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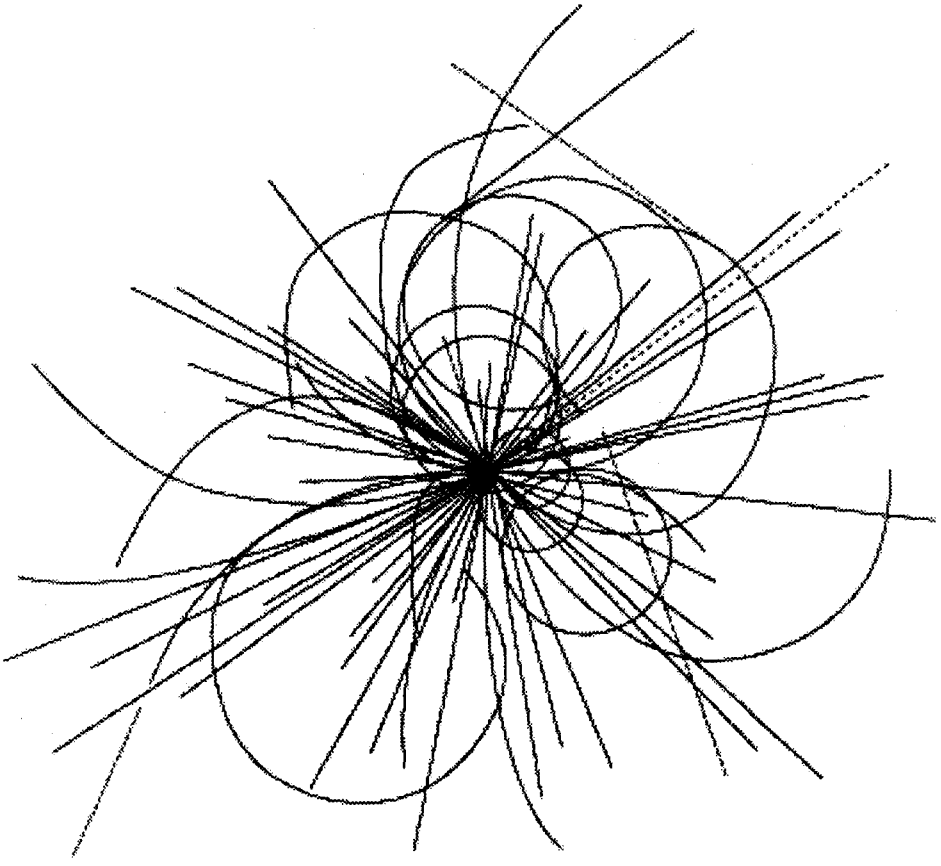

Superconducting Super Collider Laboratory

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The Thermal Behavior of an SSC Magnet in an Unconditioned Outdoor Environment*

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THE THERMAL BEHAVIOR OF AN SSC MAGNET IN AN UNCONDITIONED OUTDOOR ENVIRONMENT

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SUMMARY

The superconducting coils of the SSC magnets are subjected to potentially harmful warm temperatures during transportation and storage operations in certain outdoor environments. A realistic, harmful operating environment to which a magnet could be subjected at some point in the SSC construction would occur in the scenario in which an uncovered magnet remains outdoors during a hot , bright summer day, without environmental conditioning or protection for an extended period. Such a scenario could occur during a transportation truck breakdown, or if a magnet were left outside awaiting entry to the construction shaft over a weekend, for example. The magnet would be subjected to elevated ambient temperatures and solar radiation which could heat the magnet and raise the coil and bus assembly at some location to a temperature greater than the 32.2 °C (90 °F), at which the B-stage epoxy used in the coil ground plane insulation is thought to weaken. A thermal analysis of an FNAL 50mm Dipole style magnet under such a hypothetical operating condition was conducted to predict the maximum coil temperature rise and rate of rise during such a scenario.

The dipole magnet thermal model was reconfigured to account for the lack of cryogens and presence of atmospheric pressure dry Nitrogen gas in the cryostat for its transportation configuration. The magnet model was subjected to a 48 hour continuous outdoor soak scenario, running from midnight at the beginning of the 1st day to midnight at the end of the 2nd day. The initial temperature for the entire magnet was 26 °C (78.8 °F). A daily schedule of ambient air temperature and of solar heat flux was imposed on the magnet. The maximum ambient air temperature to which the magnet was exposed was 37.8 °C (100 °F). The heat flux schedule was generated according to ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers) standard methods for June 21 at the SSC N-15 location, for a clear sky. The results of this analysis showed that the maximum coil temperature rise of 4.4 °C over 48 hours, for an average of 0.092 °C/hour, occurred at the coil ends on the outer coil. The maximum coil temperature after 48 hours was 30.4 °C

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(86.7 °F), which is 7.4 °C (13.3 °F) less than the maximum ambient temperature of 37.8 °C (100 °F) to which the magnet is exposed, and 1.8 °C (3.3 °F) less than the coil temperature limit of 32.2 °C (90 °F). Based on the average coil temperature rise rate, it would require an additional 19.6 hours for the maximum coil temperature to reach the coil temperature limit of 32.2 °C (90 °F).

