

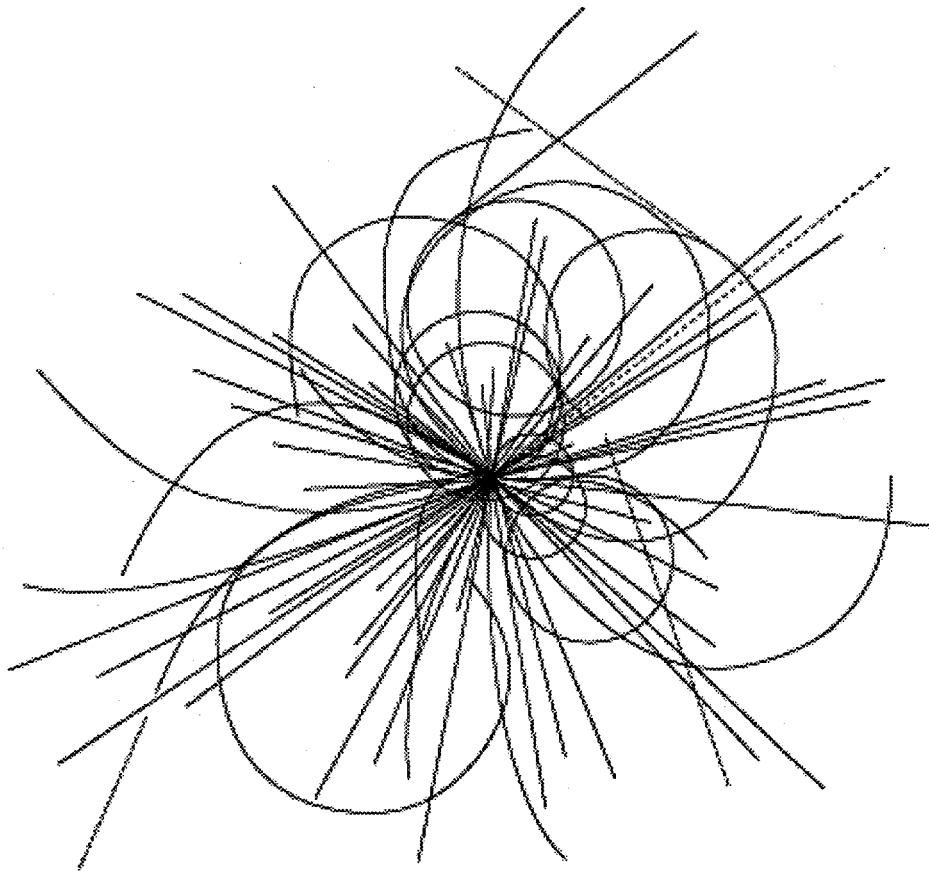
CONF-930537--118

SSCL-Preprint-212

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April 1993
Distribution Category: 414

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BY..... DATE 4/3/95

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of the SSC Magnet Cryostats***

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April 1993

*Presented at the Fifth Annual International Symposium on the Super Collider, May 6-8, 1993, San Francisco, CA.

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

THERMAL AND FLOW CONSIDERATIONS FOR THE 80 K SHIELD OF THE SSC MAGNET CRYOSTATS.

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INTRODUCTION

The nominal temperatures in the SSC cryostat range between 4.2 K in the superconducting magnet and 300 K on the cryostat outer wall. To minimize the 4 K heat load, a thermal shield cooled by liquid and vapor nitrogen flows at 84 K and one at 20 K cooled by helium flow are incorporated in the cryostat¹. Tubes attached to the shields serve as conduits for cryogens. The liquid nitrogen tube in the cryostat is used for cryostat refrigeration and also for liquid distribution around the SSC rings²⁻⁴. The second nitrogen line is used to return the vapor to the helium refrigerators for further processing. The nominal GN2 flow from a 4.3-km long cryogenic string (4 sections) to the surface is 64 g/s. The total liquid nitrogen consumption of approximately 5000 g/s will be supplied at one, two or more locations on the surface. The supply, distribution, circulation and recooling schemes for the LN2 system are described in detail by McAslan et al.³

The total heat load of the 80 K shield is estimated as 3.2 W/m. About 50% is composed of infrared radiation and remaining 50% by heat conduction through supports, vacuum barriers and other thermal connections between the shield and the 300 K outer wall. The required LN2 flow rate depends on the distribution and circulation schemes. The LN2 temperature will in turn vary depending on the flow rate and on the recooling methods used. For example, with a massflow of 400 g/s of LN2 the temperature rises from 82 K to 86 K between two compact recoolers 1 km apart. This temperature is higher than desired. The temperature can be reduced by increasing the flow rate of the liquid or by using the continuous recooling.

