Fermi National Accelerator Laboratory

FERMILAB-TM-1725

Design of the Multilayer Insulation System for the Superconducting Super Collider 50mm Dipole Cryostat*

W. N. Boroski, T. H. Nicol and C. J. Schoo
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

March 1991

* Presented at the *Third Annual International Symposium on the Super Collider [ITSSC]*, Atlanta, Georgia, March 13-15, 1991.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

DESIGN OF THE MULTILAYER INSULATION SYSTEM FOR THE SUPERCONDUCTING SUPER COLLIDER 50 mm DIPOLE CRYOSTAT

W.N. Boroski, T.H. Nicol, and C.J. Schoo

Fermi National Accelerator Laboratory
Batavia, Illinois

ABSTRACT

The development of the multilayer insulation (MLI) system for the Superconducting Super Collider (SSC) 50 mm collider dipole cryostat is an ongoing extension of work conducted during the 40 mm cryostat program. While the basic design of the MLI system for the 50 mm cryostat resembles that of the 40 mm cryostat, results from measurements of MLI thermal performance below 80K have prompted a re-design of the MLI system for the 20K thermal radiation shield. Presented is the design of the MLI system for the 50 mm collider dipole cryostat, with discussion focusing on system performance, blanket geometry, cost-effective fabrication techniques, and built-in quality control measures that assure consistent thermal performance throughout the SSC accelerator.

INTRODUCTION

The design requirements for the thermal insulation system in the SSC collider dipole cryostat dictate that heat leak from thermal radiation and residual gas conduction be limited to 0.677 W/m^2 to 80K, 0.093 W/m^2 to 20K, and 0.003 W/m^2 to 4K. Moreover, the insulation system must perform reliably throughout the 25-year operating life of the accelerator in an environment which includes severe thermal cycles, radiation exposure, and upset insulating vacuum conditions. Essential to meeting these requirements is an insulation system design that 1) limits radiant heat transfer to design limits; 2) has sufficient volumetric heat capacity to reduce the effects of thermal transients; 3) has sufficient layer density for improved gas conduction shielding; and 4) is comprised of materials suitable for extended use in a high radiation environment. Finally, the system design must be such that cost-effective fabrication and installation techniques establish consistent thermal performance throughout the entire accelerator.

The thermal insulation system for the 50 mm collider dipole cryostat is comprised of cryostat-length assemblies of multilayer insulation fabricated and installed as blankets on the 4.5K cold mass and the 20K and 80K thermal radiation shields.

Table 1. Structural Properties of Candidate Materials

ORGANIC MATERIAL	POLYESTER	POLYIMIDE	POLYAMIDE
TRADE NAME†	MYLAR, REEMAY, DACRON	KAPTON	NYLON, CEREX
MOISTURE ABSORPTION	0.4% @ 50% Rh REEMAY SPUNBONDED 0.5% @ 98% Rh	1.3% @ 50% Rh ————	8.0% @ 50% Rh CEREX SPUNBONDED 3-5% @ 95% Rh
OUTGASSED MASS PER UNIT MATERIAL MASS	DACRON NET 1.1×10^{-4} g/g DOUBLE ALUMINIZED MYLAR 2.6×10^{-3} g/g	———— DOUBLE ALUMINIZED KAPTON 3.1×10^{-3} g/g 3.9×10^{-3} g/g	NYLON NET 4.0×10^{-2} g/g ————
IONIZING RADIATION DAMAGE	5.7×10^{8} RAD (50% MAX. MECHANICAL)	5.0×10^{9} RAD (50% MAX. MECHANICAL)	7.0×10^{7} RAD (50% MAX. MECHANICAL)
IRRADIATION EVOLVED GASES	3-5 ml/g @ 10^{9} RAD H_2(70%), CO_2(20%), CO(10%)	————	20-25 ml/g @ 10^{9} RAD H_2(52%), CO(20%), CO_2(12%), N_2(8%), O_2(3%)

† DUPONT DE NEMOURS & CO; REEMAY INC; JAMES RIVER CORP.

MATERIALS SELECTION

The selection of materials for the MLI system was formulated after consideration of such design parameters as mechanical strength, radiation tolerance, hygroscopicity, vacuum outgassing rates, and thermal performance measurements[1-6]. Candidate materials that were considered for use include polyesters, polyimides, and polyamides; structural properties of these materials are tabulated in Table 1. The material of choice for each of the MLI blanket components is polyethylene terepthalate (PET), a polyester. The material was chosen for its high strength, low moisture absorption, low outgassing rate, and high resistance to ionizing radiation damage. Table 2 outlines the materials selected for use in the 50 mm cryostat insulation system.

Table 2. Materials selected for the 50 mm. cryostat insulation system

BLANKET COMPONENT	MATERIAL	DESCRIPTION	COMPANY
REFLECTOR	ALUMINUM VIA VACUUM DEPOSITION	ALUMINIZED METAL COATINGS; BOTH SIDES; EMISSIVITY <0.03	MULTIPLE VENDORS
REFLECTOR SUBSTRATE	POLYETHYLENE TEREPHTHALATE	FLAT FILM, 0.03 mm THICK, NO PERFORATIONS	DUPONT & CO.
SPACER	POLYETHYLENE TEREPHTHALATE	SPUNBONDED POLYESTER, 0.1mm THICK, 17 g/m^2	REEMAY, INC.
COVER LAYERS	POLYETHYLENE TEREPHTHALATE	SPUNBONDED POLYESTER, 0.23mm THICK, 46 g/m^2	REEMAY, INC.
HOOK FASTENER	POLYESTER	HOOK #80, WHITE #012 WIDTHS: 25mm & 50mm	VELCRO USA, INC.
LOOP FASTENER	POLYESTER	LOOP #2000, WHITE #012 WIDTH: 25mm	VELCRO USA, INC.
THREAD	POLYESTER	V125 WHITE	BELDING CORTICELLI THREAD CO.

