the context of the construction of an instrument for scientific purposes, such flexibility is cost effective.

Examples of changes in the cryogenic system requirements that have been discussed and costed in an approximate and incremental way since the time of the CDR are first, an increase in current by a factor of 1.41 in order to meet the machine luminosity requirement with beam optical conditions in the interaction regions less stringent than those assumed attainable in the CDR. A second example is operation of the cryogenic system at reduced temperatures in order to give more operating margin in the magnet system or to permit the use of an increased number of shorter dipoles at higher field, and third is operation of the collider at a factor three higher current in order to provide for luminosity increased over that taken in the CDR.

Expandability has been included among the major design goals for the refrigeration plants for the SSC[1]. The cryogenic system is, however, more than just the attached refrigeration capacity and includes all of the heat transport systems of the ring. It is very desirable for the reasons outlined above to formulate and include in the design of the relevant systems an appropriate measure of adaptability, otherwise refrigeration plant flexibility is not fully useful. This can be done in the beginning often at little or no cost where changes later could not be bought for any amount of money. In the following paragraphs we suggest three areas in the design of the collider where opportunities to provide adaptability in the cryogenic system should not be missed.

HEAT TRANSPORT IN THE DIPOLE CROSS SECTION

The most important single heat load in the SSC cryogenic system is the synchrotron radiation which is absorbed in the inside of the dipole. The longitudinal helium convection in the bore tube region of the magnet is too small to play a significant role in carrying away this heating. Instead the heat must be carried to the bulk of the helium coolant which flows in four passages in the iron yoke. The first modeling of thermal conduction in the magnet cross section has just been completed[2] and shows that the thermal resistance between the bore tube region and the flow passages is larger than was heretofore estimated by more than a factor of three. This results for the nominal synchrotron radiation heat load of 0.142 W/m in a predicted temperature difference of 0.167 K. Such a large thermal resistance. if it were observed, would create significant problems in the temperature control of the superconductor for the system as a whole, it would increase capital and operating costs of the refrigeration, and it would be a very undesirable limitation to the flexibility to increase the heat loading in machine upgrade.

It has been recognized that the natural convection of the helium provides a process of heat transport within the magnet parallel to the conduction, and spaces have been provided for convective flow, often for other reasons, in some of the collar-yoke designs used in SSC prototype magnets. Estimates of the heat carrying capacity of this process suggest that it can be adequate over the full range of thermodynamic conditions of the coolant, and that the required flow paths can be accommodated without any profound effect on the basic collar designs or significant changes in costs.

What is important is to keep in the consciousness of the designers of the magnets the necessity for heat transport in the magnet cross section. We suggest that a effective way to do this is to establish a design requirement for the heat transport ΔT under the synchrotron radiation loading in both the dipole and quadrupole, and we suggest that an appropriate value to choose is 0.050 K.

Response to such a requirement should include further modeling of thermal conduction in the magnet in order to amplify and confirm the General Dynamics results. Simple modeling of the heat convection process needs to be carried out to determine what is needed in a design in order to meet the requirement. Finite element modeling could be needed at a later stage. Finally, measurements of the ΔT should be made to confirm that the magnet designs meet the requirement.

SIZING OF THE GAS RETURN PIPELINE IN THE CRYOSTAT

The total difference that is budgeted in the current cryogenic system concept between the temperature of the superconductor and that of the saturated helium in the recooler is 0.25 K. Of this 0.14 K is allowed for the temperature rise of the single phase helium stream between recoolers, 0.50 K is allowed for heat transport within the magnet, and the rest is allowed for heat transfer processes within the recooler together with non-uniformity of the heat load and unallocated margin. To these temperature gradients present in the system at the cell level must be added the equivalent temperature drop due to the pressure drops of gravitational head and flow friction in the gas return pipeline that runs the 4 km length of the magnet string to the refrigeration plant. The total of the gradients determine the temperature at which heat must be removed by the refrigerator.

The gas return line in the cryostat returns to the refrigeration plant saturated gas from the recooler heat exchangers that are distributed in the rings, one in each cell of the machine. This line is, therefore, a primary part of the 4.35 K heat transport system, and it is the component that is of greatest concern when considering the capacity limits of this system. The size of this line in the system described in the CDR is 2.709 inches i.d. (2.5 inch nominal sch 5 pipe size). A discussion of the operating conditions of the line in various of the cryogenic system operating modes is to be found in two more recent papers[3].