This paper discusses some thermal problems caused by certain mechanical designs of the 80 K shield and the possible improvement by using continuous recooling. In the following, we present results of the 80 K shield temperature distribution analysis, the 20 K shield heat load augmentation resulting from the increased 80 K shield temperatures, the continuous nitrogen recooling scheme and some flow timing related analysis.

THE SYSTEM GEOMETRY AND OPERATION

The two parallel rings of the collider and the HEB ring are constructed in parallel tunnels at an inclination of 0.2 degrees with a local minimum of 0 degrees. The superconductive magnets strings are divided into sections ranging in length from 350 m to 1350 m with U-tube connections in-between. This arrangement allows for connecting compact nitrogen recoolers which is the basic LN2 recooling system. Vapor generated in the recoolers is returned through the GN2 line in the cryostat back to the helium refrigerator for precooling.

A possible alternative to nitrogen recooling uses controlled injection of LN2 into the GN2 lines. The controlled LN2 valve may be installed in the cryogenic isolation boxes (SPRI) on the uphill side of each section. The liquid flows downhill and by boiling it performs an additional recooling function. In sections of the tunnel where the inclination is too small this method can not be implemented and denser compact recoolers have to be used. The inlet GN2 pressure to the helium plant (on the surface) is 0.13 MPa. The lowest pressure in the GN2 line in the tunnel (in the sector Feed Box) is expected to be 0.14 MPa. In this place the ideal recooling temperature is 80.2 K. Due to the vapor flow pressure drop in the GN2 tube, the pressure in the SPRE End Box (4.3 km upstream) is 0.17 MPa with ideal recooling temperature 82 K. If the string is longer than nominal, the pressures and the recooling temperatures will be higher.

Due to the temperature approach in the LN2 recoolers, the thermal resistance between the nitrogen fluids and the walls of the tubes, the resistance of the straps connecting the tube to the shield and thermal resistance of the shield, the temperature distribution in the shield will range between 84 K and 98 K. This may cause a major increase of the 20 K heat loads compared with a baseline computed using an average shield temperature of 84 K .

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

STEADY STATE CONDITIONS FOR NOMINAL STRINGS

Figure 1 shows a sketch of the thermal shield design and the temperature changes in the LN2 line for a flow rate of 400 g/s and a recooling system based on compact coolers located at different intervals. For ideal recooling (the reclaimer output temperature lies on line a-i), the highest LN2 temperature is 85 K for a reclaimer every 1 km (point h₁), 88.2 K if the coolers are 2 km apart (point h₂), and 95 K if the coolers are 4 km apart (point h₃). In well-designed practical coolers a temperature approach 2 K may be expected. The 80 K shield temperature distributions and the corresponding 20 K heat load augmentation were calculated⁵ for various LN2 recooling temperatures between 80 K and 92 K. The vapor line temperature was fixed at 80 K. The following cases were analyzed: Case 1 where the heat is removed by both the liquid and vapor LN2 lines (with liquid injection), for conservative parameters of heat transfer. These include the effects of the relative low conductivity of the stainless steel but also due to the discontinuous or discrete nature of the connections between the shields and the pipes. Case 2 similar to Case 1 but with good thermal conductance between the straps and the nitrogen, neglecting the resistance of the pipe. Case 3 assumes the heat load is removed by the liquid nitrogen line only. Representative temperature distributions for half of a shield section between two posts are presented in Figure 2. The shield emissive power (normalized to 84 K) variations for each of these cases are shown in Figure 3. The amounts of heat removed by the vapor and liquid lines are given in Figure 4. For Case 2, the liquid temperature increases asymptotically to a steady state point if the initial liquid temperature is low, and decreases asymptotically to the same point if the initial liquid temperature is high.

