

HEAT FLUX FROM 277 TO 77 K THROUGH A FEW LAYERS OF MULTILAYER INSULATION*

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Received 19 August 1986

The insulating ability of a multilayer insulation (MLI) system, consisting of a few layers on an aluminium taped 77 K surface, was experimentally studied to understand quantitatively how thermal performance changes with the number of multilayers and vacuum level. This information can help to make design decisions trading-off the cost of material and installation manpower against liquid nitrogen consumption in many cryogenic applications. The ratios of the measured heat flux for different systems are: $Q_{\text{(painted)}}: Q_{\text{(taped)}}: Q_{\text{(5 layers)}}: Q_{\text{(10 layers)}}: Q_{\text{(20 layers)}}: Q_{\text{(30 layers)}} = 1: 0.19: 0.06: 0.037: 0.027: 0.022$. The effective thermal conductivity also increases with the number of layers so only a marginal benefit can be gained in excess of 30 layers; for large liquid vessels 30-40 layers are recommended. The heat flux and temperature distribution in the MLI were also measured as functions of vacuum pressure. The temperature of the last layer is closer to the temperature of the warm box than that of the first layer is to the cold surface, even if the last layer is separated from the warm box and the first layer is in contact with the cold surface. The results and heat transfer mechanisms through MLI are analysed and discussed.

Keywords: multilayer insulation; heat transfer; low temperature calorimetry; thermal conductivity

Nomenclature			
A	Heat transfer area(m ²)	N	Total number of layers in the multilayer insulation system
D(N)	Total layer density for N layer system(m ⁻¹)	N _{ij}	Number of layers between layer i and layer j
D _{ij}	Layer density between layer i and layer j(m ⁻¹)	Q(N)	Heat transferred through N layer system(N)
K(N)	Effective thermal conductivity of N layer system (W m ⁻¹ K ⁻¹)	Q _{ij}	Heat transferred between layer i and layer j(W)
K'(N)	= K(N) D(N) (W m ⁻² K ⁻¹)	T _i	Temperature of ith layer (K)
K _{ij}	Effective thermal conductivity between layer i and layer j(W m ⁻¹ K ⁻¹)	T _{N+1}	Temperature of warm box (K)
K'(n,n+1)	Local effective thermal conductivity between nth and (n+1)th layer: K'(n,n+1)	T ₀	Temperature of cold copper plate (K)
	=K _{n,n+1} D _{n,n+1} (W m ⁻² K ⁻¹)	△T _{ij}	Temperature difference between layer i and layer j (K)

Large scale applications of superconductivity have been developed much more during the last 10 years than ever before. Applications such as the Fermilab Tevatron, a superconducting accelerator with a diameter of 2 km, and large scale fusion devices, such as MFTF and LCT, have been completed and operated successfully. The cryogenic systems associated with such devices must not only be reliable but must also satisfy economic requirements. The thermal insulation used in cryogenic systems has always played an important role in these considerations. Any improvement in thermal insulation will bring economic benefits in proportion to the size of the device. However, the insulation systems used in aerospace applications have other special requirements. Sometimes for these special applications, a light, reliable insulation system must be installed into a narrow space.

Recognizing these general factors, the insulation system for a cryogenic device is usually chosen by

* Work sponsored by Universities Research Association under contract with the US Department of Energy

**Cryogenics 1986 Vol 26 December

optimizing the costs of manpower, multilayer insulation (MLI) material and cryogenics, and including factors for any special requirements. To perform this optimization, it is necessary to understand the heat transfer mechanism in MLI. Unfortunately, heat transfer data do not exist for many possible MLI systems applied to different temperature regimes. Additional experimental data on the thermal performance of MLI in different configurations will not only extend theoretical knowledge in the field, but will also give more alternatives to scientists and engineers in the design of cryogenic devices.

The use of aluminium tape in conjunction with MLI has been studied both from 300 to 77 K (Reference 1) and from 77 to 4.2 K (Reference 2), and the results have been adopted in practice³⁻⁶. The heat flux measurements described in Reference 1 have been extended by the authors to include using only a few layers of MLI on an aluminium taped cold surface.