Because the capacity of this line enters in such a central way into the performance of the 4.35 K cryogenic system, we believe that for the purposes of flexibility the size of this line should be increased to 3.334 inch i.d. (3 inch nominal sch 5) assuming that the space in the cryostat is available and that the costs of making the change are not too great.

To quantify the things that need to be considered in understanding this situation, take first the case in which the ring is to be operated at 3.85 K maximum superconductor temperature rather than the 4.35 K that is currently planned and the heat loads are to be unchanged. This kind of an upgrade is under way at the Tevatron and can easily be imagined at the SSC and for the same reasons. Figure I shows the effect of the pressure drop in the two sizes of gas return line on the refrigerator operating temperature for three operating modes. The curves in these figures are calculated from a lumped parameter model of the magnet string with accurate helium thermodynamics included. For the 3.85 K maximum coil operating temperature, the other temperature gradients in the system result in a warmest recooler temperature of about 3.55 K. It can be seen that for the smaller line the ability to shift half of the full load of one sector to the adjacent sector requires a refrigeration plant operating temperature of 3.25 K and that shifting the load of an entire string is not possible.

Second, consider the case in which the beam related heat load is increased by a factor of 1.7. The beam related load is more than half of the total, and the increase in refrigeration and heat transport capacity that is required is a factor of 1.4. Figure II shows the effects of increased load on the pressure drops of two sizes of gas return line. In this case it can be seen that for the smaller line the ability to shift half the load requires that the refrigeration plant temperature be lowered to about 3.73 K, and again shifting the load of an entire string is not possible in any practical way.

The ability to shift load from one sector to another in order to deal with equipment failure is a basic requirement of the SSC system. The exact system configuration requirements and the detailed system management needed to accomplish these shifts are among the subjects of computer modeling that is not yet complete. It is clear, however, that practical collider operation requires that the pressure drop of the gas return line be kept to a small fraction of the base pressure and that choking conditions can not be even remotely approached. Our current judgement is that the 2.709 inch line is not oversized for operation at 4.35 K under the nominal load and is too small for use under the conditions of the two cases described above without significant loss of system capability. Thus ring operation with the smaller line at even modestly lower temperature or at modestly higher loads could not be accomplished by a relatively simple refrigeration plant capacity upgrade, but would involve much more complicated and costly system changes. This is not a desirable situation for the SSC. The 3.334 inch line, on the other hand, we believe would be satisfactory at the lower temperature or at the higher load mentioned, and its installation would provide an important measure of system expandability.

Among the changes proposed for the design B cryostat[4] are modifications in the placing of the gas and liquid return lines. It appears from the drawings that the new cold mass slide assembly is narrower than the old one allowing somewhat more space in the body of the cryostat for these lines. If this is the case, then the materials cost of making this change should be given by the ratio of the sizes applied to a basis of about $450 per dipole, the cost of the line, bellows, and hangers[5]. This is $100 per dipole. To the materials cost should be added an allowance for additional assembly and installation time. This for the system as a whole would probably be less than $50 per dipole length. The whole machine consists something like the equivalent of 10,000 dipoles, and the total cost of this increased line size can be guessed to be $1.5M. If, on the other hand, a limitation to increases in gas line size lies in the interconnect regions where clearance for the welding and cutting tools must be allowed, then additional costs for bending the line and modifying the shields must be included. Increased complexity in the interconnect region is not desirable and must be counted as a qualitative disadvantage in this case.

We suggest that the possibilities for accomodation of the larger line be investigated and the costs and difficulty estimated. There are no cryogenic system disadvantages to the change: no inventory, time constant, or control problems. The advantages in system expandability should be seriously considered and weighed against the costs and disadvantages to the magnet system. We expect that the change will be found to be cost effective for the SSC as a whole.

REFRIGERATION PLANT EXPANSION AT THE TUNNEL INTERMEDIATE ACCESS AREAS

The discussion above concerning gas return line sizing provides a context in which to consider refrigeration plant expansion strategy. Only so much extra heat exchanger area can be built into the refrigeration plants, for example, before the cost, size, and the technical disadvantages become appreciable. Options for particular cycles can be assessed by means of process simulation calculations, and determinations can be made of the amount of expansion capability that is reasonable to incorporate in a plant for the SSC. A program of such process calculations is now under way at the CDG, and studies of this kind will soon be done. It seems likely to us that plant expansions involving combinations of half a K lower operating temperature and 40% increase in heat removal capacity will be found to be within what is practical to achieve. Thus what seems to be a reasonable overcapacity to plan for the heat transport system of the ring may also be a reasonable goal for the expansion capability of the refrigeration plants.