Shield top bottom
thickness 1.6 mm 3.5mm
circumference 1217mm 646mm
Material Al 6061-T6

Tube: stainless steel 58mmID 1.5mm thick

Straps: cross section 106.4 mm² ETP Copper
length 182.5 mm
30 straps per line

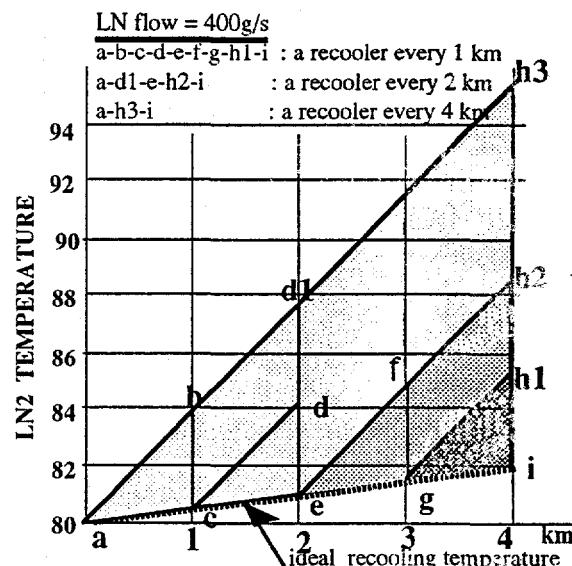
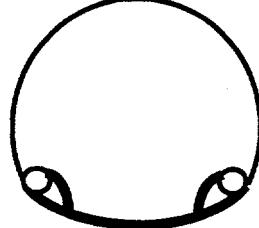


Figure 1: 80 K Shield and the Temperature Change in the Liquid Line

V: 80 K, 1.92 W; L: 84 K, 1.47 W; EmisPwr = 1.20
Hv = 0.1, Hi = 0.2 W/cm²·K

L only: 84 K, 3.39 W; EmisPwr = 1.45
Hi = 0.2 W/cm²·K

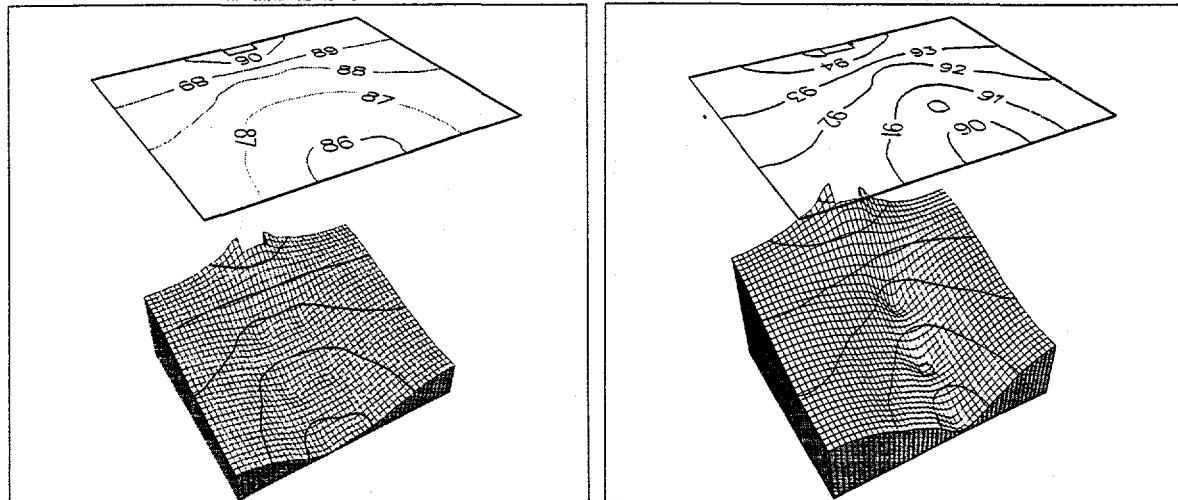


Figure 2: Sample temperature profiles for the 80 K shield.
a) Case 1: LN2 and GN2 lines active, b) Case 3: LN2 line active only.

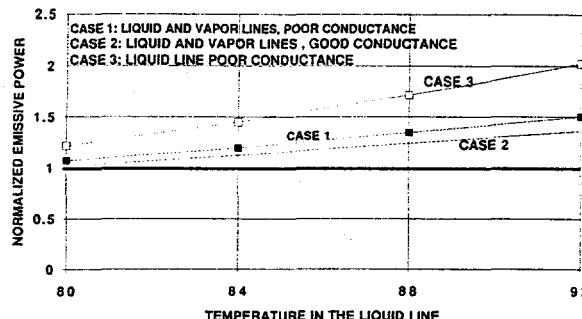


Figure 3: Emissive power as function of temperature in liquid line.

