THEORY AND TECHNIQUE FOR REDUCING THE EFFECT OF CRACKS IN MULTILAYER INSULATION FROM ROOM TEMPERATURE TO 77 K*

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Abstract

Cracks or gaps in multilayer insulation blankets can significantly increase the heat load to a cryogenic system. Our experiments gave the mean equivalent thermal conductivity of a narrow crack to be 3 to 5 W/m-K between room temperature and 77 K. The heat flux through a crack was found to be ~ 150 W/m^2. The dependence of the heat load on crack width, geometry, properties of the cold surface under the crack, the depth of the crack, and overall vacuum pressure were systematically studied. Aluminized Mylar patches covering the cracks were found to be very effective in reducing the heat load. Using the optimum number and distribution of patches determined in our experiments, it is possible to eliminate the effect of cracks on the overall heat load. In order to understand the mechanism of heat transfer through cracks, the temperature distributions in the multilayer insulation adjacent to cracks were measured. A theoretical model has been developed to explain this "black crack" phenomena and provide more quantitative heat leak estimates.

INTRODUCTION

Multilayer insulation (MLI) has been studied for a long time and many aspects of its performance are now very predictable. However, there are still serious problems associated with cracks or penetrations in the MLI system which require a better fundamental explanation. Previous experimental studies have indicated that the degradation of the thermal performance of an MLI system due to cracks is much worse than previously thought.[1] Moreover, in large cryogenic devices, e.g., Superconducting Super Collider (SSC)[2] which has 8600 magnets with a total surface area of $2.3\times10^6 m^2$, there are almost always some assembly joints, gaps,overlaps and penetrations between prewrapped MLI blankets. The economic significance of reducing the effects of cracks in MLI systems is obvious, since most of the electric power consumed in large superconducting devices is in the refrigeration system.

Our goal in the investigation was not to study MLI matarials themselves, but to focus on the basic heat transfer mechanism of cracks: why the effects are so serious, and how the effects can be reduced. The so-called Enhanced Black Cavity Theoretical Model was developed to explain the unexpectedly large heat load caused by the cracks.[3] Experimentally, several patch methods were used to reduce the effects of cracks. The optimum number and optimum distribution of these patches along cracks in a MLI blanket were determined. A good patch system can improve the thermal performance of a MLI blanket with cracks to about that of a blanket without.[4] There are many different combinations of crack dimensions, patch material and distribution, which could have been tested. Several typical combinations were chosen for this study, but the theoretical model and experimental results are of general applicability, regardless of the MLI materials used.

EXPERIMENTAL ARRANGEMENT

The apparatus has been described in detail in a previous paper.[5] The inner copper plate, with an area of

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2.26 m^2, was refrigerated to 77 K by a thermosiphon tube connected to the liquid nitrogen supply and boil-off vessel. The temperature of the outer (warmer) box was automatically maintained at 277 K. The insulation vacuum was measured by a cold cathode gauge mounted directly on the warm box inside the vacuum space. Individual MLI layers were hung vertically on the inner plate. Accurately sized cracks of various widths and lengths were cut in the fluffy MLI blanket using a razor blade and an adjustable Micarta frame. The cracks were of zero width, called slits; of finite width, called slots; and with equal length and width, called square holes. An optical transit was used to measure the actual dimensions of the cracks. To avoid errors associated with layer density, one 30-1ayer MLI blanket was used for the seven runs to investigate the effects of slot width on thermal performance, by starting with the narrowest slot and progressively enlarging it. Another blanket was used for testing heat load reduction methods. Flat, double-aluminized Mylar (DAM, 500 angstroms each side) and crinkled single-aluminized Mylar (SAMC, 300 angstroms each side) were used as patch materials. The patches were centered over the slots and square holes with a 10mm overlap and secured with tape. In order to understand the heat transfer mechanism in a MLI blanket with cracks, copper-constantan thermocouples were mounted with aluminum tape layers 5, 10, 15, 20, 25, 30 and to the cold plate and warm box. The junction was 3mm from the edge of the slot and almost in the longitudinal center. All of the thermocouple wires were led out of the cryostat to a scanner without joints or splices to avoid the errors due to thermovoltage. The heat sinking of the wires was done carefully.

