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Thermal Performance Measurements of a 100 Percent Polyester MLI System for the Superconducting Super Collider; Part II: Laboratory Results (300 K - 80 K)*

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THERMAL PERFORMANCE MEASUREMENTS OF A 100 PERCENT POLYESTER MLI SYSTEM FOR THE SUPERCONDUCTING SUPER COLLIDER; PART II: LABORATORY RESULTS (300K - 80K)

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ABSTRACT

The plastic materials used in the multilayer insulation (MLI) blankets of the superconducting magnets of the Superconducting Super Collider (SSC) are comprised entirely of polyesters. This paper reports on tests conducted in three separate experimental blanket arrangements. The tests explore the thermal performance of two candidate blanket joint configurations each employing a variation of a stepped-butted joint nested between sewn blanket seams. The results from the joint configurations are compared to measurements made describing the thermal performance of the basic blanket materials as tested in an ideal joint configuration. Twenty foil sensors were incorporated within each test blanket to measure interstitial layer and joint layer temperatures. Heat flux and thermal gradients are reported for high and degraded insulating vacuums, and during transient and steady state conditions. In complement with this paper is an associate paper bearing the same title head but with the title extension PART I: INSTRUMENTATION AND EXPERIMENTAL PREPARATION (300K-80K).[1]

OVERVIEW

The tests reported herein continue the work conducted in a heat leak test facility (HLTF) to evaluate the thermal performance of candidate MLI systems for the SSC.[2] Besides meeting the design heat leak requirements for thermal radiation and residual gas conduction, 638 mW/M^2 to 80K, 87 mW/M^2 to 20K, and 3.3 mW/M^2 to 4.5K at an insulating vacuum of 1×10^{-6} Torr, the SSC MLI system must also maintain good performance during extended periods of operational upset conditions including thermal cycles and poor insulating vacuum. It is therefore essential to the operation of the accelerator that a functional SSC blanket design must include high MLI layer density to enable gas conduction shielding, and must have sufficient MLI material mass and heat capacity to dampen transient effects.[3]

The materials selection and blanket design for the SSC were formulated after careful consideration of several published works reporting MLI material properties and operational performance. A comparison of MLI properties is listed in Table 1. Table 2 summarizes the thermal performance of SSC candidate MLI systems as tested to date in the HLTF.

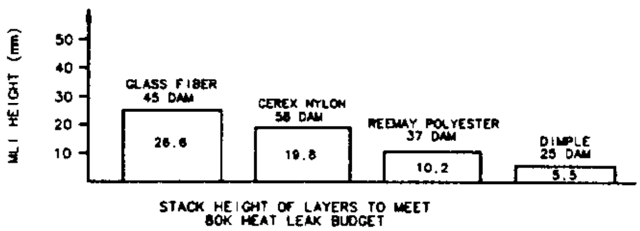
Table 1. Comparison of MLI material properties

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.

Table 2. Summary of thermal performance of SSC candidate MLI systems tested in the HLTF

TEMPERATURE BOUNDARIES 300K-80K	LAYERS DAM N	LAYER HEIGHT H, mm	LAYER DENSITY N/H̄ mm^{-1}	LAYER • HEATFLUX (N+1)q W/M^2	APPARENT k μW/cmK	TO MEET 80K HEAT LEAK BUDGET q = 0.64 W/M^2		SSC DIPOLE CRYOSTAT BLANKET DESIGN LAYERS OF DAM	
						LAYERS N	HEIGHT H, mm	LAYERS N	HEIGHT H, mm
GLASS FIBER DAM	11	6.50	1.69	29.3	0.72	45	26.6	48	28.4
CEREX NYLON DAM	26	8.87	2.93	37.5	0.56	58	19.8	64	21.8
DIMPLE DAM	26	5.71	4.55	16.7	0.16	25	5.5	28	6.2
REEMAY POLYESTER DAM	32	8.86	3.61	24.2	0.30	37	10 2	64	17.7



It has been shown that joint or crack characteristics in an MLI installation can overwhelm the operational behavior of the MLI system and contribute negatively to its thermal performance.[4] To ensure a consistent thermal performance in SSC MLI blankets, an apparatus and blanket fabrication method was developed to mass produce pre-fabricated blankets.[5] The apparatus and blanket fabrication method ensure consistency in mass produced blankets by providing positive control of the dimensional parameters that contribute to the thermal performance of an MLI system. The sewn seam technology developed for the SSC MLI blankets has proven to be mass producible, mass installable, and cost and time effective.