In thinking ahead to changes in the capacity of the collider cryogenic system beyond these reasonable upgrade capabilities, changes such as a factor of three increase in the beam related loss that was mentioned above, it must be expected that the installation of significant additional refrigeration plant equipment will be required. In addition, because such changes are not within the heat transport capabilities of the system, this additional refrigeration equipment will have to be installed not in the service areas but in the intermediate access areas.

Exactly what might be needed in these areas depends, of course, on the extent of the expansion of the system requirements. For increases in the 4 K capacity alone, the most likely eventuality, no additional cryogen storage, helium gas storage, inventory handling capacity, or 20 K refrigeration capacity would be needed, and any additional increase in liquification capacity could be provided by upgrade of the plants in the service areas. What would have to be connected to the rings at the intermediate points is a 4 K cold box with one or two expanders and compressor plant. This would be somewhat like a

Tevatron satellite except that each unit would be larger and would have its own compressor.

Following out the case of a factor of 3.4 increase of the beam related loss illustrates what is involved. This change requires an increase in the ring heat removal capacity of about 2.4. This can be accomplished by using upgraded plants in the service areas and adding new plants in the access areas of the nearly the same capacity. In the attached figures Case A under these conditions describes operation with full plant failure. Figure II for the load of 2.4 relative to nominal gives a refrigerator operating temperature of 3.65 K in the failure mode and near 3.75 K for normal conditions. This latter value is determined principally by the cell level temperature gradients. Thus what is needed at the intermediate access areas is a plant capable of operation at about 3.7 K with a peak load capability of about 6500 watts. This is a large refrigerator comparable in size to a non-upgraded SSC plant or to one of the HERA plants.

If there is any expectation of an upgrade of the SSC requiring these additional installations, it is clearly a good idea to keep this in mind during the design of the intermediate access areas. These should be designed with the same provisions for cryogenic connection to the rings as are used in the service areas and with adequate land area for a compressor building, cooling water and so on. Obviously this listing should not be carried too far because a machine upgrade of this magnitude is far in the future and could take many forms when it comes. However, it would be worth while to think through now the installation of a refrigeration plant at an access area and to avoid any obvious problem with the current designs.

SUMMARY AND CONCLUSION

In the preceding paragraphs we have suggested a more or less coherent approach to cryogenic system upgrading. Many of the details of this are still vague, but as system modeling proceeds it will be possible to develop specific plans along the lines indicated for several possible upgrades. Three suggestions are offered for things that need to be done in order that upgrading in the ways discussed will be possible. These are: First, that attention be paid to providing for adequate heat transport in the cross section of the magnet. We suggest particularly that a system requirement of a total temperature gradient of 0.050 K under the 0.142 W/m synchrotron radiation heat load be established as a goal of the design. Second, we suggest that the gas return line in the cryostat be increased in size from 2.709 inch i.d. to 3.334 inch i.d. if, as we expect, this change can be accomodated within the currently proposed cryostat outer dimensions. And third, we point out that major changes in the capacity of the cryogenic system of the collider can be accomplished only by the use of the tunnel intermediate access areas for the installation of additional refrigeration plant equipment. We suggest that a simple plan for this installation be developed now before the initial construction so that unnecessary difficulties in the future will be avoided.

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[1]M. McAshan, "Refrigeration Plants for the SSC", SSC – 129 (May 1987)

[2] General Dynamics thermal modeling study of the dipole (their report No. SSC-CDG-364-SDP, undated but received about September 20).

[3] Ibid. note 1 above and P. VanderArend, "Criteria for the SSC Helium Refrigerator", SSC – 124 (March 1987)

[4]Unnumbered Fermilab document titled "Proposal [for the] Design B SSC Dipole Magnet Cryostat" September 1987

[5]The relevant WBS items are: .1.2.1.2.3.1.1 (Helium Pipes and Supports) and .1.2.1.2.5.1.7 (Helium Gas Return Bellows) plus some minor components and welding supplies