BLANKET DESIGN GEOMETRY

80K MLI System Configuration - The insulation system for the 80K thermal shield must have a mean apparent thermal conductivity of 0.76 x 10^{-6} W/cm-K to meet the design heat load budget to 80K. This is achieved by using a multilayer insulation system comprised of reflective layers of aluminized polyester separated by spunbonded polyester spacer layers. The apparent thermal conductivity of an MLI blanket comprised of these materials has been measured to be 0.52 x10^{-6} W/cm-K in the temperature range 300K to 80K[6].

The 80K MLI system consists of two 32-reflective-layer blanket assemblies for a total build of 64 reflective layers. The blankets are designated as the inner 80K and outer 80K blanket, respectively. Each 32-layer blanket has a nominal stack height of 8.86 mm which equates to a mean layer density of 3.61 layers/mm. The design geometry of the 80K outer MLI blanket is shown in Figure 1. The design geometry for both 80K MLI blankets is the same with the exception of the emissivity flap. The emissivity flap consists of three layers of DAM which are folded over the seam area of the blanket during cryostat assembly. The flap serves to maintain the low emissivity of the blanket over the entire outer surface area. The inner 80K MLI blanket does not require an emissivity flap as the outer 80K MLI blanket covers the stepped joint / stepped seam area of the inner blanket.

The reflective layers of the 80K MLI system are comprised of 0.03 mm thick PET film, aluminized with a nominal coating thickness of 350 angstroms, or 0.9 ohms/square, per side. The reflective layers are held apart by single spacer layers of 0.10 mm spunbonded PET material. Single layers of 0.23 mm spunbonded PET cover the blanket top and bottom, and serve to position the polyester hook and loop fasteners at the blanket edges. The fasteners are affixed to the cover layers by sewing. A third 0.23 mm PET layer is located midway through the blanket assembly to separate the upper and lower 16 reflective layers. The multiple blanket layers are sewn together as an assembly along both edges of the blanket. Non-lubricated polyester thread is used in all sewing operations.