It is acknowledged that the sewn seams used in the MLI blanket degrade the ultimate thermal performance of the MLI due to thermal shorting of MLI layers by the polyester thread. The benefits provided by the seams, however, allow the MLI blankets to have inherent features such as dimensional stability and controlled layer density. Sacrificing "ideal" performance to assure "consistent" thermal performance is an engineering trade-off that is well made. Therefore, the sewn seams remain in the MLI blanket design, and measurements to determine the effects of altered sewn seam geometries are under study in the HLTF with the intent of identifying a seam geometry that meets the SSC heat leak budget.

MEASURING HEAT LEAK PARAMETER RELATIONSHIPS IN THE HLTF
APPARENT THERMAL CONDUCTIVITY, $k_{ap'nt}$, VERSES N-LAYERS HEAT FLUX, (N+1)q

Implicit in the use of apparent thermal conductivity is the understanding that for heat leak calculations to agree with the actual heat transfer through the MLI system, the MLI installation must have the same dimensional consistency and operate under the same environmental conditions that were present when the value of "mean apparent thermal conductivity" was determined. In practice, the calculated and measured quantities of heat transfer through an MLI system using this method will often disagree by factors of two and more because of the difficulty in duplicating in a global installation the same MLI geometry (same mean apparent thermal conductivity) as was tested in the laboratory.

Although the apparent thermal conductivity is a common parameter for comparing MLI systems, it contains two kinds of independent variables (q, and T verses H) that are measured with different degrees of accuracy. The measurement of MLI height (H) (or thickness build) has an inherently large reading error, due to the difficulty of maintaining a constant layer thickness and layer density during the fabrication of the MLI and its later installation into a cryostat. The measurements of heat flux (q) per unit area and temperature (both T_h and T_c) are done with much better accuracy. The N-layers heat flux constant is a better parameter for comparing MLI performance. Its relationship to apparent thermal conductivity is shown by the following:

Given, $$k_{ap'nt} = \frac{q}{(T_h - T_c)} H$$

Where:
$k_{ap'nt}$ = Apparent k, (W/cm K)
q = Heat Flux, (W/cm^2) (Heat Load/Cold Area)
T_h = Hot Boundary Temp.,(K)
T_c = Cold Boundary Temp.,(K)
N = Number of layers, (1)
L = Layer density, (1/cm)

By definition, MLI layer density (L) is the number (N) of reflective layers per unit height (H), L = N/H, and is expressed as the number of layers per centimeter. For MLI layers numbering N, the number of surfaces emitting thermal radiation to the cold surface include the warm surface, i.e., N+1 Arranging for H and substituting,

$$k_{ap'nt} = \frac{q}{(T_h - T_c)} \frac{(N+1)}{L}$$

The equivalent (N+1)q parameter for $k_{ap'nt}$ is then,

$$(N+1)q = k_{ap'nt} (T_h - T_c) L = \text{Constant}$$

Within identical MLI systems having the same materials and fabrication conditions, and given the same boundary temperatures and system pressure, the N-layers heat flux parameter is constant; and q varies inversely with the number of MLI reflective layers. The N-layers heat flux constant is a more accurate parameter for describing MLI thermal performance because the parameter inherently integrates in its measurement the difficult to measure variable of MLI layer density. It does so in terms that are precisely measured, i.e., the number of reflective layers, which we can count, and the heat flux, which we can accurately meter.

MLI BLANKET TEST ARRANGEMENTS IN THE HEAT LEAK TEST FACILITY

Thermal performance measurements were conducted in the HLTF in three experimental arrangements of a polyester MLI system. Each experiment measured the thermal performance of a 32-layer MLI blanket instrumented with twenty foil sensors that measured interstitial layer and joint temperatures. Fourteen of the sensors were located in the main body of the blanket on reflective layers 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, 29, 30, 31, and 32; and, six temperature sensors on layers 1, 8, 16, 17, 24, and 32 in the joint area between sewn seams. The instrumentation and experimental preparation required to do these thermal measurements are discussed in detail in Reference 1. Herein, the reported temperatures, pressures, heat flux and equilibrium times are supported by that work.