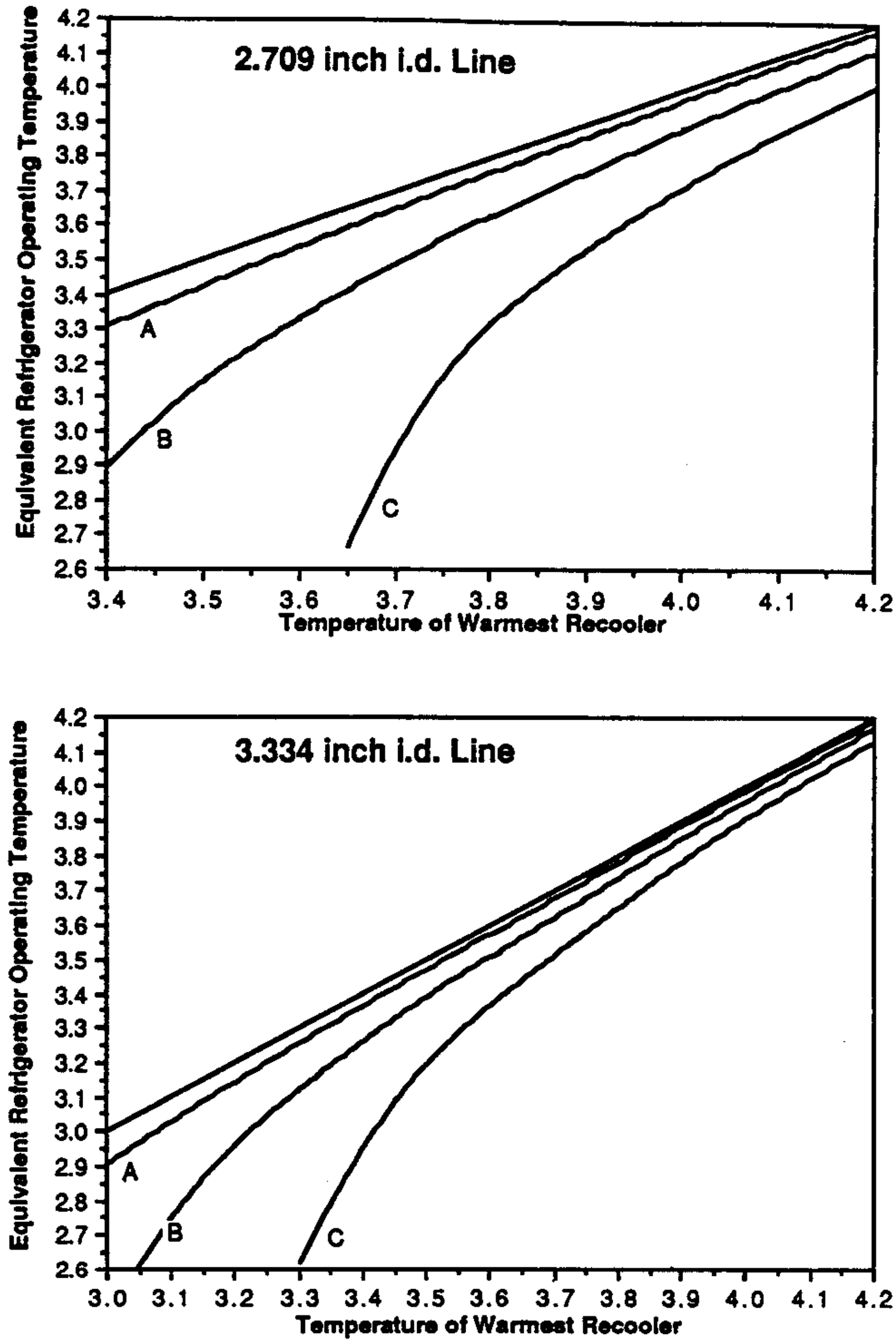
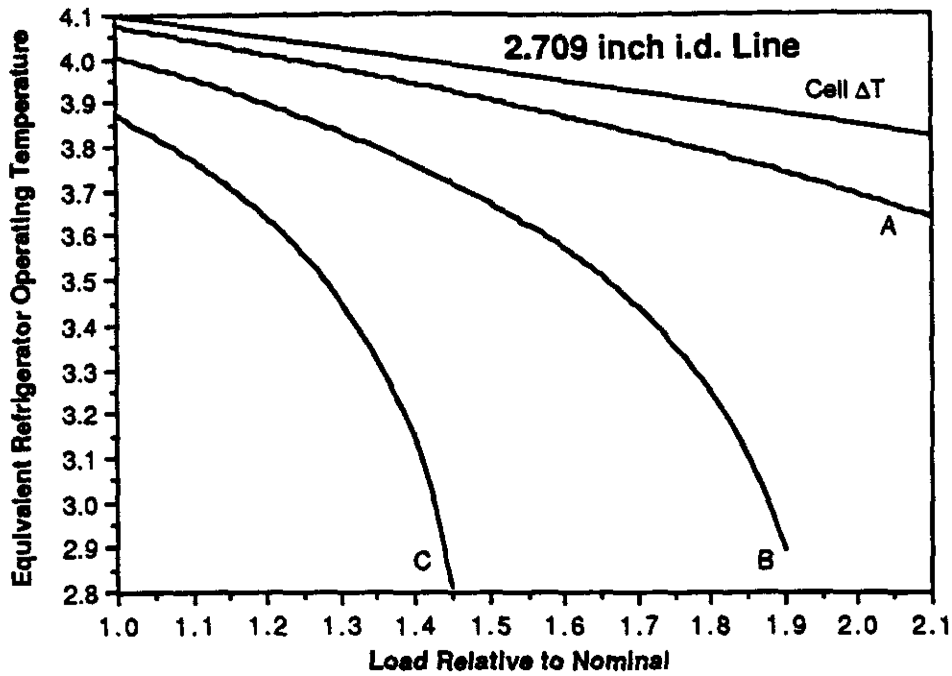