The temperature distribution through an MLI system is important because from it one can infer the dependence of the thermal performance on radiation, residual gas and solid conduction. A knowledge of the temperature distribution is also helpful when locating intermediate temperature radiation shields. A simplified but widely used theoretical model of the temperature distribution through an MLI system⁷ is shown in Equation (1)

$$T_i = \left[T_0^4 + \frac{i}{N+1} (T_{N+1}^4 - T_0^4) \right]^{1/4} \quad (1)$$

A comparison of measured temperature distributions with those calculated using Equation (1) will be helpful in understanding the basic heat transfer phenomena.

EXPERIMENTAL METHOD AND SYSTEM

The experimental system is shown schematically in Figure 1. The inner copper plate with an area of 2.26 m² was refrigerated by a thermosiphon tube connected to the liquid nitrogen supply and boil-off vessel. The surface of the inner plate was taped with 3M, No. 425 aluminium tape and was then wrapped by vertically hanging individual crinkled single aluminized Mylar sheets (NRC-2* with aluminium thickness 300 Å**). The nitrogen boil-off vessel was shielded by a liquid nitrogen guard vessel and copper shields.

To control the temperature of the outer (warm) box and to measure the temperature distribution in the MLI, copper-constantan thermocouples (diameter 0.07 mm) were taped to the box and plate, and placed between some of the multilayers. All the thermocouple wires were provided with a heat sink by taping them to a liquid nitrogen temperature surface or to an ambient temperature surface, depending on which temperature was closer to the measured point. To avoid measuring errors due to thermo-voltages, each thermocouple wire was led out of the test cryostat and to the scanner without joints or splices. Temperatures were recorded at 12 different points: two on the outer box, two on the guard vessel and shield, one on the cold plate and seven in the MLI. One of the thermocouples on the outer box was used by a temperature controller to adjust the current in heater resistors on the box to maintain the temperature of the box at 277 K.

A high capacity cold trap was located between the insulating vacuum space and a diffusion pump. Cold cathode vacuum gauges were mounted on the room temperature vacuum lid and on the outer box inside the vacuum space. The readings of the gauge on the box were used to monitor all the data presented here. Figure 2 shows the simple but very effective arrangement used to automatically maintain a specific vacuum level to

* King-Seeley Company, Winchester, Massachusetts, USA

** 1 Å = 0.1 nm

within $\pm 0.2 \times 10^{-5}$ Torr* by adjusting resistor R4. The block and bleed circuit was installed as a gas control system⁸ to permit a known amount of helium (or nitrogen) to be added to the vacuum space to simulate leaks in a liquid nitrogen shielded superconducting magnet or helium transfer line.

