Optimization of Layer Densities for Spacecraft Multilayered Insulation Systems

W.L. Johnson
Cryogenics Test Laboratory
Mailstop: KT-E
Kennedy Space Center, FL 32899
(321) 867-4865

Abstract

Numerous tests of various multilayer insulation systems have indicated that there are optimal densities for these systems. However, the only method of calculating this optimal density was by a complex physics based algorithm developed by McIntosh. In the 1970's much data were collected on the performance of these insulation systems with many different variables analyzed. All formulas generated included number of layers and layer density as geometric variables in solving for the heat flux, none of them was in a differentiable form for a single geometric variable. It was recently discovered that by converting the equations from heat flux to thermal conductivity using Fourier's Law, the equations became functions of layer density, temperatures, and material properties only. The thickness and number of layers of the blanket were merged into a layer density. These equations were then differentiated with respect to layer density. By setting the first derivative equal to zero, and solving for the layer density, the critical layer density was determined. Taking a second derivative showed that the critical layer density is a minimum in the function and thus the optimum density for minimal heat leak, this is confirmed by plotting the original function. This method was checked and validated using test data from the Multipurpose Hydrogen Testbed which was designed using McIntosh's algorithm.

Introduction

Multilayered insulation (MLI) was first experimentally tested by Sir James Dewar in 1900 when he experimented with three layers of aluminum foil. However, it was not until the late 1940s when Cornell described his layered radiation shield system that MLI was born.[1] Black, Fredrickson, Kropshot, and many others continued to research MLI mostly for applications involving long duration lunar and martian missions.[2-4] Their research often focused on trying to define the best insulation system for a specific mission. In the late 1960s and early 70s, Keller and Cunnington delivered the most complete set of data on several different types of MLI systems.[5,6] Their tests were completed both on flat plate calorimeters and small tanks. Since the mid-1970's aerospace cryogenic engineering has seen a sharp decline in the quantity of research. The subject of variable density multilayer insulation (VD-MLI) was pioneered and patented by Dr. Glen McIntosh.[7,8] Many others studied the effects of layer density on MLI throughout the years preceding and following Dr. McIntosh's innovation.[9-12] While NASA claims that VD-MLI is the ultimate superinsulation others disagree.[13-14]

There has been a long chain of research on optimizing MLI systems, however none has focused on optimizing the layer density analytically. While several have shown that there is an optimum density, none have shown an equation or method for determining such a density.

The Basics of MLI Heat Transfer

Heat transfer through multilayer insulation systems are assumed to be dominated by radiation. For this assumption to be true, the insulation system is usually operated in a high vacuum environment. The ideal MLI system is made of floating shields that do not touch each other, however due to gravitational limitations this is not feasible and a low conductivity material is placed between the radiation shields so that they do not touch. The heat conduction through these spacers must be accounted for. Finally, even at high vacuum, gas molecules exist between the layers of radiation shields and spacers. All three modes of heat transfer are accounted for in equation 1. A more complete discussion of these modes is presented by McIntosh.[8]

As noted by Hyde and Stuckey[9], for every MLI system there is a layer density where heat transfer is minimized. This layer density is independent of thickness; it will be the same for all thicknesses given that the boundary temperatures and material stay the same, it is the balance point in a real MLI system between the conduction between layers and the number of radiation shields within a certain thickness. This can be generalized to state that for every layer within an MLI system there is an optimal layer density, this is the basic premise of VD-MLI carried out to its logical conclusion.

A few points of clarification are needed before proceeding further. First, it is well understood that decreasing the layer density while maintaining a constant number of radiation shields/layers will asymptotically decrease the heat flux through a flat plate, when the test chamber is at high vacuum. This is due to the effects of decreasing thermal contact of the radiation shields and increasing thickness of the spacers (an effect predicted by Fourier's law) between layers. Figure 1 shows heat flux for MLI with a constant number of layers for various published data sets for varying layer densities. It is important to notice that in theory, simple radiation models do not care about the layer density. They model floating shields that never touch and are separated by vacuum only.