RESULTS OF CRACK EXPERIMENTS

Increase in Heat Load

The heat load, Q_0, from a 277 K copper box to a black painted fin, with an area A=2.24 m^2, through 30 layers of MLI without cracks is 1.4 W and the corresponding heat flux, Q'_0, (Q_0/A) is 0.63 W/m^2. The total heat load, Q_C, from the same warm box to the same fin through 30 layers of MLI with fourteen slots (each nominally 4×254 mm^2, and total measured area A_S = 0.0114 m^2) is 2.74 W. The increment of heat load, which is the heat load through the slots, ($Q_S = Q_C - Q_0$) is 1.34 W. The heat load through the slot per unit slot area labeled as the heat flux through the slot, Q_S/A_S = 117.5 W/m^2. This flux, Q'_S, is about 200 times larger than the heat flux through a similar MLI blanket without cracks, i.e., $Q'_S / Q'_0 \cong 200$.

Effect of Crack Width on Heat Flux

In order to investigate the effect of slot width on heat flux, the heat load through a 30-layer MLI blanket was measured for crack widths of 0, 2, 4, 6, 9, 15 and 30 mm.

One-dimensional slit. The measured data with one-dimensional slits shows clearly that such slits do not increase the heat flux through a MLI blanket. They do, however, simplify evacuation of the MLI blanket.

Two-dimensional slot. For slots, Q_C/A is a monotonically increasing function of slot width. The slope of the curve up to a slot width of about 2 mm was 33.5 W/m^3, for widths between 2 and about 9 mm the slope was 243 W/m^3; above 9 mm it was 179 W/m^3. Figure 1 shows the Q_S/A_S and the equivalent thermal conductivity as a function of the slot width. The heat flux increases rapidly with width to a broad maximum of about 150 W/m^2 at 9 mm,then decreases slowly and approaches the bare plate value of 24.7 W/m^2.[5] The maximum value is more than 200 times the heat flux through a 30-1ayer MLI blanket without slots.

Effect of Crack Geometry on Heat Flux

To investigate the effect of crack geometry on heat flux, square holes were cut in the 30 - layer MLI blanket in the same geometric distribution and the same area as the 4 mm slots. The overall heat load increment caused by the square holes is 1.57 W; and the heat flux through the slot is 149 W/m^2, which is slightly larger than that caused by the 4-mm slots.

Effect of the Properties of the Cold Surface Under Slots

The effect on the heat flux of the properties of the cold surface under the slots was tested with two runs using the same MLI blanket with fourteen 4 × 256 mm^2 slots. For one run the cold copper surface was painted black; in the other it was covered by 3M #425 aluminum tape. The experimental data shows that the increment of heat flux due to the slots is almost independent of the cold surface emissivity: the values were 1.34 W for the black painted surface and 1.40 W for the aluminum taped surface.

Effect of Slot Depth on Heat Flux

In order to study the effect of slot depth on heat flux, fourteen 6-mm wide, 245-mm long slots were cut on both a 30-layer and a 90-layer MLI blanket. The measured data shows that the heat flux through the slots is 130 W/m^2 for the 30-layer blanket and 139 W/m^2 for the 90-layer blanket. Evidently the deeper the slots, the more heat goes through the slots.

The Effect of Overall Vacuum on Heat Flux

Figure 2 shows the overall heat flux through MLI blankets with various slot widths as a function of overall vacuum pressure. It can be seen that slots in an MLI blanket provide less thermal protection under poor vacuum conditions.

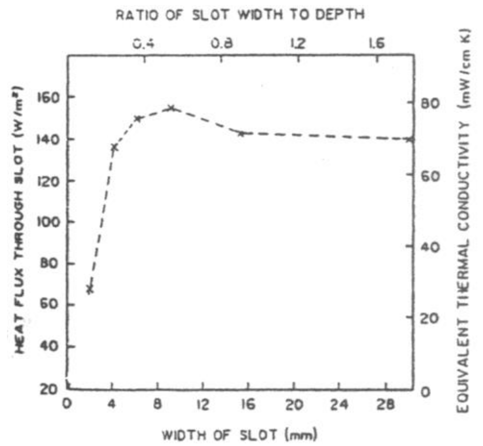

Fig. 1. Heat flux through slot and equivalent thermal conductivity of slots as a function of slots width for exposed slots.

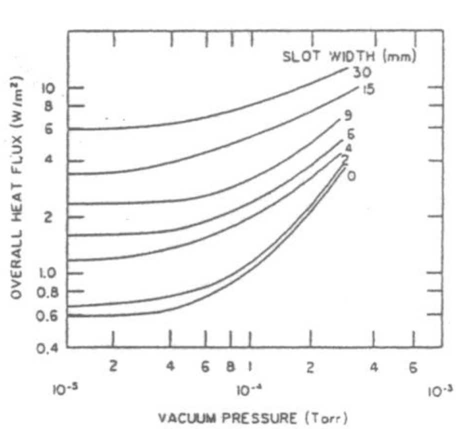

Fig. 2. Heat flux as a function of overall vacuum level for exposed slots of various widths.

