Cooldown Stresses on the Coldmass of SSC Dipole Magnets

B. Aksel and K. Leung
Magnet Systems Division
Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue, Dallas, TX 75237

Abstract

Cooldown rate is one of the critical factors determining the availability of the Superconducting Super Collider ring because of its large size. Considerable time saving is possible with different cooldown scenarios which generate large temperature gradients on the magnets. Purpose of this study is to understand the stresses generated due to largest possible temperature gradients that can be supplied by the cryogenic system and to predict the relation between the cooling rate and the coil stresses. Under the assumptions made in this study, it is found that maximum coil stress is independent of cooling rate. This result is in contradiction with the general belief and more investigation needs to be done before reaching a definite conclusion.

I. INTRODUCTION

The magnitude of the Superconducting Super Collider (SSC) requires cooling a large number of magnets in series by the same cooling line. There is one refrigeration plant for each 8.64 km sector of the ring[1]. Ten dipoles and two quadrupoles are placed between each recooler. With this configuration, the rate at which the ring is cooled down is an important factor for the availability of the machine. Fastest cooldown can be obtained by pumping 4.15 K helium directly into room temperature magnets. However, there is serious concern that generating large temperature gradients will damage the magnets. Presently, experimental know-how sets the limit on how fast a magnet can be cooled. The present SSC design suggests using a milder cooldown for the ring, which is composed of three thermal waves at different temperatures.

II. ANALYSIS

Analysis of a cooldown cycle is a very complex, three dimensional, transient, thermomechanical problem. As an initial approach only the inlet and outlet cross-sections, which experience the largest temperature gradients, are analyzed. Magnet is cooled from both inner and outer surfaces at the inlet. Due to the small flow rate, coolant on the inner surface heats up and loses its effectiveness as it travels along the length of the magnet. Therefore, outlet cross-section is cooled from outside only. For further simplification, the cross-section is assumed to be axisymmetric by assuming the coil extends into the pole tip region. Although this assumption is expected to provide answers which are different than the real case, it facilitates more aggressive analyses which are otherwise impossible. Validity of the axisymmetry assumption will further be investigated by comparing it with exact cross-section models. ANSYS commercial finite element package is used as the numerical tool. Each coil, collar, yoke, and insulation material (kapton) between the two coils and between the outer coil and collar, are meshed separately. Gap elements are used at each interface. First, a heat transfer analysis is done to determine the transient temperature distribution. In SSC dipoles, coolant flows through four bypass holes located in the yoke and through the annular gap between the beam tube and the inner coil. The radius of the bypass hole is 14.6 mm. For a 45 mm beam tube outer diameter and 50 mm magnet aperture, width of the annular gap is 2.5 mm. From 100 g/sec total helium flow, 3.32 g/sec flows through the annular gap and 96.68 g/sec flows through the bypass holes. Heat transfer to the helium flow is simulated by convection elements which are kept at constant bulk temperatures of 4 K. Necessary heat transfer coefficients are taken from Ref.[2]. The temperature dependance of all the material properties are incorporated. Effective heat transfer coefficients, obtained from copper and kapton layers, are used for the coils in both radial and azimuthal directions. All the interfaces are assumed to be perfect heat conductors. Temperature response of the coldmass at the inlet cross-section is shown in Figure 1, which shows the temperature of each coldmass component in kelvins as a function of time in seconds. The fastest cooling line represents the average temperature for the inner coil. The outer coil follows a parallel path 16 K higher than the inner coil. The average temperature of the collar is about 16 K higher than the outer coil, and the average temperature of the yoke is about 5 K higher than the collar most of the time. The 10 mm thick inlet cross-section takes about 45 minutes to cool from 300 K to 4 K.