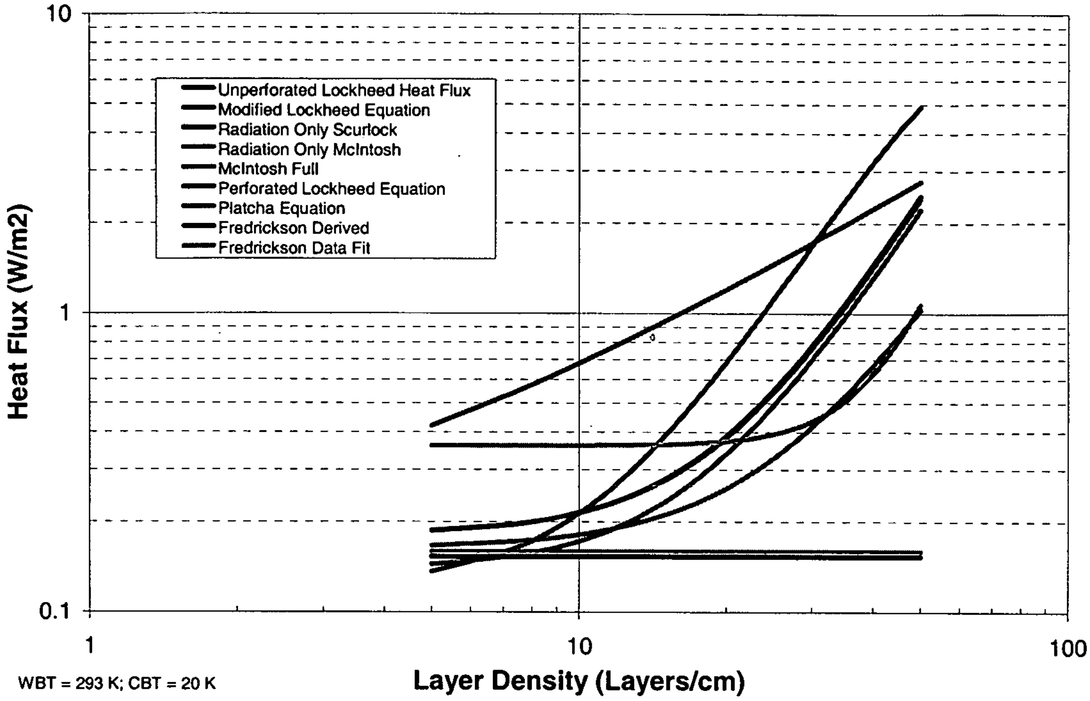

Figure 1: Heat flux as a function of layer density with a constant number of layers.[2-4]

As can be seen from Figure 1, it appears that the lower the density of the MLI, the lower the heat leak is. However, this is offset by the increasing thickness of the blanket as the space between the layers increases. Seeing how every MLI blanket has a finite thickness, this thickness treated as such. Figure 2 shows the heat flux for MLI with a constant thickness for the same data sets. Figure 2 shows that for the same conditions as in Figure 1 with the exception of holding the thickness constant instead of the number of layers, for each of the published data curve fits, there is a minimum point. That minimum point is generally where conduction begins to take over as the dominant heat transfer mode and the curve breaks from the theoretical radiation lines. Again, it should be noticed that the blue and gold lines that represent theoretical radiation heat transfer only (the floating shield concept) are independent of layer density (at a constant thickness, increasing the layer density increases the number of shields, so the downward slope is due to the increased number of shields).