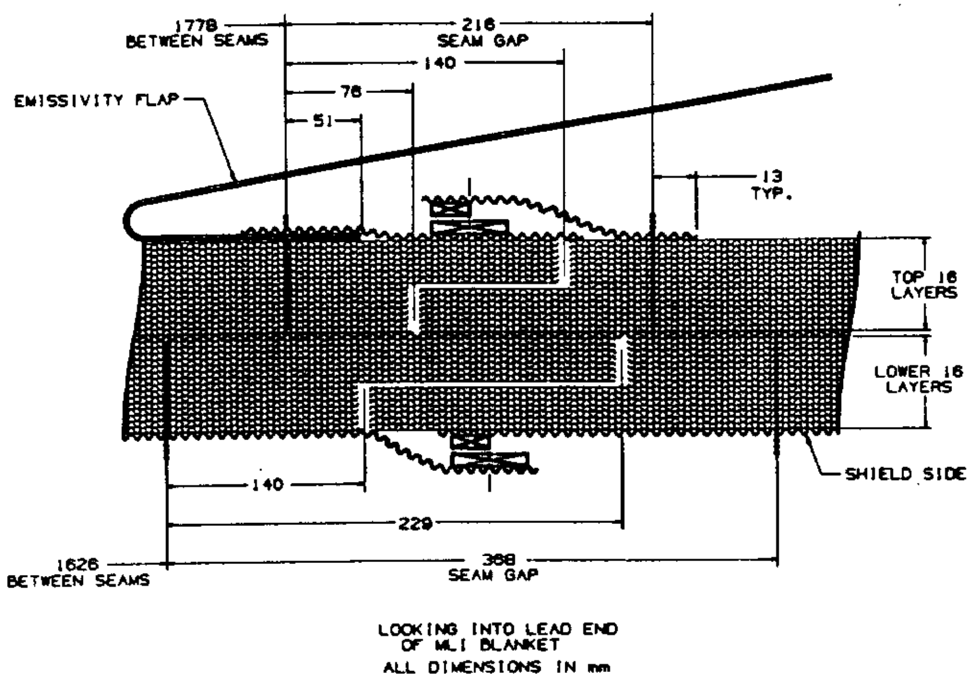

Figure 1. Outer 80K MLI blanket geometry

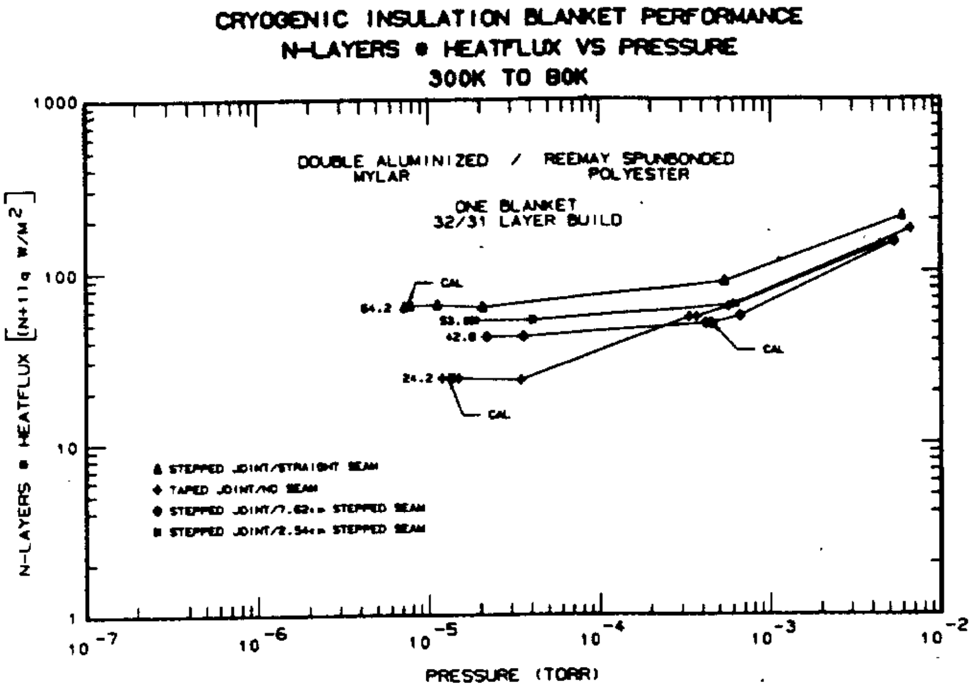

Figure 2. Thermal performance of the stepped seam geometry

At each blanket edge, the upper MLI layers are sewn together from the upper cover layer through to the midlayer, with the thread terminated in the heavier midlayer material. The seam location is then incremented 7.62 cm laterally along the midlayer, and the lower MLI layers are sewn together from the heavy midlayer through to the lower cover layer. The resulting stepped-seam geometry is shown in Figure 1. Sewn seams are advantageous in that they hold the many layers together in a package that can be treated as a single entity during shipping, handling, and cryostat installation. The trade-off comes through increased conduction through the blanket.

Thermal performance measurements have been conducted on various sewn seam geometries to study the effect of sewn seams on MLI blanket thermal performance[6]. Results from these measurements that illustrate the effect of various sewn seam geometries on MLI blanket performance are presented in Figure 2. As evidenced by the data, solid conduction through a straight-through seam significantly increases the heat transfer rate through the blanket. However, a step of 7.62 cm in the sewn seam reduces the amount of solid conduction heat transfer through the blanket to acceptable levels by interrupting and lengthening the conductive heat path of the thread. With the stepped seam geometry, the MLI system design meets the infrared heat load budget to 80K.

<u>20K MLI System Configuration</u> - The MLI system for the 20K thermal shield must have a heat flux less than 93 mW/m² to meet the heat load budget to 20K. Calculation of radiation heat transfer between two aluminum dipole cryostat thermal radiation shields of "ideal" surface finish, with no MLI installed, predicts that the heat transfer rate will be 29 mW/m², which is well below the design heat load budget. This prediction is substantiated by experimental data which shows low heat transfer rates between aluminum-taped surfaces for temperatures below 80K[7,8]. Furthermore, evidence has been presented that suggests that MLI should not be installed on surfaces below 80K[8,9]. However, several conditions and assumptions exist which must be addressed when considering these statements.

Experimental results which show low heat transfer rates between two aluminum surfaces are made under ideal laboratory conditions where 1) surface contamination is controlled to assure low surface emissivity; and 2) insulating vacuum levels are in the region where residual gas conduction is negligible. In practice, the thermal shields of the cryostat will be used as is, with no special actions taken to achieve as low a value of surface emissivity as theoretically possible. The result will be surface emissivities significantly higher than those experienced under ideal conditions. In fact, assuming "working" shields with surface emissivities approaching 0.1, the heat flux to 20K increases to 129 mW/m^2, substantially higher than the design budget. With respect to insulating vacuum, it is a reality of accelerator operation that the system be operable during periods of insulating vacuum considerably above 10^{-6} torr. Heat leak into the 80K shield is rather insensitive to fluctuations in insulating vacuum as it is driven primarily by radiation heat transfer. However, heat leak into the 20K shield is highly sensitive to pressure, and increases rapidly above 10^{-5} torr. The addition of an MLI blanket on the 20K shield serves not only as an impedance to infrared heat transfer but to gas conduction as well, as the radiation shields also function as gas conduction shields[10,11].

With respect to measurement results which suggest that MLI should not be installed on surfaces below 80K, one must consider the effects of aluminum coating thickness on MLI performance at very low temperatures. If the addition of an MLI blanket on a low temperature surface (in the region 4K - 20K) causes an increase in the heat transfer rate between boundary surfaces, then one must consider what has changed. Given the same degree of insulating vacuum, the only change is in emissivity of the cold boundary.

Since aluminum has electrical resistivity, an electromagnetic wave will penetrate some distance into the aluminum before being absorbed or reflected. This phenomenon, known as radiation tunneling, explains why the thickness of a metallized coating has a considerable effect on the emissivity of metallized films. The thicker the metallized coating, the higher the reflectivity and lower the emissivity. And as electromagnetic wavelengths increase with decreasing temperature, then the radiation tunneling depth also increases, causing a subsequent increase in emissivity[10,12]. This effect has been seen experimentally by Obert, et al.[13], during surface emissivity measurements. When aluminized Mylar was placed over a stainless steel surface, the reflectivity for the 300K to 77K case improved by a factor of 5. However, for the 77K to 4K case the emissivity was found to "deteriorate drastically", becoming worse than the stainless steel surface itself.