Figure I Comparison of the pressure drops in two sizes of cryostat return line as a function of line operating temperature. The mass flow in each case is 50 g/s per 18 cell string, and the pressures are expressed as the equivalent saturated temperatures. Case A is that of the normal operating condition of a line 18 cells long. Case B is a failure mode in which the line is lengthened to 27 cells to intercept one half of the load in the adjacent sector. In Case C the line is 36 cells long representing the case of full refrigeration plant failure.



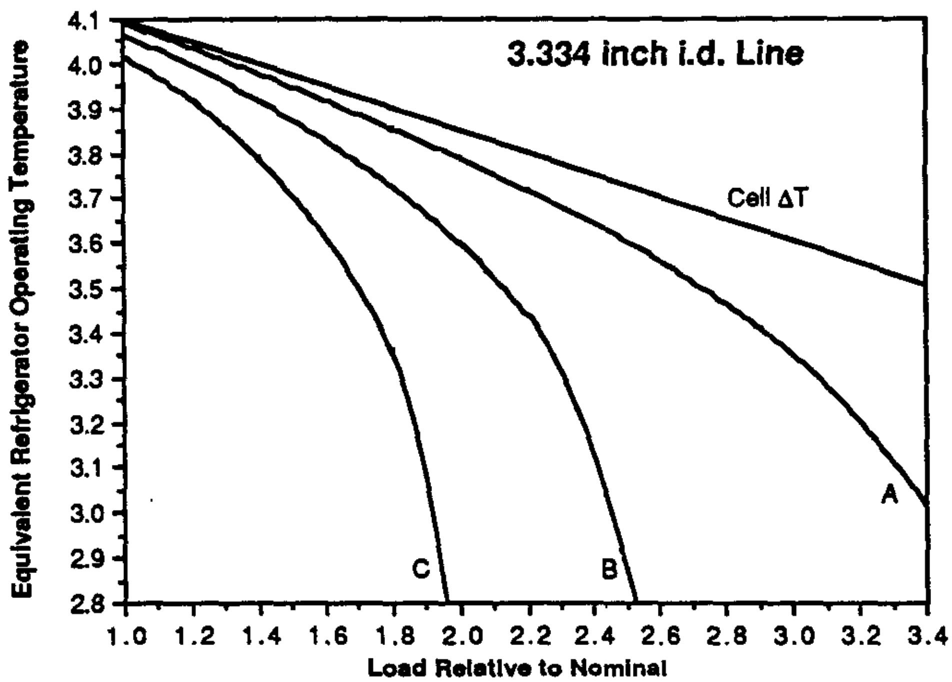


Figure II Comparison of the pressure drops of two sizes of cryostat return line as a function of line mass flow. The mass flow in each case is given in units of the nominal value of 50 g/s per 18 cell string, and the pressures are expressed as the equivalent saturated temperatures. Cases A, B, and C describe the same three operating conditions considered in Figure I. The line "Cell ΔT" models other heat transport temperature gradients in the magnet, recooler, and so on. This is taken as 0.25 K for the nominal load.