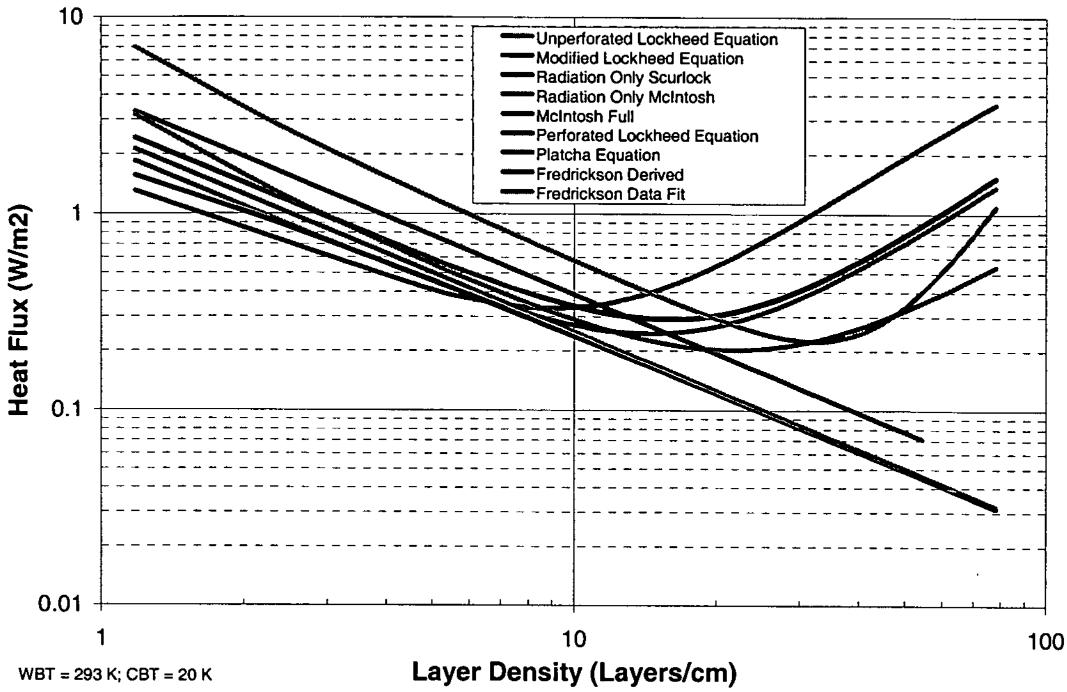

Figure 2: Heat Flux as a function of layer density for a constant thickness (1 inch).

Figure 3 shows the heat flux, thermal conductivity, and estimated mass as a function of layer density for a constant number of layers. As previously shown in Figure 1, the heat flux decreases exponentially with the number of layers, however, when that is normalized to thickness (thermal conductivity) there is a minimum. Interestingly in comparison is the mass. The mass decreases exponentially as the layer density increases; this is because the surface area for every individual layer is decreased when the distance between the layers is decreased. In the later derivations, the mass of the blanket is not taken into account, though it could be through a complex set of equations to relate MLI blanket areal density to layer density with a known tank surface area. A FORTRAN program has been developed by NASA which is capable of performing such analysis.[15]

Equation Generation

Quasi-empirical equations such as those from references 2 and 6, contain both layer density ($\overline{N}$) and the number of layers (*N*) in them. In order to make the equations a function of layer density only, the equations for heat flux (Q/A) are converted to thermal conductivity, k. As shown in Figure 4, the first derivative can then be taken with respect to layer density and set equal to zero. Solving for layer density yields an equation for the minimum heat flux normalized to thickness.