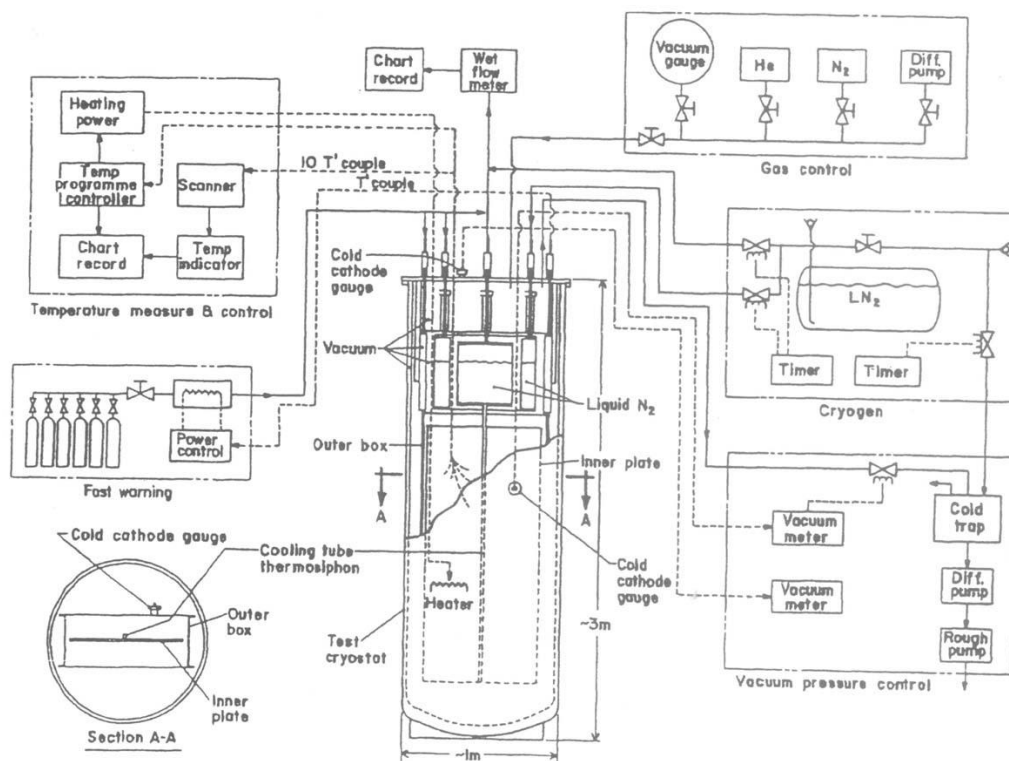


Figure 1 Schematic flow diagram of the heat transfer experiment

A wet test meter was used to measure the nitrogen gas boil-off to an accuracy of $\pm 0.2\%$. The correction factor to relate nitrogen boil-off data to evaporation rate is 1.0058; this was ignored in analysing the data.

Two timers and several solenoid valves were installed on the nitrogen transfer line to fill the boil-off vessel, guard vessel and cold trap automatically during the experimental run period of ≈ 10 days. The system could be warmed quickly after the run to permit a short turn-around time. Several relief valves were mounted in the liquid nitrogen transfer line to protect against over-pressure.

HEAT FLUX WITH A GOOD VACUUM

Figure 3 shows the heat flux measured with a few layers of MLI on an aluminium taped 77 K fin at an overall vacuum pressure of 2×10^{-5} Torr. The heat fluxes for copper surfaces painted black and polished without MLI are given for comparison (data taken from Reference 1). The new data for 30 multilayers is seen to compare favourably with that recorded earlier. The heat flux through five multilayers was compared to that from other surface finishes without MLI

$$Q_{(\text{painted})}: Q_{(\text{polished})}: Q_{(\text{taped})}: Q_{(5 \text{ layers})} = 1.0: 0.56: 0.19: 0.06$$

It is obvious that using even a few multilayers greatly reduces the heat flux through a vacuum space. Therefore, it is worthwhile putting a few layers on each surface even for a difficult geometry. It can be seen that although increasing the number of layers plays an important role in decreasing the heat flux when the number of layers is < 30 or 40 , the improvement from additional layers becomes increasingly marginal. A taped surface should be better than a bare, heavily oxidized surface regardless of the number of layers applied.