Of further concern is the increase in transmissivity of thin aluminum coatings at low temperatures. Transmissivity can be defined as the percent of radiant energy striking an object that passes through without restriction. Figure 3 is a theoretical calculation[14] of the transmissivity through various aluminized coating thicknesses as a function of temperature. Note that a coating thickness of 300 angstroms serves well to impede the passage of radiant energy above 100K. However, a rapid increase in transmittance is seen with decreasing temperature until at 10K approximately 55% of all radiant energy striking the surface will pass through unhindered. It is interesting to note that several researchers have compared the performance of aluminum tape to NRC-2 insulation at 4K; the nominal coating thickness for NRC-2 is 250 angstroms per side. Some increase is seen in performance as the metallized film thickness increases, although it becomes rather small above 500 angstroms. The nominal aluminized coating thickness specified for the 20K MLI system is 600 angstroms per side.

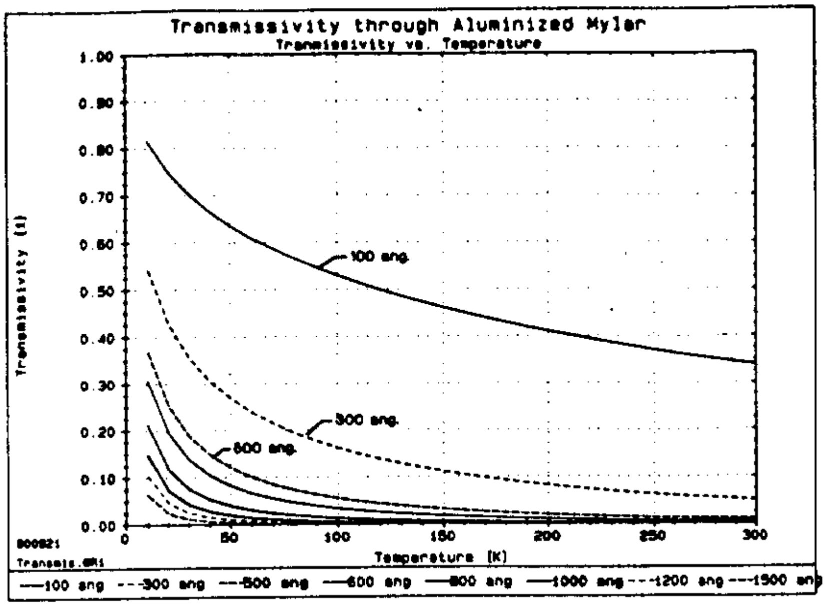

Figure 3. Transmissivity as a function of coating thickness

The final issue which must be addressed in MLI performance below 80K is that of solid conduction through the blanket layers. Below 80K, solid conduction becomes the dominant mode of heat transfer through an MLI blanket. Since infrared heat transfer drops off rapidly below 80K, the 20K MLI system does not require a large number of reflective layers. Hence, the total number of reflective layers in the 20K blanket has been decreased from 32 on the 40 mm design to 10 layers for the 50 mm design. To further limit solid conduction through the blanket, three spacer layers have been added between each set of reflective layers to decrease layer density.

A series of thermal performance measurements between 80K and 20K are underway to experimentally evaluate the design of the MLI system for the 20K shield. The first measurement completed was on a 32-layer MLI blanket modeled after the SSC 40 mm dipole cryostat design. With the warm surface operating near 80K, the measured heat flux through the blanket was 231 mW/m^2, a factor of 2.5 higher than the design budget. The aluminized Mylar had a nominal coating thickness of 350 angstroms per side. Thermometers installed on the individual blanket layers showed evidence of thermal shorting between adjacent layers. A graph of the data plotting individual layer temperatures through the body of the blanket at steady-state is presented in Figure 4. The high degree of thermal shorting between layers, evident in the data, offers one explanation for the excessive heat load.

Performance measurements on a MLI blanket modeled after the present design of 10 reflective layers each separated by three spacer layers are currently underway. The test blanket will have sewn seams comparable to those specified in the cryostat design. Finally, the blanket will contain thermometers to evaluate the interlayer temperature distribution under various operating conditions.

At present, the blanket design specified for the 20K MLI system incorporates 10 reflective layers of PET film aluminized with a nominal coating thickness of 600 angstroms, or 0.45 ohms/square, per side. The reflective layers are held apart by sets of three spacer layers of 0.10 mm spunbonded PET material. Single layers of 0.23 mm spunbonded PET cover the blanket top and bottom to position the polyester hook and loop fasteners. The multiple layers are sewn together along both edges of the blanket.