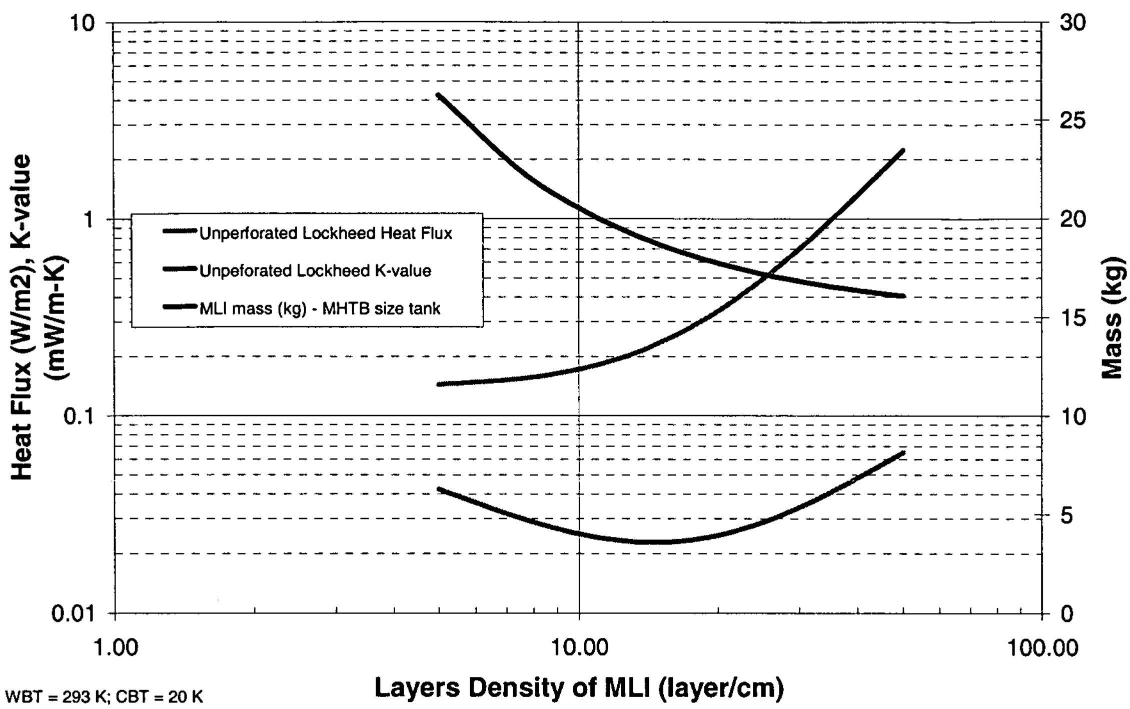

Figure 3: Heat Flux, Thermal Conductivity, and Estimated Mass for MLI as a function of Layer Density with 40 shields.

For example, the process will be demonstrated on the Lockheed equation for double aluminized mylar and Dacron net, where the mylar is 0.55% open due to perforations. First the heat flux is demonstrated by the following equation:

$$q = \frac{C_s * \overline{N}^{2.63}(T_h - T_c)*(T_h + T_c)}{2*(N+1)} + \frac{C_R * \varepsilon * \left(T_h^{4.67} - T_c^{4.67}\right)}{N} + \frac{C_G * P * \left(T_h^{0.52} - T_c^{0.52}\right)}{N} \quad (1)$$

Using Forier's law (equation 2), and assuming that the number of layers is sufficiently large (equation 3), the equation for heat flux can be transformed into a thermal conductivity (equation 4).

$$k = q * \frac{\Delta x}{\Delta T} \quad (2)$$

$$N \cong N + 1 \quad (3)$$

$$k = \frac{C_s * \overline{N}^{2.63}(T_h - T_c)*(T_h + T_c)*\Delta x}{2*N*(T_h - T_c)} + \frac{C_R * \varepsilon * \left(T_h^{4.67} - T_c^{4.67}\right)*\Delta x}{N*(T_h - T_c)} + \frac{C_G * P * \left(T_h^{0.52} - T_c^{0.52}\right)*\Delta x}{N*(T_h - T_c)} \quad (4)$$

This equation for thermal conductivity can then be simplified using equation 5 and algebra to get equation 6.

$$\overline{N} = \frac{N}{\Delta x} \tag{5}$$

$$k = C_s * \overline{N}^{1.63} * \frac{(T_h + T_c)}{2} + \frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{(T_h - T_c) * \overline{N}} + \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{\overline{N} * (T_h - T_c)} \tag{6}$$