* 1 Torr=133.3Pa

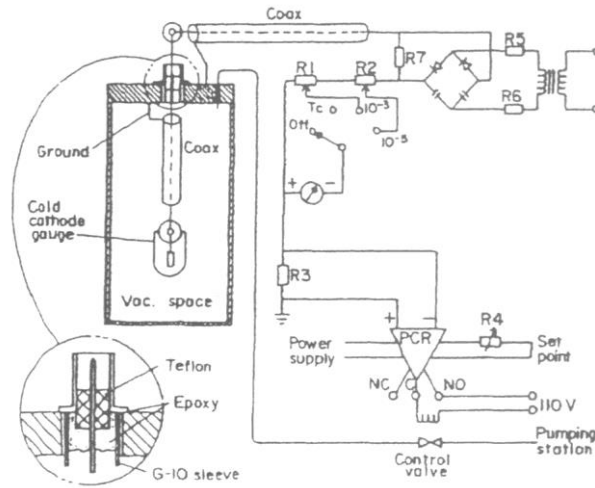


Figure 2 Schematic diagram of the vacuum control system

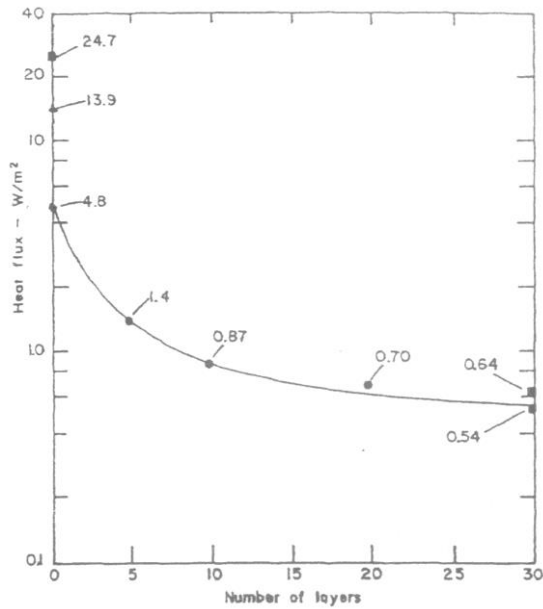


Figure 3 Heat flux as a function of the number of MLI layers and surface preparation at a vacuum of 2×10^{-5} Torr. Data on polished and painted copper taken from Reference 1. ■, MLI on copper painted black; ▲, polished copper; ●, MLI on taped copper

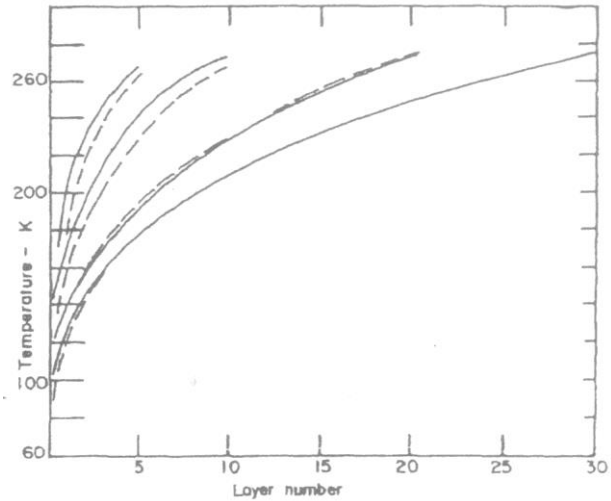


Figure 4 Temperature distribution of MLI system applied on aluminium taped copper surface with a vacuum of 2×10^{-5} Torr. — — —, Calculated distributions; —, measured distributions

TEMPERATURE DISTRIBUTION AND THERMAL CONDUCTIVITY

Figure 4 shows the measured temperature distribution in MLI blankets on an aluminium taped 77 K copper surface at an overall vacuum pressure of 2×10^{-5} Torr. The distributions calculated from Equation (1) are plotted with dashed lines. Although Equation (1) is a simplified model, considering only radiation heat transfer, comparison of measured and calculated values indicates the relative contributions of radiation, and residual gas and solid conduction to the overall heat transfer as a function of depth. This understanding is helpful in finding ways to improve the thermal performance of MLI insulation systems⁹⁻¹¹.

Good agreement was found between calculated and measured temperature distributions at temperatures > 230 K (outermost region) and < 140 K (innermost region) for both 20 and 30 layer blankets. The measured and

calculated temperature distributions in the temperature range 140--230 K (intermediate regime) differ by 3-4K.