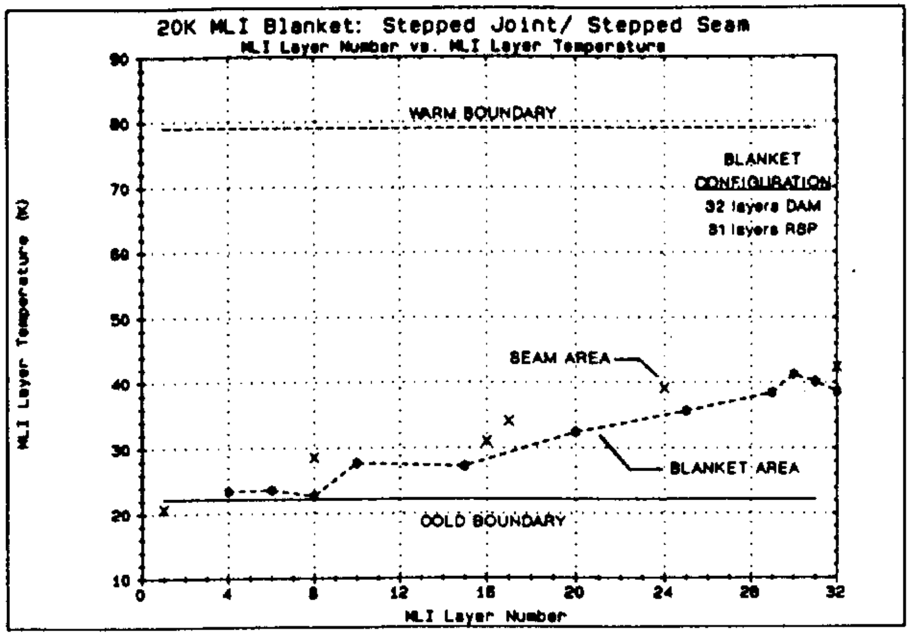

Figure 4. Temperature profile through a 32-layer MLI blanket

At each blanket edge, the upper MLI layers are sewn together from the upper cover layer through to the middle three layers of 0.10 mm PET material, with the thread terminated in the three layers. The seam location is then incremented 7.62 cm laterally along the midlayer, and the lower MLI layers are sewn together from the middle three layers through to the lower cover layer. The resulting stepped-seam geometry is shown in Figure 5.

<u>Cold Mass MLI Configuration</u> - While radiation heat transfer between 20K and 4K is almost negligible, the region is very sensitive to changes in insulating vacuum. Results from computer modeling have shown that the presence of a 10-layer MLI blanket on the cold mass significantly reduces the heat leak into the cold mass at pressures above 10^{-6} torr[15]. Thus, the primary function of the cold mass blanket is to impede residual gas conduction between 20K and 4K.

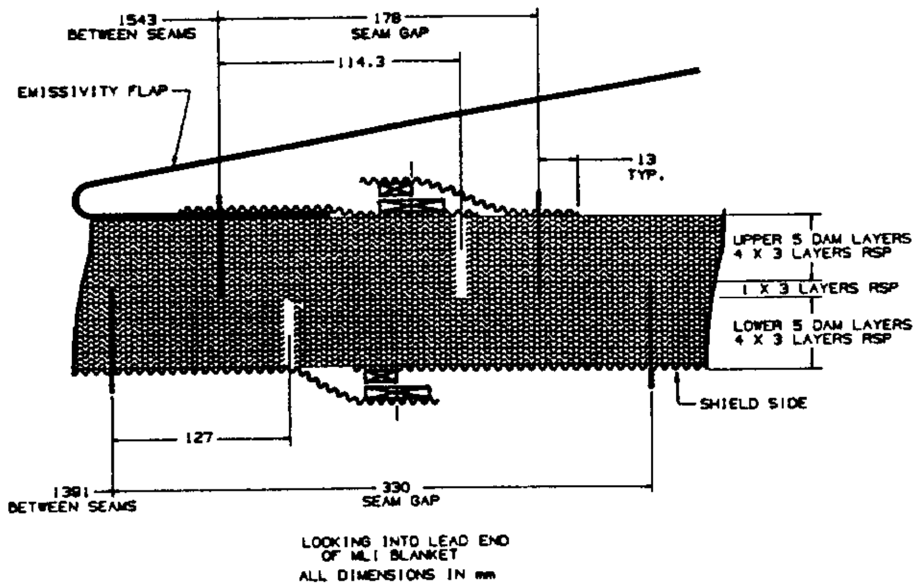

Figure 5. 20K MLI blanket geometry

The MLI system for the 4K cold mass consists of a single 5-reflective-layer blanket assembly, spirally wrapped twice around the cold mass surface for a total of 10 reflective layers. The MLI is installed on the cold mass between support locations; there is no MLI around the cold mass cradle assemblies. The blanket design incorporates 5 reflective layers of double-aluminized PET film, separated by single spacer layers of 0.10 mm spunbonded PET material. The cold mass blankets do not employ heavy PET cover layers or hook and loop fasteners, but are held in place with 7.62 cm wide reflective adhesive-backed tape. The MLI layers are sewn together near both edges of the blanket during blanket fabrication. During cryostat installation, one sewn seam is cut off as the blanket is spirally-wrapped onto the cold mass. The remaining sewn seam serves to maintain layer registration and hold the blanket assembly together.

METHOD OF FABRICATION

A large diameter winding apparatus is used to fabricate the MLI blankets for the 4.5K cold mass and the 20K and 80K shields. The apparatus consists of a rotatable mandrel having a 5.5 meter fixed diameter with an outer surface that is crowned with a convex cross-section. A cross-section view of the mandrel is illustrated in Figure 6. Adjacent supply spools hold the blanket reflective and spacer materials. The function of the apparatus is to wrap the appropriate number of MLI blanket layers around the fixed mandrel. Since each wrap of MLI material increases the circumference of the mandrel, each successive layer of material is slightly greater in length than the preceding layer. Additionally, the convex surface of the mandrel causes the amount of material between sewn seams in the width direction to increase as successive layers are wrapped. Thus, the blanket fabrication method provides integral material in its length and width dimensions to accommodate thermal contraction to cryogenic temperatures. The last layer wrapped onto the mandrel has the greatest length; therefore, it becomes the first layer against the cryogenic surface.