Taking the first derivative yields:

$$\frac{\partial k}{\partial \overline{N}} = 0.815 C_s * \overline{N}^{0.63} * (T_h + T_c) - \frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{(T_h - T_c) * \overline{N}^2} - \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{\overline{N}^2 * (T_h - T_c)} \tag{7}$$

In order to solve for a critical point for the equation, the first derivative should be set to zero (equation 8), then solve for the critical point, the optimal layer density.

$$\frac{\partial k}{\partial \overline{N}_{opt}} = 0 \tag{8}$$

$$\overline{N}_{opt} = \left[\frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67}) + C_G * P * (T_h^{0.52} - T_c^{0.52})}{0.815 C_s * (T_h^2 - T_c^2)} \right]^{\frac{1}{2.63}} \tag{9}$$

Taking the second derivative (equation 10) shows that when all coefficients, Cr, Cs, and Cg are positive, that the second derivative will always be positive. This means that the critical point solved for in equation 9 is indeed a minimum according to the second derivative rule.

$$\frac{\partial^2 k}{\partial \overline{N}^2} = \frac{0.513 C_s}{\overline{N}^{0.37}} + \frac{2 * \left[C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67}) + C_G * P * (T_h^{0.52} - T_c^{0.52}) \right]}{(T_h - T_c) * \overline{N}^3} \tag{10}$$

The equations derived in this manner are functions only of the materials (Cs, Cg, Cr, ε) and environment (T_2, T_1, P). Where Cs, Cg, and Cr are the coefficients of solid conduction, gas conduction, and radiation heat transfer, ε is the emissivity of the radiation shields, T_1 and T_2 are the cold and warm boundary temperatures respectively, and P is the environmental pressure (for $P \leq 10^{-4}$ Torr, or in the free molecular flow regime).

$$q_{\min} = \frac{C_s * \overline{N}_{opt}^{2.63} (T_h - T_c) * (T_h + T_c)}{2 * (N + 1)} + \frac{C_R * \varepsilon * (T_h^{4.67} - T_c^{4.67})}{N} + \frac{C_G * P * (T_h^{0.52} - T_c^{0.52})}{N} \tag{11}$$

Since the layer density is an input for these equations, the optimized density can be plugged back into the equations to solve for the heat flux as shown in equation 11. Similar equations can be derived for other equations, such as the Modified Lockheed Equation, developed at MSFC, with different coefficients.[16]

$$\overline{N}_{opt,MLE} = \left[\frac{C_R * \varepsilon * \left(T_h^{4.67} - T_c^{4.67}\right) + C_G * P * \left(T_h^{0.52} - T_c^{0.52}\right)}{1.63 C_s * \left(T_h - T_c\right)} \right]^{\frac{1}{2.63}} \quad (12)$$

Validation of Theory

In reference 6, three different sections are assumed for the variable density MLI, and each section has a separate layer density. Thus there is the opportunity to solve for three different optimized layer densities, one at each section. This was previously done by both Dr. Glen McIntosh and in designing the system defined in reference 7. The results of the above derivation (Figure 4) closely agree with the design parameters from reference 7. Dr. McIntosh's work was completed by hand calculations in a much different method than is presented here. No derivates were taken as his equations cannot be differentiated with respect to layer density.[8]