The experimental results proved that radiation heat transfer in the outermost region of a MLI blanket dominates the overall heat transfer. The residual interstitial gas is more easily pumped out in this region. The difference between the calculated temperature distribution in the intermediate region, based on a pure radiation model, and the measurements can be attributed both to interlayer gas conduction, which is a function of the interlayer vacuum pressure, and to solid conduction between adjacent layers which depends on the layer to layer bearing pressure. In the innermost region the evacuation of interlayer gas is not good, but the residual gas pressure is a function of temperature, $(T_1/T_2)^{1/2} = P_1/P_2$, so the residual gas pressure is lower in the innermost region than in the intermediate region. The good agreement between the theoretical and measured distributions in the innermost region implies that solid conduction from 277 to 77 K in a MLI blanket of low packing density is less important than radiation heat transfer.

The difference between the calculated and measured distributions shown in Figure 4 for five and 10 layer blankets may also be caused by a boundary effect, since the emissivity of the inner surface of the outer box is very different from the emissivity of the aluminized Mylar. However, the emissivities of the outer box and the aluminized Mylar were assumed to be the same in Equation (1), This causes a greater difference for fewer layers than for more layers.

The temperature distributions with normalized depth are shown in Figure 5, where the dashed lines show calculated values. It can be seen that the temperature calculated at any depth in systems with more layers is higher than in systems with fewer layers. However, the measured temperature distributions are more complicated. The temperature first increased with an increasing total number of layers and then decreased. This behaviour is determined by the relative importance to the effective thermal conductivity of radiation, residual gas conduction and layer to layer solid conduction in each region.

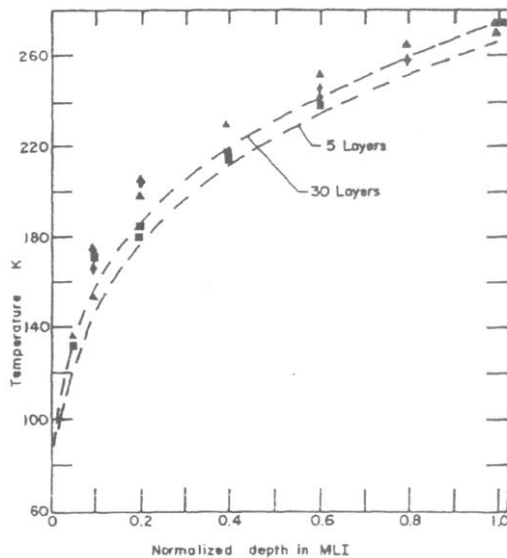


Figure 5 Temperature distribution versus normalized depth, ●, Five layers; ▲, 10 layers; ■, 20 layers; ◆, 30 layers. --, Calculated results

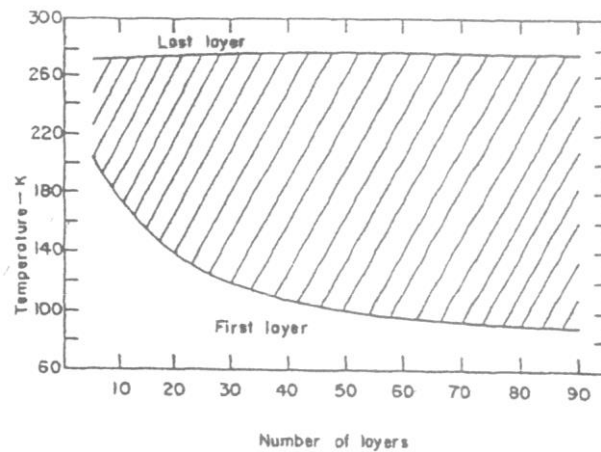


Figure 6 Temperature of first and last multilayers as a function of total number of layers

Figure 6 shows the temperature of the last layer (closest the warm surface), T_N , and of the first layer (closest the cold surface), T_1 , in MLI blankets between 77 and 277 K as a function of the total number of MLI layers. The possible temperatures in MLI blankets of from five to 90 layers fall in the cross-hatched area. It can be clearly seen that the temperature of the first layer in systems with fewer layers is higher than in systems with more layers. However, the temperature of the last layer in systems with fewer layers is lower than in systems with

more layers. Moreover, the temperature of the first layer is a much more sensitive function of the total number of layers than is that of the last layer. Table 1 gives T_N and T_1 values for typical numbers of layers.