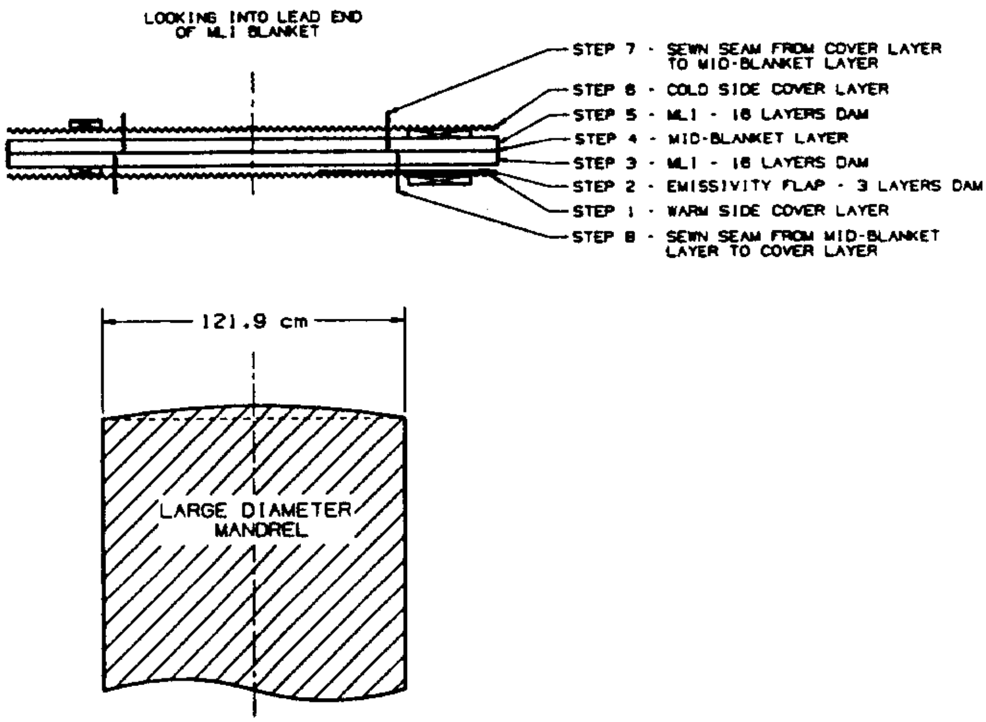

Figure 6. MLI blanket fabrication procedure

Each finished blanket is bound together at its edges by sewing through the blanket with a lock-stitch set at 1.5 stitches per cm. The sewn seams are made by rotating the blanket through a stationary sewing machine while the blanket remains on the mandrel. This method serves to "lock in" the extra material for thermal contraction, as well as fixing the mean layer density of the blanket. Once the sewing operation is completed, a single cut is made across the width of the blanket parallel to the mandrel axis and the assembly removed from the mandrel.

The resulting MLI blanket has sufficient length and width for an SSC shield or cold mass assembly. In addition, the sewn seams serve to control layer density while insuring interlayer cleanliness, three-dimensional stability, and extra material to accommodate thermal contraction. Finally, the sewn seams fix interlayer registration to maintain support post penetrations and blanket edge alignment during shipping, handling, and installation onto the cryostat.

The final stage in blanket fabrication is to locate and cut support post penetrations and alignment fiducials along the blanket length. As an additional allowance for thermal contraction of the blanket assemblies during thermal cycling, the support post penetrations are located 3.81 cm farther apart than the actual support post locations. This builds into the blanket sufficient material to compensate for local thermal contraction. Alignment fiducials marked on the inner layer of the blanket perpendicular to the blanket length function as quality control measures during cryostat installation. Alignment of the fiducials during cryostat assembly assure that the blanket has been installed parallel to the cryostat axis.

CRYOSTAT INSTALLATION

Locations of the MLI blankets in the 50 mm dipole cryostat are shown in Figure 7. During cryostat assembly, the MLI blanket is wrapped around the shield such that the edges of the blanket overlap to form a stepped, butt-joint connection as illustrated in Figure 1. The effect of the joint connection on overall thermal performance is significantly decreased by staggering the blanket penetrations; there are 24 uninterrupted layers at any point along the 80K shield, and 5 uninterrupted layers along the 20K shield length. Thermal measurements made on MLI joint configurations prove that connections made in this manner approach the performance of a MLI blanket with no seams[16]. To further reduce the effects of the blanket joint on thermal performance, the inner and outer 80K blanket seams are staggered on the cryostat.

Blanket installation begins by securing opposite ends of the inner blanket lower cover layer to each other by full engagement of the hook and loop fasteners. As the lower cover layers are overlapped and secured, the perpendicular alignment marks are superimposed, thereby confirming a cylindrical blanket assembly along the cryostat length. The MLI layers between the cover layers are then joined along the cryostat length using the stepped-butted joint. As the blanket edges are drawn together, tension on the blanket is taken by the sewn seams and cover layers. The MLI material located in the greater blanket area between sewn seams is isolated from the tension by the seams. The joint configuration is completed by full engagement of the upper cover layer hook and loop fasteners over the joint area. The resulting blanket installation is secured from opening by the closure of the two hook and loop pairs. Thermal testing of the hook and loop fasteners disclosed that the connection became more solid during cooldown due to the thermal contraction of the hook/loop connection.