THEORETICAL MODEL

In order to explain the unexpectedly large heat transfer through a crack in a MLI blanket and to optimize procedures for reducing this significant effect, a theoretical model, the so-called Enhanced Black Cavity Model was developed.[3] The steps in the model analysis can briefly described as follows:

1. A crack in a MLI blanket was first considered as a cavity in a low emissivity enclosure, with the edges of the cut MLI acting as a wall which absorbed all the incident radiant energy in the sandwich structure of the MLI edges.
2. The multi-reflection of radiation flux between the shiny MLI Mylar and the polished inner surface of the vacuum jacket greatly enhances the radiant flux into the crack.
3. The temperature distribution in the region near the crack affects the heat transfer through the MLI blanket, which in turn increases the heat flux to the crack.
4. The relative dimensions of a crack also influence its absorptivity; this is considered here as a cavity effect.

Figure 3 shows that radiant fluxes from the warm external environment enter directly and indirectly into a crack and are totally absorbed by the structure of the MLI and the cold surface after successive reflections inside. Figure 4 is a simplified example, showing one black surface DC (represented as a slot in the MLI) surrounded by three shiny surfaces. The radiation energy from point 1 of plane C reflected by A to the slot, appears to come from an image point 1' in an image plane C(A). In this case there are thirteen additional image surfaces, all of which emit additional radiation to the slot greatly and enhancing the transmitted energy flux. So if Q_E is the radiation energy directly emitted from warm box, then the total increment of heat flux due to the slot is

$$Q_T = \eta Q_E \tag{1}$$

where

$$\eta = \eta_R \, \eta_T \, \eta_C \tag{2}$$

and η is the total enhancement factor, which unifies the enhancement factor for multi-reflection η_R, the enhancement factor for temperature distribution change η_T, and the cavity factor η_C . η can be determined by a combination of theoretical calculations and experimental results. Once η is determined, the total enhancement of the heat flux due to cracks can be calculated using E_q. (3) from Reference 3:

$$Q_T = \eta \sum_{i=1}^{N} \varepsilon_2 \alpha T_2^4 \left[S_i \left(F_{Si-A} + F_{Si-B} + F_{Si-C} \right) \right] \tag{3}$$

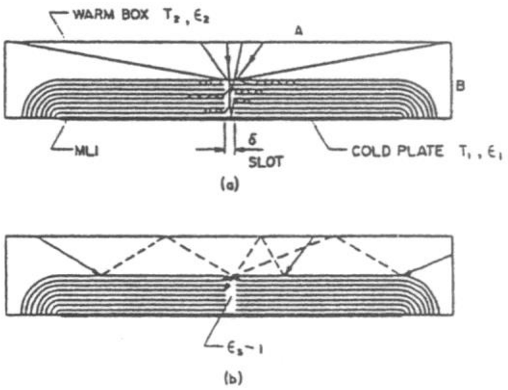

Fig.3. Radiation flux entering crack in MLI; (a) directly, (b) by reflection.

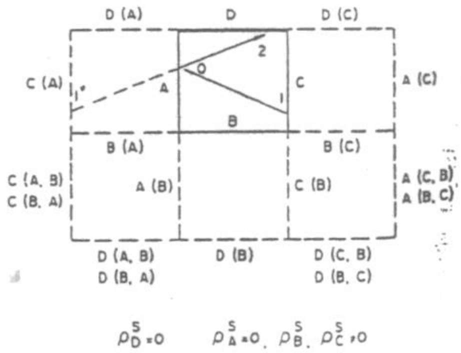

Fig.4. Theoretical approximation of a slot in a MLI blanket.

where N is the number of slots, α is the Stefan-Boltzman constant; ε_2 is the emissivity of warm box; T_2 is the temperature of warm box; S_i is the area of slot i, and F is the corresponding view factor. Figure 5 is an example of the calculated of heat load through the crack for our experimental apparatus.

CRACK COVERING TECHNIQUE USING PATCHES

Most of the results of the work to reduce the effects of cracks by using patches to cover them are shown in Fig. 6. We optimized the number and distribution of the patches, and studied two different patch materials.

Optimum Patch Distribution

Four data runs were made to find the optimum patch distribution. DAM patches were used, and as shown in Fig. 6d-g, could reduce the heat flux to approximately that of a MLI blanket without cracks. Locating a few patches in the outer (warm) half of the blanket, is as effective as a uniform distribution of patches and better than patches in the inner (cold) half. Figure 6m shows that locating all patches on the top of the crack is not effective.