Design B Configuration MLI Test Blanket - In the first arrangement, the test blanket employed a stepped-butted joint located between straight sewn seams as found in an SSC Design B blanket geometry. (See Fig. 1.) The blanket incorporates 32 reflective layers of double aluminized polyethylene terephthalate (PET) film. Each reflective layer is separated by a single thin spacer layer of spunbonded PET material. A thick layer of spunbonded PET material covers the blanket top and bottom, and positions polyester hook and loop Velcro fasteners at the blanket edges. The fasteners are secured to the cover layer by sewing. The multiple blanket layers and cover layers are sewn together straight through the MLI assembly along both blanket edges. Polyester thread is used in all sewing processes.

The tightness of the blanket wrap during installation is fixed by the blanket design. Parallel Velcro strips sewn to the outer blanket layers serve to secure the blanket at installation to the cold plate test surface. The Velcro strips are separated by a distance determined empirically by trial fitting blanket sections to the test surface and adjusting the Velcro separation until the desired blanket fit around the test surface was obtained. Since both edges of the blanket are sewn, the MLI material locked between seams is caused to wrinkle or wave as the blanket is wrapped around the surface. This wrinkling occurs as a result of the regimented layers being unable to slide separately across each other as would be the case, for example, if only one edge of the blanket were sewn. Because of layer-to-layer registration, these wrinkles or waves usually have a uniform thickness along the wave that is roughly the same thickness as in the main body of the blanket. The MLI layer density is therefore minimally affected by the wrinkles. A favorable element of these wrinkles is that they provide additional material for thermal contraction of the blanket.

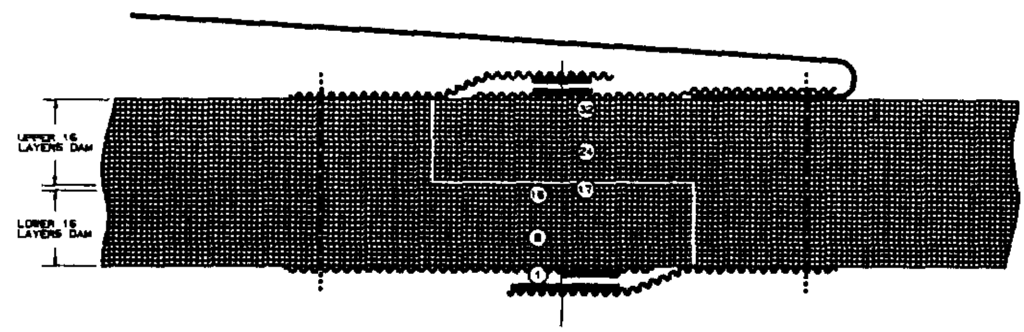


Fig. 1. Design B blanket - stepped joint / straight seam.

The blanket joint is made at installation by wrapping the blanket around the test surface such that edges of the blanket overlap. Next, opposite edges of the lower cover layer are secured to each other by the full-width engagement of the Velcro strips. The overlapped edges of the MLI layers are then joined along the entire blanket length using a stepped-butted joint geometry. The upper cover layer edges are drawn together over the stepped joint and secured by the full-width engagement of the upper Velcro strips. The completed blanket installation and stepped-butted-joint are doubly secured from opening by the engagement of the two Velcro pairs.

<u>Polyester</u> <u>Material</u> <u>Ideal</u> <u>Configuration</u> <u>MLI</u> <u>Blanket</u> - The second test made modifications to the MLI blanket of the first arrangement while the blanket remained in position on the test surface. In the second test, the threaded stitches in the sewn seam and the hook and loop fasteners were removed from the blanket. The parent polyester blanket material was then tested with the joint closure secured using MLI adhesive tape, and approximating an ideal joint configuration. Corresponding joint layers were overlapped and each third layer exiting the blanket was taped. (See Fig. 2.) All sensors in the main body of the blanket and joint area remained intact.

<u>Design</u> <u>C</u> <u>Configuration</u> <u>MLI</u> <u>Test</u> <u>Blanket</u> - The third arrangement tested the Design C MLI blanket joint geometry. The construction of the Design C blanket employs a stepped sewn seam at its blanket edges, and a stepped-butted joint for the blanket closure. (See Fig. 3.) The blanket geometry uses the same 32-reflective layer construction as in the other blankets tested, but with the following differences. A thicker PET layer is added to the Design C blanket and is located midway in the blanket to separate the upper and lower 16 reflective layers of MLI. And at each blanket edge, the upper cover and MLI layers are sewn together through to the midlayer with the thread ended in the thicker midlayer. The seam location is incremented laterally along the midlayer where the lower MLI layers are sewn through to the lower cover layer. The resulting stepped sewn seam attempts to reduce heat conduction through the blanket by interrupting and lengthening the solid conduction path of the thread. Velcro fasteners attached to the blanket are used to close the joint.