Based on this result, the coils seem to be adequately buffered against exposure to undesirable temperatures in the event of an exposure not exceeding 67.6 hours to an unconditioned outdoor environment. Since the predicted coil temperature rise rate is low, it is recommended to consider an actual outdoor soak test of a dipole magnet for the purpose of measuring coil temperatures and environmental conditions, to verify the analysis results.

ANALYSIS

The 50mm FNAL Dipole thermal model [1] was used as the basis for the study. In the magnet's transportation configuration, the cryogen lines are dry and capped at the ends, the interconnect shield bridges are not present, the ends are covered with the shipping bell, and the magnet cryostat is filled with dry Nitrogen gas at atmospheric pressure. The standard Dipole thermal model was modified to account for these differences.

A magnet in an outdoor environment will be heated at the vacuum vessel surface through natural convection from ambient air which is initially at a higher temperature than the vacuum vessel surface and by the total solar thermal radiation which falls on the unshaded magnet exterior surface. A worst case scenario for outdoor heating of the magnet was developed. The magnet was assumed to be outdoors at the SSC N-15 site location during a clear, hot summer day typical for this climatic region. The daily ambient air temperature profile to which the magnet was exposed is shown in Figure 1 (results section).

The total solar heat flux incident on an unshaded surface is comprised of three components. The direct normal solar flux is that which is received by an unshaded surface directly from the solar disk. The diffuse solar flux is the direct solar flux which is scattered and reflected by the atmosphere and reaches the exposed surface indirectly from all portions of the sky visible to the surface. Reflected solar flux is the direct and diffuse solar flux which is reflected from the ground and other surfaces and reaches the exposed surface indirectly from these other surfaces. The worst case daily total solar heat flux incident on the magnet was calculated using the ASHRAE method [2] for a horizontal magnet oriented with its long axis North to South on June 21 at the N-15 site, for a clear sky condition. The surface over which the magnet rested was assumed to be light colored concrete with a nominal solar reflectivity of 0.3 [3]. Since the ASHRAE method applies to flat surfaces, the circular magnet vacuum vessel exterior surface was treated as a 12 sided regular polygon, and the solar heat flux incident on each facet calculated separately and averaged over the circumference to obtain the hourly average. For purposes of the diffuse and reflected solar components, the possible presence of other surfaces near the magnets was ignored, and the magnet was assumed to be exposed to the sky and ground only. The resulting total solar heat flux generated for the assumed worst case magnet outdoor environment is also shown in Figure 1.

In the outdoor environment, the magnet will exchange heat with it's surroundings via convection with the ambient air and thermal radiation to surrounding surfaces. In the worst case, the magnet would not have the benefit of being cooled by a breeze, so that it was assumed that the magnet resides in still, windless air and exchanges heat with the atmosphere by free, rather than forced, convection. The solar thermal radiation is treated as a net heat load on the magnet surface, and is equal to the incident total solar heat flux multiplied by the solar absorptivity of the magnet surface. A solar absorptivity of 0.9 was used as a worst case for gloss red paint on metal surface [3]. However the magnet surface will still exchange heat by thermal radiation with surrounding surfaces such as the ground

and sky, since these surfaces will emit and absorb thermal radiation apart from the solar heat flux. The worst case (highest) apparent sky temperature occurs for the case of blackbody sky radiation, in which case the sky temperature is equal to the local atmospheric ambient [4]. The temperature of the ground surface, assumed to be concrete, is a complex function of absorbed solar flux, ground conductivity and initial temperature, and heat transfer coefficient with the ambient air. As a worst case, approximation the ground temperature was assumed to follow the ambient air temperature profile.

The magnet thermal response to the estimated hot soak environment was simulated over a 48 hour period. The magnet was assumed to be exposed to the outdoor environment starting at midnight of the 1st day. An initial temperature of 26 °C (79 °F) was used to represent the magnet coming from a benign, conditioned environment such as a building interior. A 48 hour soak would adequately characterize the daily coil temperature rise and reveal any hysteresis in the day to day thermal behavior of the coil temperatures.

RESULTS

The predicted temperatures of the exposed magnet over the duration of the outdoor soak scenario are shown in Figure 1. The vacuum vessel, exposed directly to the ambient air and solar radiation, tracks the ambient temperature until the sun rises the 1st day, at which point it heats rapidly to a maximum temperature of 75.8 °C (168 °F) between 12 P.M. each day. The results show that the vacuum vessel peak daily temperature does not vary significantly during the 2nd day. Figure 1 shows that the 80K shield peak temperature is 62.9 °C (145 °F) on the 2nd day, and that the 20K shield peak temperature is 55.7 °C (132 °F) also on the 2nd day. The 20K shield peak temperature does show some hysteresis from the 1st to the 2nd day. The results also show the advance of the heat input by the shift in the peak temperature times as one goes inward from the vacuum vessel to the shields and finally to the Cold Mass. The large difference in the magnet cryostat components daily peak temperatures and the daily peak ambient temperature indicates that the component temperatures are primarily driven by the solar heat input rather than heat input from the ambient air.