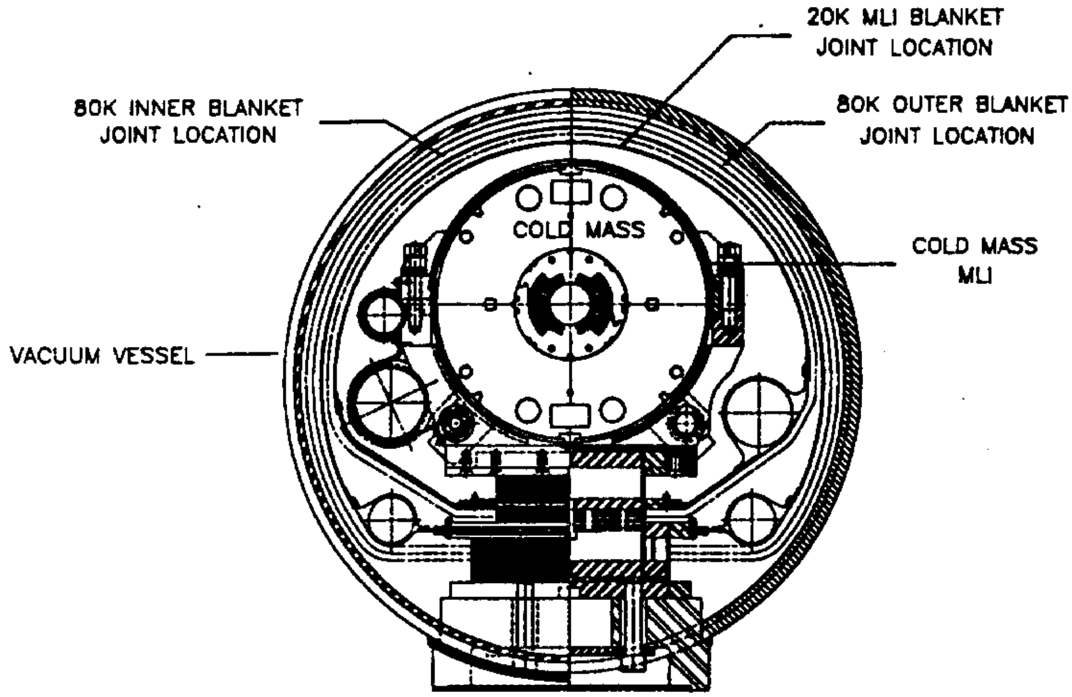

Figure 7. MLI locations in the 50 mm cryostat

The outer blanket is installed in a like manner. However, the outer cover layer of the outer blanket must be removed to uncover the outermost, or warm, layer of reflective DAM. Additionally, the emissivity flap, which consists of several layers of DAM, must be folded over the heavy spacer material covering the seam area to provide a low emissivity surface to thermal radiation.

QUALITY CONTROL

Quality control features inherent in the blanket design permit quick and easy assessment of the quality of each MLI blanket installation during cryostat production.

Uniform distance between sewn seams after blanket installation is a concise indication of proper blanket installation. As a fixed amount of material is contained between sewn seams, and as the amount of material remains constant from assembly to assembly as a function of the fabrication method, then maintaining a fixed distance between sewn seams maintains a fixed layer density from cryostat to cryostat. The result of controlled layer density is consistent thermal performance throughout the accelerator. During the 40 mm cryostat program, the preferred distance between seams across the joint connection was empirically determined for each blanket connection by trial fitting sections of MLI onto actual shields. The separation of the hook and loop fasteners was adjusted until the desired blanket fit was obtained. When the fasteners are superimposed during cryostat installation, the blanket installation is correct. A like procedure will be employed during the initial phase of 50 mm cryostat production.