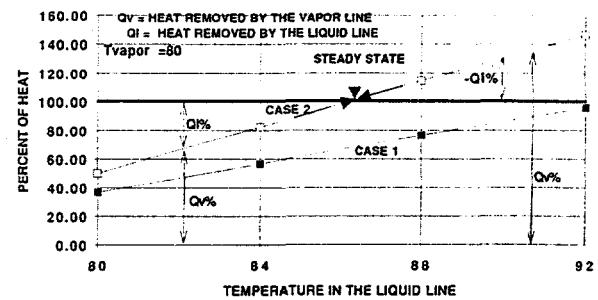


Figure 4: Percent of heat absorbed by each line.

THE CONTINUOUS RECOOLING MODEL AND THE INITIAL TRANSIENTS

Liquid nitrogen injected into the GN2 line flows downhill. The pressure in the line is maintained as low as possible due to other system constraints, to enable adequate boiling conditions in the recoiling system. Figure 5 represents a typical 1080 meter long section in the collider. The inlet vapor flow to the section is given by $Mv(0)$ and varies from 0 to 48 g/s. The vapor flow rate at the end of each section, $Mv(1)$, can be 16, 32, 48, or 64 g/s as it flows back to the feed box. The flow rate of the injected liquid at the upstream location, M_l , is nominally taken to be 16 g/s. Also shown in Figure 5 is a typical control volume used for analysis purposes with a length dx , that has $q(x)$ of nominal heat transfer and q_{wall} of transient heat transfer from cooling down of the tube wall in the full transient situation, and liquid evaporating at a rate of M_{lv} . The flow direction of liquid in the line around the collider ring may be clockwise, counterclockwise, uphill or downhill depending on the N2 delivery and distribution system in use, which may change occasionally during normal operation.

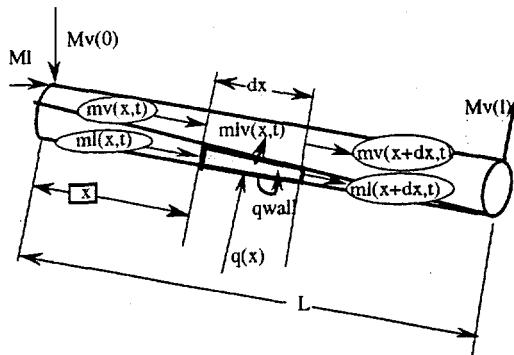


Figure 5: Flow in the vapor line

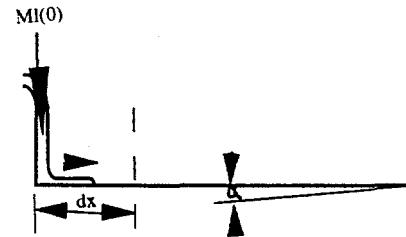


Figure 6: Flow development in the inclined plane

THE FLOW MODEL

Under ideal continuous recoiling conditions the whole heat load is absorbed by the latent heat in the vapor line. If the injection rate is smaller than ideal and sections of the tube are dry, the parallel liquid line is assumed to absorb the heat load and the vapor line remains isothermal. Also for ideal continuous recoiling liquid nitrogen there should be no collection of the liquid at the end of the nitrogen line to prevent flooding. For the analysis of the continuous recoiling scheme, it was assumed that the continuous cooler liquid flow is driven primarily by gravity, the flow of liquid was assumed to be stratified, and that the transient channel flow equations of Manning⁶ would apply for the liquid. Additional assumptions made are that the liquid-vapor interface is frictionless, there is perfect heat transfer between the liquid and the shield, and the shield has a high thermal conductance and may be considered isothermal. The mass of liquid evaporated in a control volume is taken as the 80K heat load divided by the latent heat at the line pressure.

STEADY STATE FLOW

The steady state temperatures are evaluated for different liquid injection rates. The local liquid flow cross section, mass flow rate, velocity and integral liquid inventory are calculated. In Figure 7, the steady state inventory of liquid nitrogen for the first 400 meters is shown for different injection rates. Figure 8 shows the time required for the liquid to reach a certain location for the same parameters.