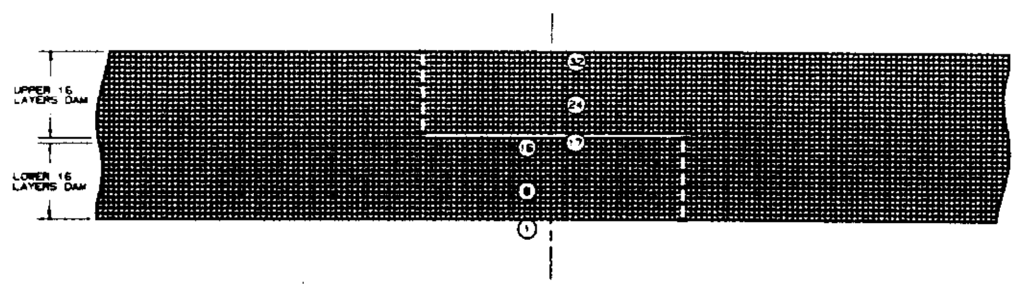


Fig. 2. Basic blanket - taped joint / no seam.

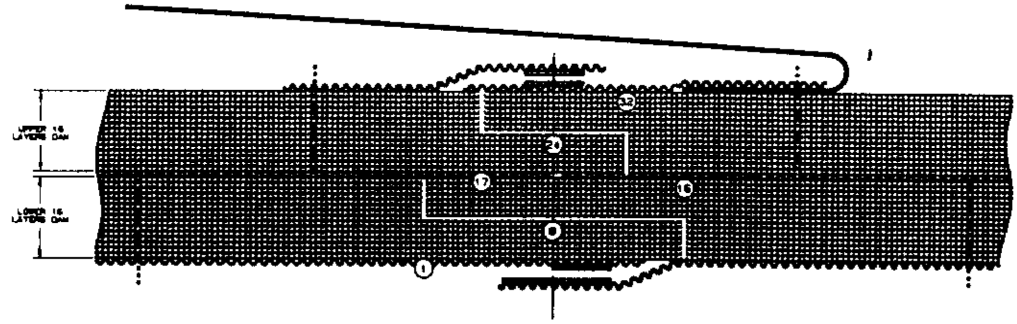


Fig. 3. Design C blanket - stepped joint / stepped seam.

TEST RESULTS AND DISCUSSION

The thermal performance results of the sewn seam configuration and joint tests are compared to the performance of the basic blanket having an ideal taped joint. Heat flux and thermal gradients were measured at different steady state insulating vacuums ranging between $1x10^{-6}$ and $1x10^{-2}$ Torr. In Fig. 4, the N-layers heatflux parameter, (N+1)q, for each test arrangement is plotted as a function of pressure. It is observed from the plots that the thermal performance of the Design C seam geometry approaches the performance of the ideal joint. It is also recognized that two MLI blankets made in the Design C geometry, even if installed seam above seam, would meet the SSC design heat leak budget to 80K. In practice, the SSC MLI design specifies that the lower and upper blankets alternate respective sewn seam locations to different sides of the shield. As a result, the lower blanket seam and joint area is completely covered by the main body blanket region of the upper blanket. The net heat flux through a two blanket assembly (64 reflective layers) will result in even lower heat flux than that required by the SSC magnet systems design requirements.

Temperature gradients across each respective blanket at steady-state conditions near $5x10^{-5}$ Torr are illustrated by Figs. 5 and 6. Figure 5 compares the interstitial layer temperatures in the main body of each blanket away form the sewn seams. It is seen by Fig. 5 that the MLI layer temperatures in the main body of the three blankets behave much alike. The colder layer temperatures between layers 6 and 25 of the stepped joint-stepped seam plot is attributed to increased conduction coupling between these layers due to a wider joint area between sewn seams of the Design C geometry. Compared with the Design B geometry, the Design C joint configuration places greater seam/joint area, and less main body area in test on the fixed surface of the cold plate. Figure 6 compares the interstitial layer temperatures in the blanket joint area between sewn seams. Comparing temperatures of the Design B and Design C geometries to that of the ideal taped joint, it is seen that the MLI layers between the seams operate colder at the warm boundary, and warmer at the cold boundary. The heat load performances of the different blankets described in Fig. 4 are decidedly affected by the amount of solid conduction present in the joint area as evidenced by the MLI temperatures and the degree of thermal shorting of interstitial layers. The flat heat leak response of the stepped joint/stepped seam geometry is witnessed by a reduction of thermal shorting in the seams, thereby allowing the Design C joint configuration to rival the performance of the ideal joint at high vacuum and to out perform the ideal joint at degraded vacuum.