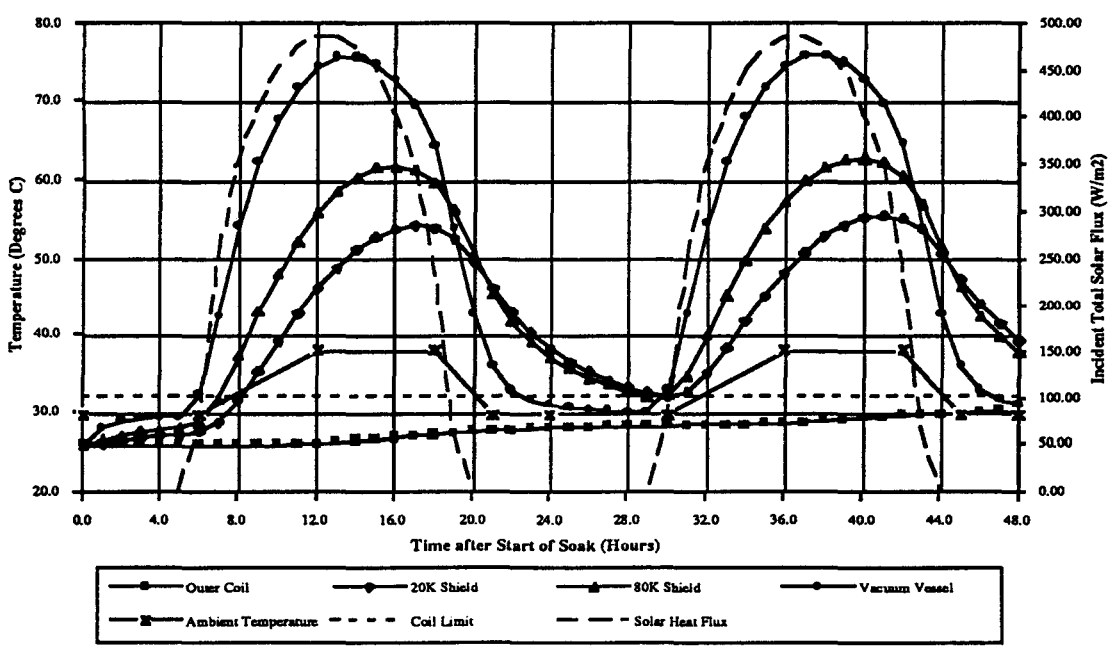

Figure 1: Dipole Magnet 48 Hour Unshaded Outdoor Hot Soak Results

The maximum coil temperature occurs at the lead and return ends of the magnet. It shows a steady, nearly linear rise at a rate of 0.15 °C/hour during a period of duration nearly equal the daylight period of 14 hours, but offset forward from the daylight period by about 4 hours. The average maximum coil temperature rise rate over the 48 hours was 0.092 °C/hour, resulting in a maximum coil temperature of 30.4 °C (86.7 °F). The maximum coil temperature falls below the nominal coil temperature limit of 32.2 °C (90 °F). Based on this 48 hour average rise rate, the coil temperature would not reach the limit for an additional 19.6 hours. This would be till the end of daylight on the 3rd day of soak, based on a June 21 solar heat profile. The reason that the Cold Mass responds very slowly to the exterior conditions is due primarily to its very large thermal capacitance compared to that of the cryostat components.

Although the coils appear to be protected against any excursions above the nominal high temperature limit of 32.2 °C during the 48 hour outdoor unshaded hot soak scenario, several other failure modes due to high temperature may also exist. Exceeding the char/ignition point temperature of the MLI PET layers could create a fire hazard, and excess temperatures could be detrimental to the structural integrity of the support post tubes. It is recommended that a review of the maximum temperature limits of these and other non-metallic magnet components be conducted to determine of any additional failure modes due to high temperatures exist.

If a scrap dipole magnet was or becomes available, an outdoor soak test could be conducted to experimentally determine the coil region temperature and verify the analytical predictions. Such a test would involve the measurement of temperatures of the coils, shields, vacuum vessel, and ambient air, and the measurement of direct and diffuse solar flux and wind speed over the duration of the test. In addition, or as an alternative, additional analysis may be performed to improve the modeling. There was insufficient time to remove the shields from the interconnect region, and the ground temperature behavior and free convection effects inside the cryostat need to be more adequately modeled. An immediate solution would be to require that all transported magnets be equipped with an independently powered air conditioning unit and that all magnets which must be placed outdoors for any reason be completely shaded. Otherwise, it is recommended that the magnets be tested in outdoor conditions to measure their response to the environment, so that adequate handling requirements may be drafted.

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