TRANSIENT FLOW

Transient calculations were performed to determine the time required to reach a steady state liquid flow in the nitrogen line. The analysis and the numerical solution procedure used is described by Abramovich et al.⁷ The transient distribution of liquid nitrogen mass flow for a constant initial injection rate of 16 g/s with a tube inclination angle of 0.2 degrees is shown in Figure 9. The liquid front is seen to be very steep, and due to evaporation of the liquid along the tube, the flow linearly decreases proceeding down the tube. The predictions indicate that at these conditions it takes 16,000 seconds for the liquid flow to reach a steady state condition at this inclination angle.

One purpose of this investigation is to provide some analysis that supports the development of a control strategy for continuous injection of liquid into the nitrogen vapor line of the 80K shield. The previous cases provide some fundamental solutions that provide time scales for filling the tube at a constant mass flow rate of 16g/s, and the times for some perturbations to propagate along the liquid stream. Simulations were carried out for various step changes in the injection rates.

Another important result is for a case where the initial injection rate of 30 g/s was applied and after some period reduced to a nominal value of 16 g/s. This would be done to reduce the time required to supply liquid along the whole length of the nitrogen vapor line. Figure 10 shows results for an inclination of 0.2 degrees with an initial liquid injection rate of 30g/s which is stepped down after 2000 seconds to a mass flow of 16 g/s. It is seen in this figure that the liquid pulse travels the whole 1000 meter length without completely disappearing. For this case the tube contains liquid along its entire length after 12000 seconds which is about 4000 seconds less than the constant injection case.

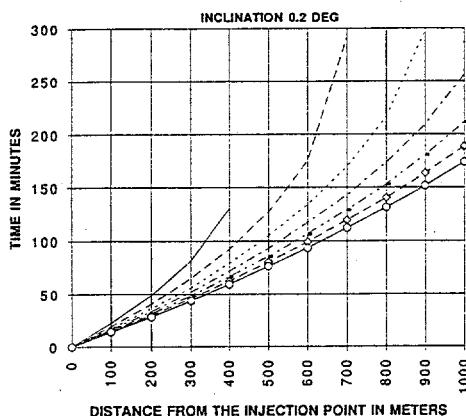


Figure 7: Inventory of LN₂ for different injection rates

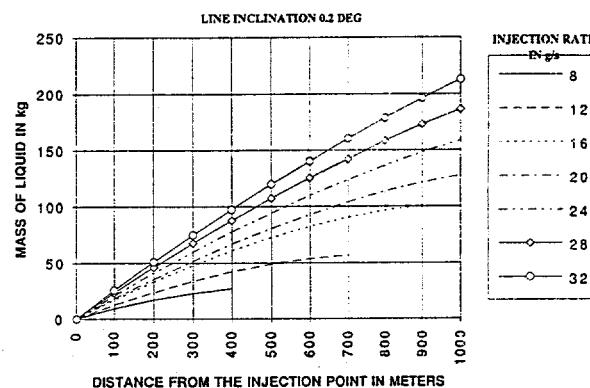


Figure 8: Time of motion of the liquid wave front for different injection rates

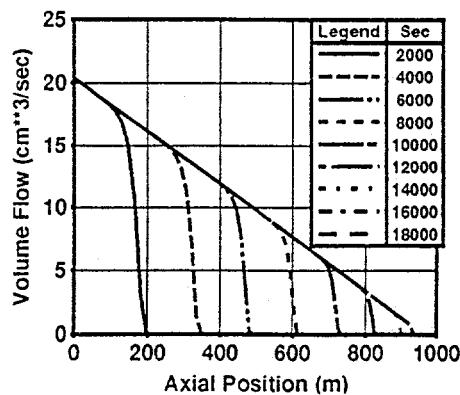


Figure 9: LN₂ transient mass flow distributions for constant 16 g/s injection.

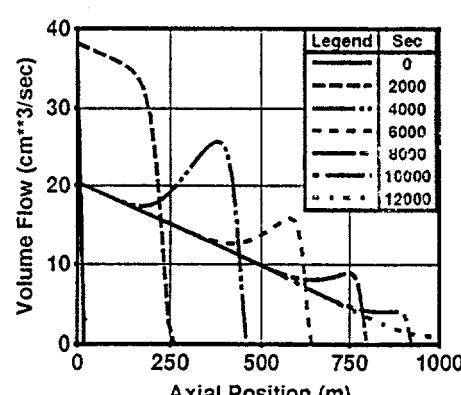


Figure 10: LN₂ transient mass flow distribution for 30 to 16 g/s step.

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