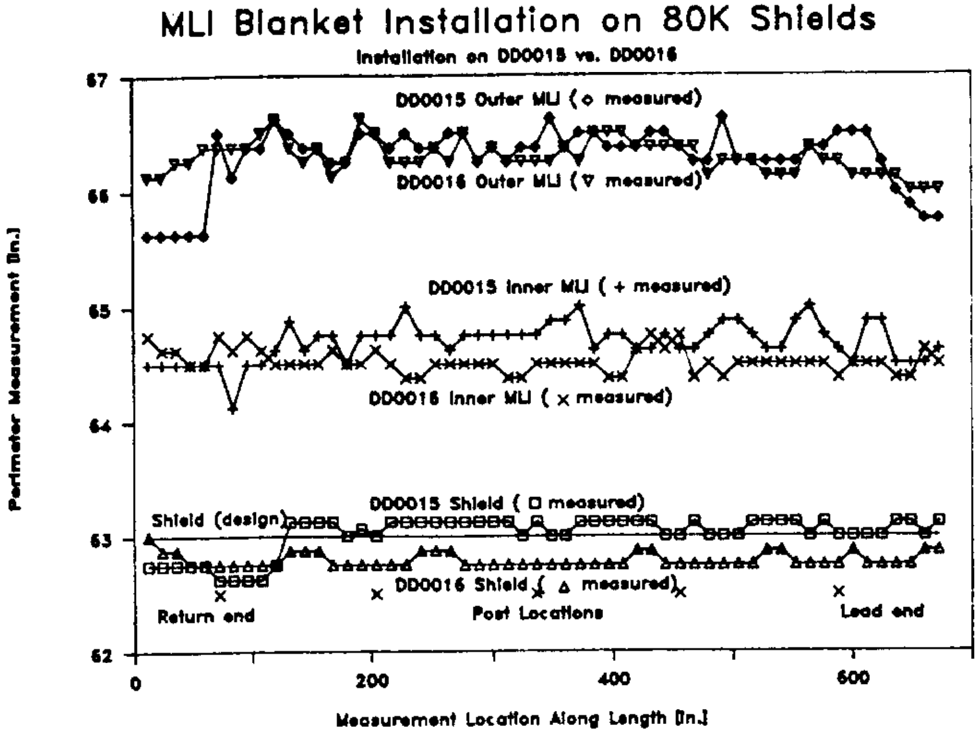

Figure 8. Quality control of MLI installations

During blanket fabrication, the seams are sewn parallel to within 32.0 mm along the entire blanket length. Hence, the distance between sewn seams across the body of the blanket is a fixed and known parameter. As a quality control procedure, measurements of the distance between sewn seams are made along the length of each blanket immediately after cryostat installation. These measurements provide a clear indicator of the quality of each blanket installation. Furthermore, the results, when compared with data from other cryostat installations, allow assessment of installation consistency from cryostat to cryostat. Figure 8 illustrates the consistency of blanket installations between cryostats; shown is data taken from the MLI installations on two SSC 40 mm dipole cryostats.

Finally, a visual confirmation that alignment marks, placed on the MLI blanket perpendicular to the cryostat axis, are superimposed during cryostat installation assures that the blanket is installed parallel to the cryostat axis. Moreover, it is a positive indication that sufficient material is contained between support locations to accommodate thermal contraction.

SUMMARY

The MLI system for the SSC 50 mm collider dipole cryostat closely resembles the MLI system for the 40 mm cryostat. The performance of the 80K MLI system has been experimentally evaluated, with results indicating that the design geometry meets the heat load budget for the 80K thermal shield. Thermal performance measurements are underway to quantitatively define the thermal performance of the MLI system design to 20K. All materials selected for use in the MLI system have properties appropriate for use in the SSC accelerator environment. Finally, the MLI blanket design allows for cost effective fabrication techniques which assure consistent thermal performance throughout the SSC accelerator.

ACKNOWLEDGEMENTS

The development of the MLI system for the SSC dipole cryostat has involved the talents and efforts of many individuals. In particular, the design and development of the system to its present state has been accomplished through the efforts of J. D. Gonczy, J.G. Otavka and M.K. Ruschman. Further appreciation is given to J. Kerby for analytical contributions and to D. Arnold, K. Sarna and K. Swanson for their assistance in preparing the illustrations for this work.

REFERENCES

1. M.H. Van de Voorde and C. Restat, 'Selection guide to organic materials for nuclear engineering,' CERN 72-7 (1972).
2. H. Burmeister, et al., Test of multilayer insulations for use in the superconducting proton-ring of HERA, in: "Advances in Cryogenic Engineering," Vol. 33, Plenum Press, New York (1988), p. 313.
3. A.P.M Glassford and C.K. Liu, 'Outgassing rate of multilayer insulation materials at ambient temperature,' J. Vac. Sci. Technol., Vol. 17, No. 3, May/June 1980, p. 696.
4. W. Burgess and Ph. Lebrun, Compared performance of Kapton and Mylar based superinsulation, in : "Proceedings of the Tenth International Cryogenic Engineering Conference," Helsinki, Finland (1984), p. 664.
5. T. Ohmori, et al., Thermal performance of candidate SSC magnet thermal insulation systems, in: "Advances in Cryogenic Engineering," Vol. 33, Plenum Press, New York (1988), p. 323
6. J.D. Gonczy, W.N. Boroski, and R.C Niemann, Thermal performance measurements of a 100 percent polyester MLI system for the Superconducting Super Collider: Part II, Laboratory Results (300K-80K), in: "Advances in Cryogenic Engineering," Vol. 35, Plenum Press, New York (1989), p. 497.
7. E.M.W. Leung, et al., Techniques for reducing radiation heat transfer between 77K and 4.2K, in: "Advances in Cryogenic Engineering,", Vol. 25, Plenum Press, New York (1980), p. 489.
8. T.R. Gathright and P.A. Reeve, Effects of multilayer insulation on radiation heat transfer from 77K to 4.2K, Proc. MT-9 Zurich, 1985, p. 696.
9. K. Kutzner, F. Schmidt, and I. Wietzke, Radiative and conductive heat transmission through superinsulations - experimental results for aluminum coated plastic foils, Cryogenics, July 1973, p. 396.
10. C.L. Tien and G.R. Cunnington, Cryogenic insulation heat transfer, in: "Advances in Heat Transfer," Vol. 9, Academic Press, New York (1973), p. 349.
11. P.E. Glaser, et al., Thermal insulation systems, a survey, NASA SP-5027.
12. R.G. Scurlock and B Sauli, Development of multilayer insulations with thermal conductivities below 0.1 $\mu W\ cm^{-1}\ K^{-1}$, Cryogenics, May 1976, p. 303.
13. W. Obert, et al., Emissivity measurements of metallic surfaces used in cryogenic applications, in: "Advances in Cryogenic Engineering,", Vol. 27, Plenum Press, New York (1982), p. 293.
14. R.P. Schutt, Some thoughts on superinsulation, Isabelle Division, Technical Note No. 21, Brookhaven National Laboratory (1976).
15. "Integrated thermal math model of the production dipole magnets for the Superconducting Super Collider," Report No. SSC-CDG-364-SDP.
16. Q.S. Shu, R.W. Fast, and H.L Hart, Theory and technique for reducing the effect of cracks in multilayer insulation from room temperature to 77K, in: "Advances in Cryogenic Engineering," Vol. 33, Plenum Press, New York (1988), p. 291.