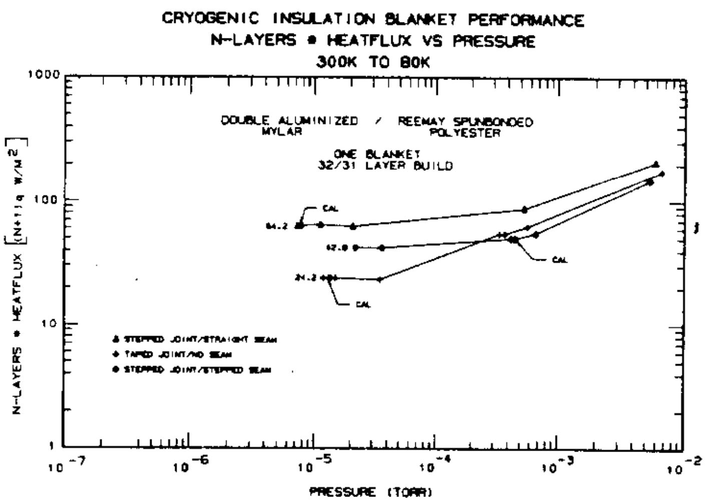


Fig. 4. N-layers heatflux vs. pressure.

Figure 7 shows the departure of the joint layer temperatures from the main body temperature gradient in the Design C configuration. Figure 8 charts the temperature gradient measured in the ideal geometry of the basic polyester blanket. The graph shows the concurrence of joint layer temperatures with the main body layer temperatures and corroborates the slope of the temperature gradient across interstitial MLI layers. Figure 8 also attests to the quality of the measurements as evidenced by the layer temperatures in the joint area of the first test arrangement equating with the temperatures of the main body sensors in the second test arrangement after the sewn seams were removed.

Figure 9 compares the steady-state temperature gradients measured across the basic polyester blanket at two steady-state vacuum conditions; the higher steady-state vacuum was 1.5×10^{-5} Torr; the lower vacuum was 5×10^{-4} Torr. The move towards a linear gradient in the main body MLI temperatures at the higher pressure is attributed to greater conductive coupling arising from increased (factor of 33) gas pressure.

A gas pressure rise (factor of 19) from 2.1×10^{-5} to 4×10^{-4} Torr for the Design C blanket shows no significant changes in the temperature gradient. (See Fig. 10.) The near linear gradient appears to be a characteristic of the Design C blanket due to conduction coupling of the layers by the sewn seams. The additional heating by gas conduction appears to be small compared with the solid conduction established in the MLI by the seams.

Other measurements that verify a coalescence of MLI thermal performance at degraded vacuums are the similarities of thermal gradients across MLI layers, as seen in Figs. 9 & 10, and looking back at Fig. 4, the N-layers heatflux heat transfer parameters at upper pressure regions.

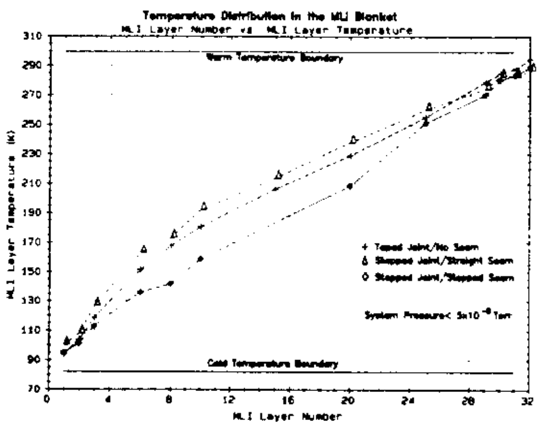


Fig. 5. MLI main body temperatures.