All of the effects influencing the temperature distribution in MLI blankets will cause the effective thermal conductivity to be a function of depth in the MLI blanket. The total effective thermal conductivity can be defined as

$$K(N) = \frac{Q(N)}{D(N)} \frac{N}{\Delta T(N)} \quad (2)$$

Defining K_{ij} as the effective thermal conductivity between the i th and j th layer

$$K_{ij} = \frac{Q_{ij}}{D_{ij} A} \frac{N_{ij}}{\Delta T_{ij}} \quad (3)$$

Table 1 Measured temperature of first and last layers

Total number of layers, N	Temperature of first layer, T_1 (K)	Temperature of last layer, T_N (K)
5	205	269
10	177	273
20	138	274
30	120	275
60	97	276
90	91	276.5
Cold surface	77	--
Warm surface	--	277

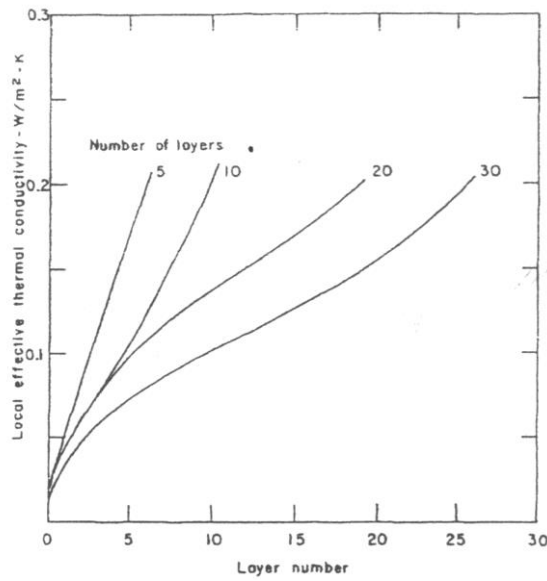


Figure 7 Local effective thermal conductivity as a function of depth
Five layers; ▲, 10

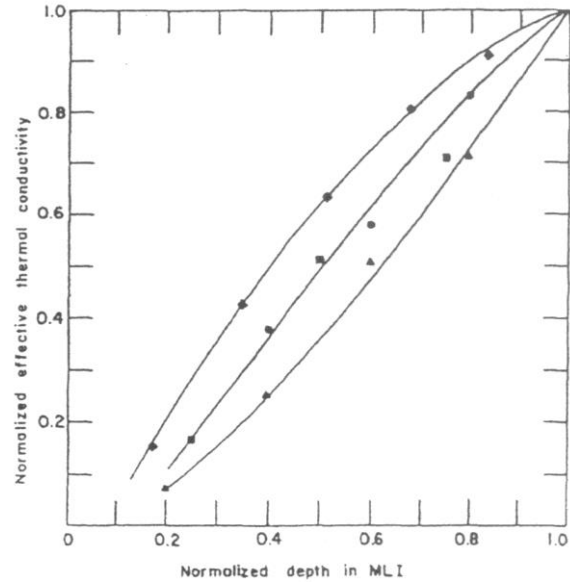


Figure 8 Normalized local effective thermal conductivity as a function of normalized depth. ●, layers; ■, 20 layers; ◆, 30 layers

If there are neither sources nor sinks of heat in the blanket, $Q_{ij} = Q = Q(N)$. For a given system, K_{ij} is proportional to N_{ij} and inversely proportional to ΔT_{ij} . D_{ij} is approximately constant, but we use $K_{ij} D_{ij}$ in the following considerations for completeness. For adjacent layers, $i = n$ and $j = n + 1$, Equation (3) becomes

$$K_{n,n+1} D_{n,n+1} = \frac{Q}{A} \frac{1}{\Delta T_{n,n+1}} \quad (4)$$

The local effective thermal conductivity, defined as $K'(n,n+1) = K_{n,n+1} D_{n,n+1}$, is plotted in Figure 7 as a