The temperature profile obtained in heat transfer analysis is then used as the input to the structural analysis which makes use of the same mesh. Coils are prestressed in the azimuthal direction up to approximately 70 MPa in order to prevent motion of the conductor during cooldown and energization. Behavior of the magnet cross-section under such high prestress is modeled by generalized plane strain, which means all points in the cross section have to move together, in the axial direction. Elastic modulus of the coils in radial and azimuthal directions are determined experimentally. Since only room temperature values are available, temperature dependance of the elastic modulus of pure copper is used by matching its room temperature value to that of the coil's. Due to the unavailability of the data, elastic modulus in the axial direction is taken to be the same as in the radial direction. The magnet is assumed stress free at 300 K. Components of stress, as well as the equivalent stress, are monitored carefully

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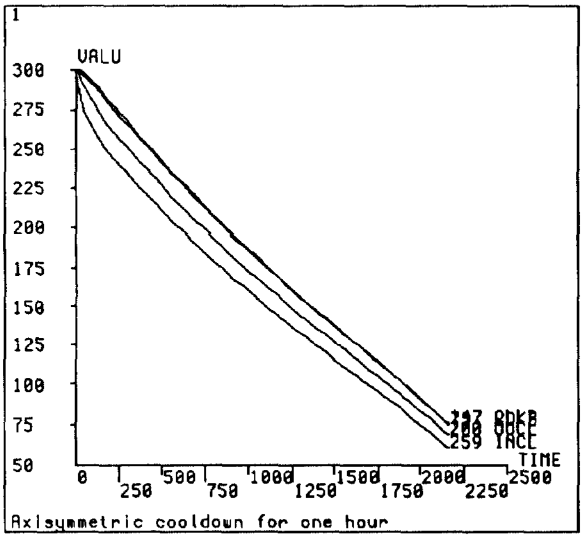

Figure 1- Temperature (K) history for the coldmass at the inlet. Time is in seconds.

during the cooldown period. There is no considerable stress development in the radial direction on the inner coil. This result should be interpreted with caution because the prestress state is neglected in this analysis. Since the inner coil is colder than the rest of the magnet at all times for the inlet cross-section, prestress in the radial direction is going to relax during cooldown. Figure 2 shows the history of axial stresses at different radial locations on the inner coil, and that the inner coil is subjected to a uniform axial stress at any instant.

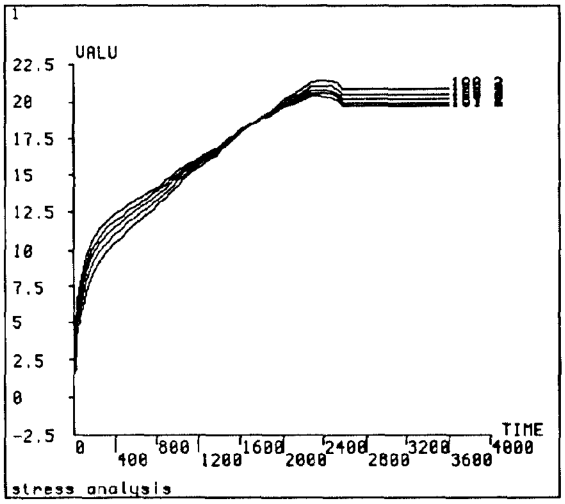

Figure 2- Axial stresses (MPa) on the inner coil as a function of time (sec) at the inlet.

Maximum axial stress of 21 MPa is reached a little before reaching the uniform temperature at 4 K. There are no shearing stresses generated due to the geometry of the structure and a small amount of hoop stresses, on the order of 1.5 MPa, are observed. Similar observations can be made for the outer coil. Axial stresses are shown in Figure 3. Equivalent stresses on both coils behave similar to the axial stresses because of their dominance. Same observations can be made for the outlet cross-section even though it is cooled only from

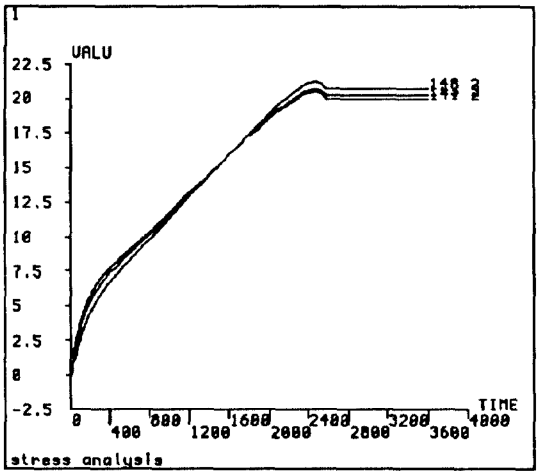

Figure 3- Axial stresses (MPa) on the outer coil as a function of time (sec) at the inlet.