Optimum Number of Patches

Having quantitatively determined that patches in the warm part of the blanket were very effective in reducing the effect of cracks, the number of patches was investigated. The results are shown in Figure 6h-m. It appears that between four and six patches is the minimum necessary to achieve a significant reduction in the heat flux, and the effect becomes marginal above about six. The optimum, for this geometry at least, is six patches.

Patch Material

Figure 6 shows that 2 × 500 angstrom DAM may be more effective as a patch material than 300-angstrom SAMC. For an identical, uniform distribution of patches, i.e. Fig. 6g and i, it is quite clear that the DAM is preferable.

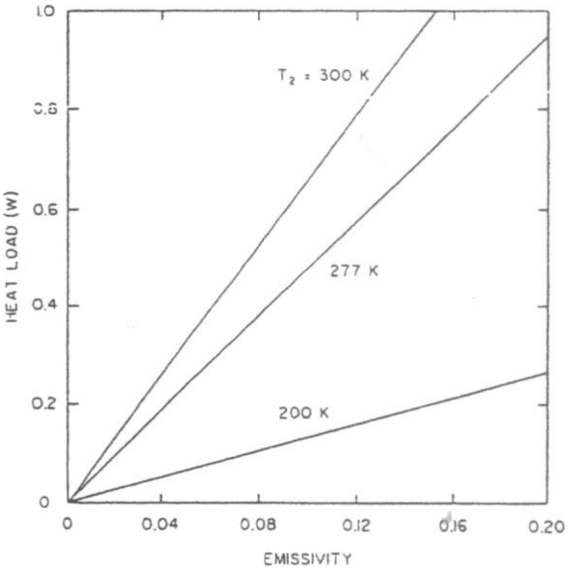

Fig.5. Heat load as a function of the temperature and emissivity of warm surface.

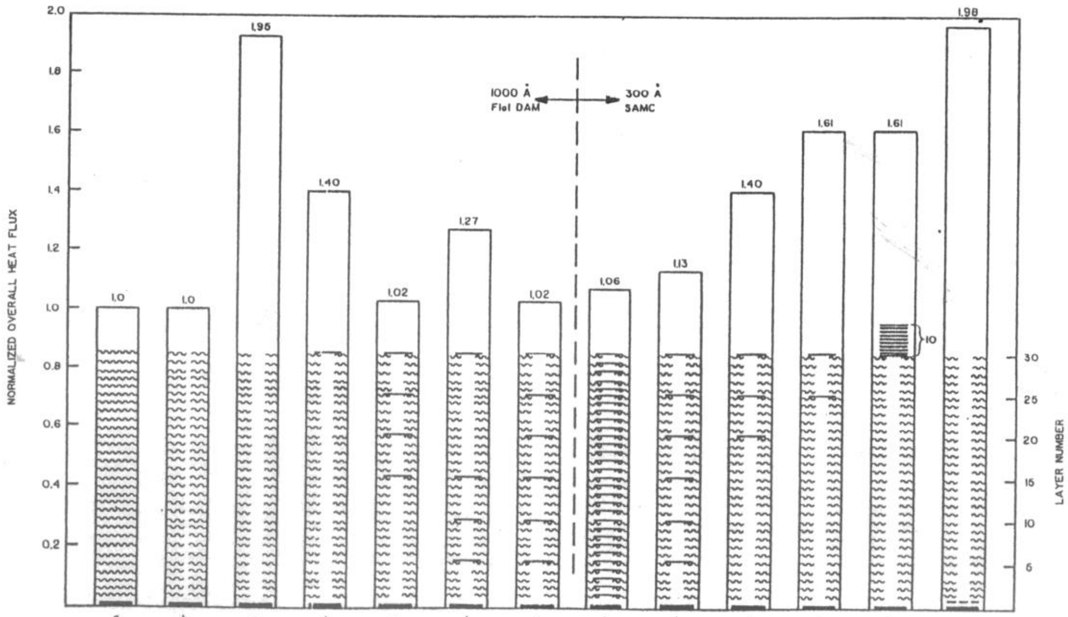

Fig.6. Graphic summary of experimental patch study. a, no cracks; b, one-dimensional slits; c to m, various patch geometries; n, no patches.

Parches on Square Hole

The square holes in the 30-layer MLI blanket were covered by four patches, located at the 15th, 20th, 25th and 30th layers. This reduced the overall heat flux from 1.57 W/m^2 to 0.83 W/m^2, which is the same as that for DAM patches on slots of the same area.