function of depth in the MLI blanket. It can be seen that the local effective thermal conductivity in the region near the warm surface is larger than that in the region near the cold surface and for a 30 layer system has the ratio

$$K'(1,2): K'(5,6): K'(15,16): K'(25,26) = 1: 2.5: 5.0: 7.3$$

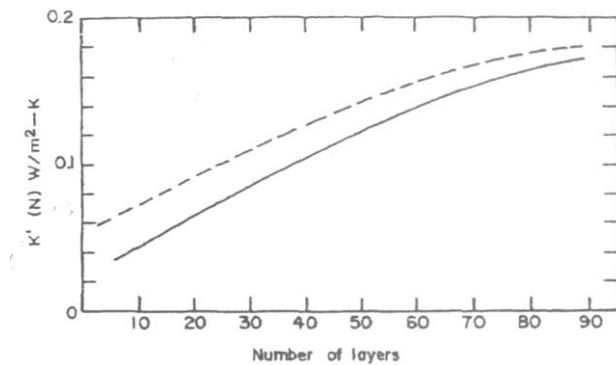


Figure 9 $K'(N)$ as a function of the total number of vacuum MLI layers.—, Results using temperatures of first and last multilayer; —, results using plate and box temperatures

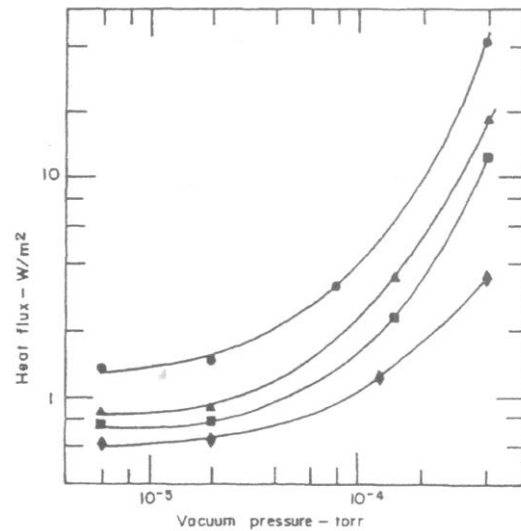


Figure 10 Heat flux as a function of overall level. ●, Five layers; ▲, 10 layers; ■, 20 layers; ◆, 30 layers

Figure 8 shows the normalized effective thermal conductivity as a function of normalized depth. The normalizing factor is the effective thermal conductivity in the outermost (warmest) region, defined as layers 25-30 for a 30 layer system, layers 16-20 for a 20 layer system, layers 8-10 for a 10 layer system, and layers 4-5 for a five layer system.

The overall effective thermal conductivity of a MLI blanket can be calculated from Equation (2) with Figures 3 and 4. $K'(N)$ is plotted as a function of the total number of layers in Figure 9. It can be seen that $K'(N)$ increased as the total number of layers increased

$$K'(5): K'(10): K'(20): K'(30): K'(60): K'(90) = 1:1.3:2:2.4:4:4.9$$

It can be appreciated that for a given insulation system, i.e. number of layers, the $K'(N)$ based on the temperatures of the box and plate will be less than that based on the temperatures of the first and last multilayers. Furthermore, for systems with few layers this underestimate will be significant.

EFFECT OF OVERALL VACUUM LEVEL

Figure 10 shows the heat flux as a function of overall vacuum for the five, 10, 20 and 30 layer insulation systems. It can be seen that the heat flux through a MLI system of only a few layers is a much stronger function of vacuum level than that through a system with more layers. This is because the gas conduction mechanism becomes more like free molecular conduction as the number of MLI layers is decreased.

One concludes from this that more layers should be used on cryosystems which may be unable to achieve high vacuum. The heat flux is almost independent of the vacuum below 5×10^{-5} Torr with > 10 layers of MLI,

and the heat flux rises rapidly with vacuum pressure above that value.