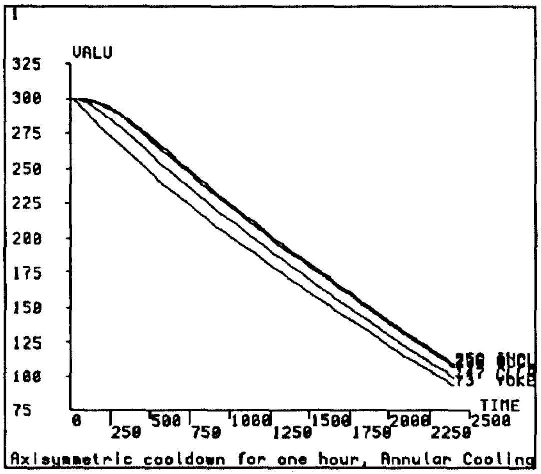

Figure 4- Temperature (K) history for the coldmass at the outlet. Time is in seconds.

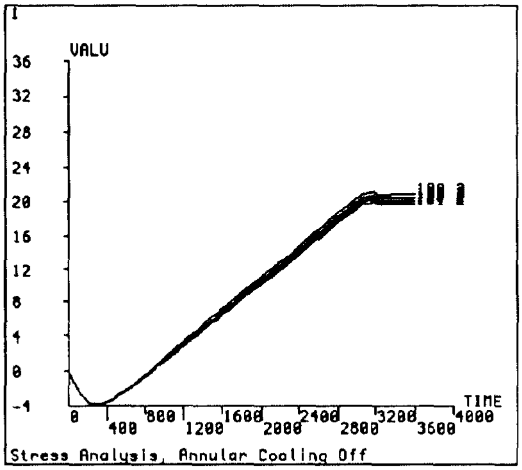

Figure 5- Axial stresses (MPa) on the inner coil as a function of time (sec) at the outlet.

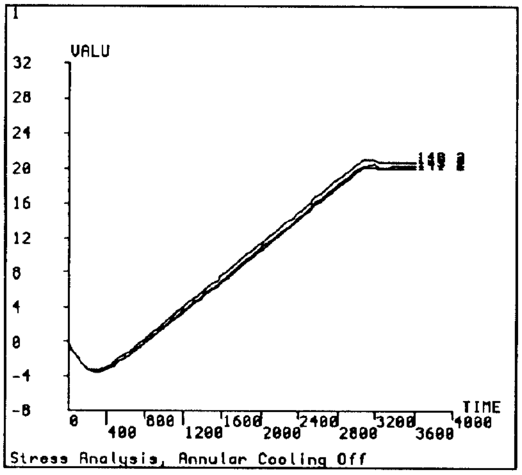

Figure 6- Axial stresses (MPa) on the outer coil as a function of time (sec) at the outlet.

outside. Only difference is the compressive axial stresses generated on the coils at early times because of the high temperature of the coils. Results for the outlet cross-section are given in Figures 4-6. Stress states within the collar and yoke packs are more complicated because of the temperature gradients generated within themselves. Due to the space limitations, stresses other than the coils' will not be addressed in this paper.

III. CONCLUSION

Caution should be experienced while interpreting the maximum stresses obtained in this study due to underlying assumptions, the most important of which is the elastic modulus of the coil in the axial direction. The axial constraining mechanism of the coil plays a very important role in the stress generation. More detailed analysis is needed for definite answers on its effect, however, a very important outcome of this analysis is the fact that axial stress in the coils increases monotonously with time (Figures 4 and 5), which means that maximum axial stress obtained on the coils is independent of the cooldown rate. In fact, an analysis in which the whole cold mass is dropped from 300 K to 4 K uniformly gives the same stress distribution as the transient one. This finding should not be confused with the cooldown issues on the radial stresses which are not addressed in this study due to the axisymmetry assumption. Further study is planned to address this issue.

IV. FUTURE WORK

For future work, the next step is to model the exact cross-section by using the same assumptions in the axial direction and run the model with the same thermal boundary conditions. This will give an idea how good the axisymmetric assumption is. Three dimensional models of the complete magnet are already in progress. They will provide valuable information on the effects of the temperature rise of the coolant as it flows through the magnet, especially the annular gap as well as the axial conduction within the coils.

V. REFERENCES

[1] *Site-Specific Conceptual Design Report,* Superconducting Super Collider Laboratory, SSCL-SR-1056, July,1990.

[2] R.P.Shutt, "SSC Magnet Cooling, Reconsidered", SSC-N-522, May 27,1988