TEMPERATURE DISTRIBUTION AND EQUIVALENT THERMAL CONDUCTIVITY

The temperature distribution in MLI near cracks is a sensitive function of the crack width and the patch locations among the layers. This provides considerable information on the heat transfer mechanism through the insulation blanket. A typical temperature distribution, Fig. 7, shows that the presence of cracks changes the entire temperature distribution. The local equivalent thermal conductivity in the vicinity of the cracks was calculated from the temperature distribution, and is shown in Fig. 8. From these data, the temperature in the last patch (on the warmest layer) is an indication of the improvement in thermal performance resulting from the patches. Qualitatively, the higher the temperature of the last patch, the smaller the heat flux transmitted through the crack.

CONCLUSIONS

The quantitative effects of cracks in MLI blankets on the heat load to a cryogenic device are dependent on the MLI material, the geometry of the device and the care with which the MLI is applied. Nevertheless, the experimental results and theoretical model presented here lead to conclusions which should be of general interest. These can be summarized as follows:

1. A significant increase in the heat flux will be caused by cracks. The mean equivalent thermal conductivity of a narrow crack between room temperature and 77 K is 3-8 W/m-K. The heat flux through a crack is a function of the aspect ratio of the crack,with a maximum of about 150 W/m^2.

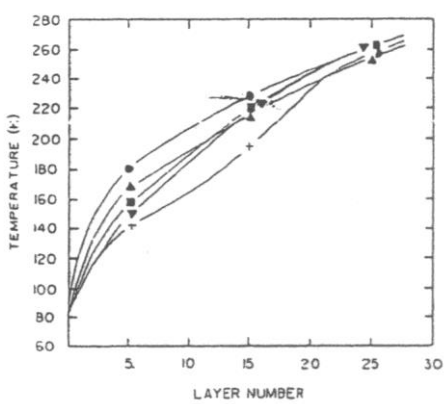

Fig. 7. Temperature distributions for slots with DAM patches ●, slots with out patches; ▲, single patches on layer 30; +, patches on layers 15, 20, 25, 30; ■, patches on layers 5,10,15,30; ▼, patches on layers 5,10,15, 20, 25,30

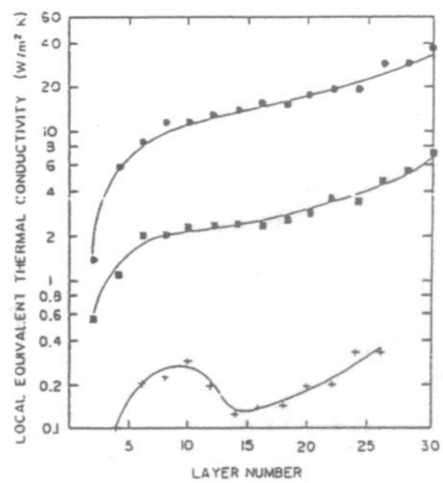

Fig. 8. Local equivalent thermal conduc tivity for slots with DAM patches as a function of depth in blan ket.●, slots without patches; +, patches after layers 15, 20, 25,30; ■, patches on layers 5,10,15,30

2. According to the Enhanced Black Cavity Model, the unexpectedly large heat transfer can be attributed to: (a) the crack acting like a black cavity and, (b) the multi-reflection of the radiation flux outside the crack. The temperature distribution in a blanket with cracks corresponds to greater heat transfer. There is a geometric factor, determined by the dimensions of the crack, which parameterizes the black cavity effect. Once this enhancement factor is determined, the heat increment due to the cracks can be calculated.
3. The use of aluminized Mylar patches to cover the crack at each layer is good, but may not be easy to install. On the other hand, the use of flat, DAM, 1000 angstrom patches on a few layers will give almost the same improvement as patches between each layer. Placing the patches in the outer (warmer) half of the blanket is much better than in the inner (colder) half. Putting patches on the outside of the crack is not very effective.
4. Mylar with more aluminizing (1000 angstroms) is better as a patch material. Crinkled Mylar with 300-500 angstrom single aluminizing is easier to install since spacers are not required.

5. Reducing the emissivity of the cold surface under a narrow crack does not significantly effect the heat flux.
6. The presence of cracks and patches changes the temperature distribution in the MLI blanket near the cracks. The temperature of the layer closest to the cold surface increases and that of the layer closest to the warm surfaces decreases as the width of the slots increases. Patches have the effect of lowering the temperature of the MLI blanket near a crack below that for an exposed slot. The higher temperature of the last (warmest) patch indicates the ability of a patch system to protect the cold surface against incoming radiation.
7. The local equivalent thermal conductivity of a crack is a sensitive function of the distribution and number of patches along the crack. It is a minimum around the first patch from the cold surface, and a maximum a few layers after the first patch.

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