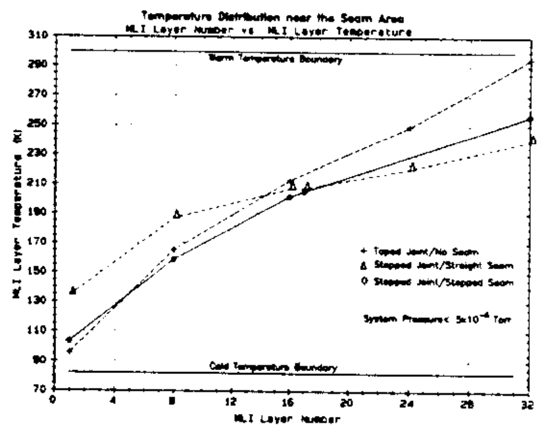


Fig. 6. MLI seam/joint temperatures.

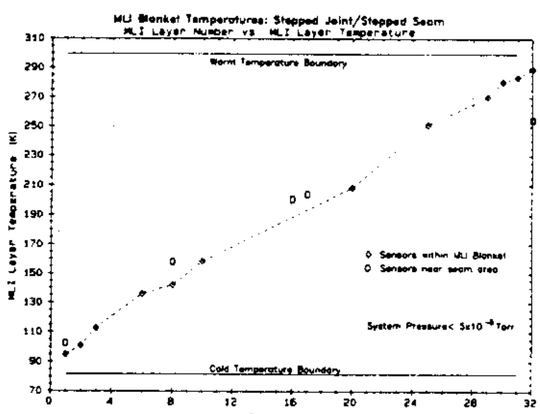


Fig 7. Design C thermal gradient.

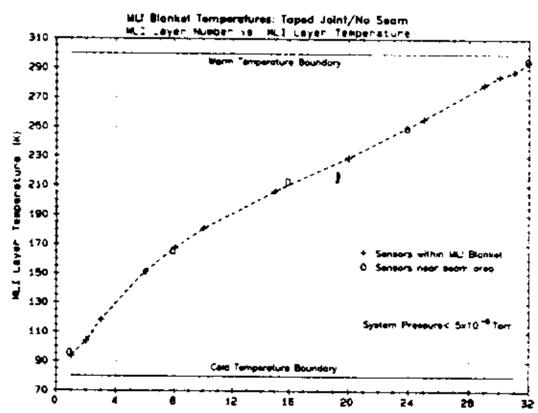


Fig 8. Basic blanket thermal gradient

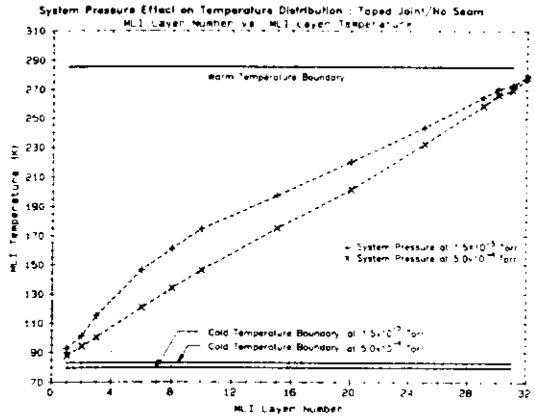


Fig. 9. Basic material blanket temperature vs. pressure.

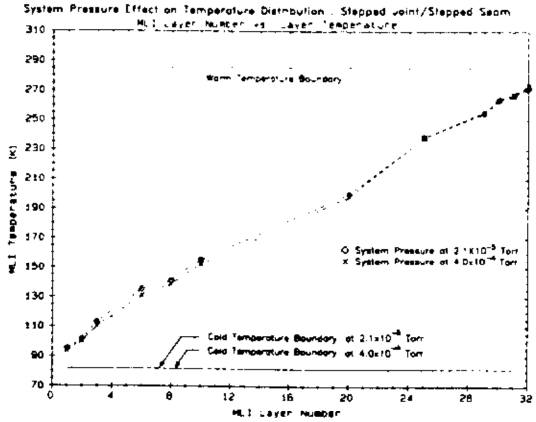


Fig. 10. Design C blanket temperature vs. pressure.

CONCLUSIONS

The plastic materials used in the Design C MLI blanket construction are comprised entirely of polyester materials. Stepped sewn seams serve to control MLI physical parameters that affect thermal performance while providing an MLI blanket package that is easy to handle and install.

The thermal performance of a 32-reflective layer MLI blanket fashioned in the SSC Design C geometry has been measured between 300K and 80K. The measurement results indicate that two MLI blankets fabricated and installed as specified by the dipole magnet cryostat Design C configuration will satisfy the SSC design requirements of heat load to 80K.

ACKNOWLEDGEMENTS

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