Figure 11 shows the temperature distribution in the intermediate layers as a function of overall vacuum pressure. The temperature of a given layer decreases with increasing vacuum pressure. For a 30 layer MLI system, the temperature of the fifteenth layer is 230 K at 2×10^{-5} Torr, 204 K at 8×10^{-5} Torr and 175 K at 4×10^{-4} Torr. This decreasing temperature indicates that the effective thermal conductivity is a direct function of vacuum pressure.

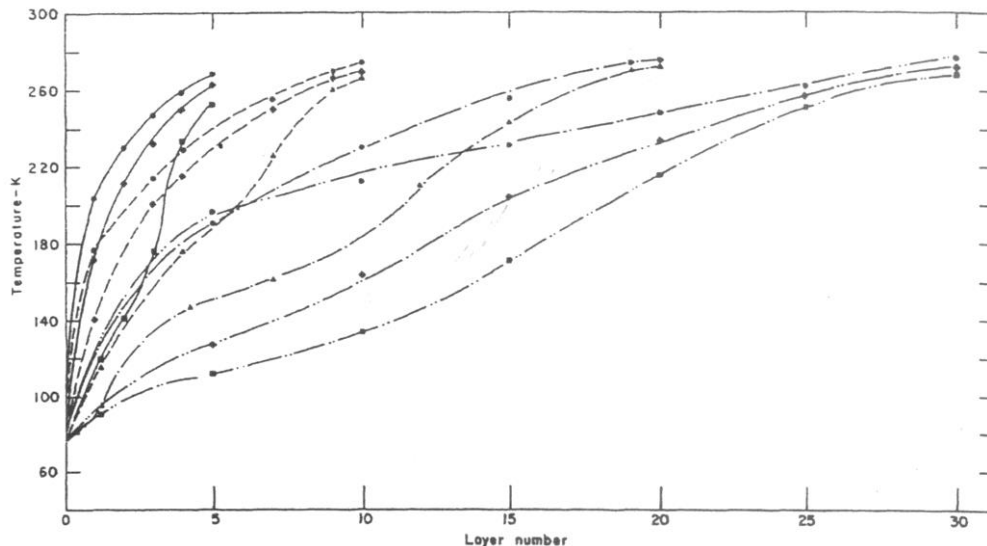


Figure 11 Temperature distribution MLI as a function of overall vacuum level. ●, 2×10^{-5} Torr; ◆, 8×10^{-5} Torr; ▲, 1.4×10^{-4} Torr; ■, 4×10^{-4} Torr

RECOMMENDATIONS

Based on the results of these experiments, several recommendations can be made:

- 1 a few layers of MLI play an important role in reducing the heat flux. For example, the application of aluminium tape and five MLI layers to a heavily oxidized surface will reduce the heat flux by a factor of 17. In any case, it is worthwhile to put a few layers on cold surfaces where the geometry makes it difficult to apply many layers. Also, taping a heavily oxidized surface should bring an improvement regardless of the number of MLI layers;
- 2 the overall heat flux through a MLI system can be decreased by applying more MLI layers. However, the benefit becomes marginal after a certain number of layers. This is because $K'(N)$ increases with the total number of MLI layers and above a certain number of layers becomes so large that the heat flux cannot be reduced by increasing N . When wrapping crinkled single aluminized MLI on a large liquid vessel, 30—40 MLI layers are recommended. Of course, the costs of cryogen, manpower and MLI must be compared to reach an optimum number;
- 3 although in this experiment the first layer is wrapped directly on the cold surface and the last layer is always separated from warm box, the temperature of the last layer is closer to the temperature of the warm box than the temperature of the first layer is to the cold surface temperature. There is a temperature difference of only a few degrees Kelvin between the last layer and the warm box when > 10 or 20 layers are used. This implies that if the outermost layer touches the warm box the heat flux will not increase significantly; however, touching should be avoided while using only a few MLI layers;
- 4 the use of only a few MLI layers, while speeding the pump down, does not provide much protection in the event of poor vacuum.

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