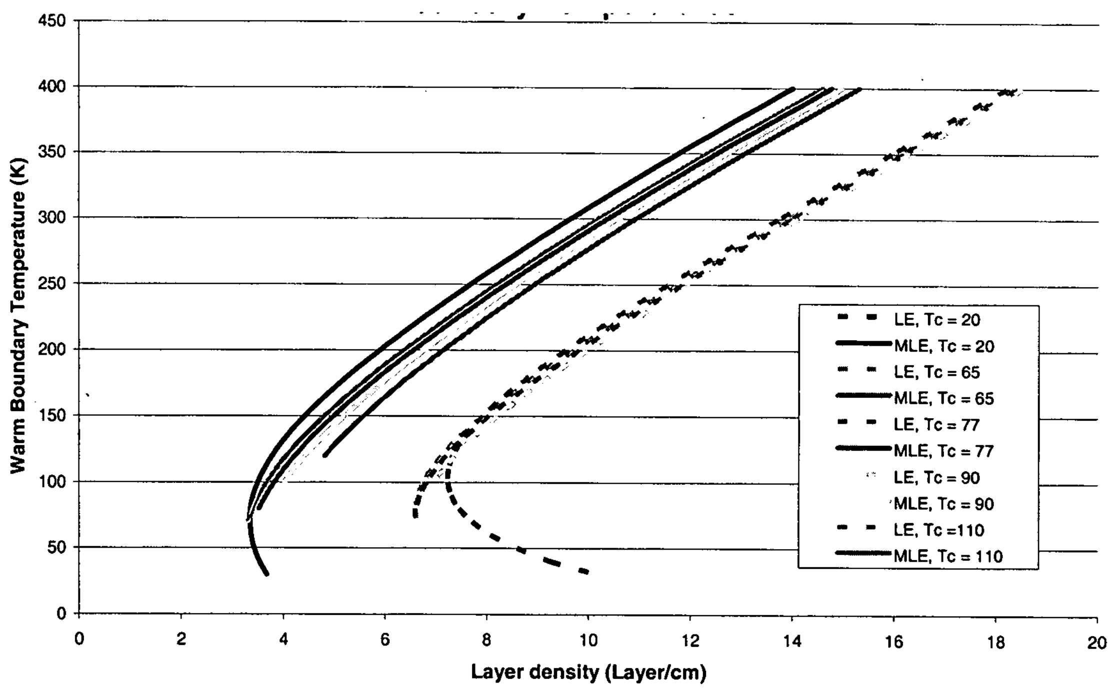

Figure 4: Optimal Layer Densities for Perforated Double Aluminized Mylar and Dacron Net MLI configurations as a function of boundary temperatures for $P = 10^{-5}$ Torr.

For boundary temperatures of 90 and 300 K, the optimal boundary layer densities for a three segment blanket in ratio of 10:15:20 layers are: 8:12:15 layers/cm. For a similar blanket with the cold boundary temperature of 20 K, the layer densities are: 6:12:15 layers/cm. The current MHTB blanket, which was designed in that layer ratio was designed for layer densities of 8:12:16 layers/cm.[7] A simple excel routine has been developed to verify this calculation. This insulation system has been shown to be the most efficient and lightest cryogenic thermal insulation system designed.[12]

Conclusions

A method for the determination of the optimal layer density for each individual MLI blanket has been developed. This method uses existing semi-empirical equations based on large quantities of test data as the basis for the method. While it is often hard to physically match a desired layer density, various companies are working on methods of developing the low density MLI that is optimal for a majority of applications.

Once an optimal layer density has been calculated, a simple trade can be run to determine the optimal thickness of the insulation blanket by calculating the heat flux verses number of layers at a constant layer density.

This process of optimally designing MLI blankets has been programmed to work in several cryogenic thermal insulation design tools.

Acknowledgements

The author would like to acknowledge both Dr. Glen McIntosh and Eric Hyde for sharing parts of their large knowledge base on multilayer insulation systems.

References:

1. W.D. Cornell, Radiation shield supports in vacuum insulated containers, US Patent No. 2,643,022, 1947.
2. Black
3. Fredrickson
4. Kropschot
5. "High-Performance Thermal Protection Systems, Final Report" Vol. I, Contract NAS8-20758. Lockheed Missile and Space Company, Sunnyvale, CA. Dec. 31, 1969.
6. Keller, C.W., Cunnington,G .R., and Glassford,A.P., "Thermal Performance of Multi-Layer Insulations," Final Report, Contract NAS3-14377, Lockheed Missiles & Space Company, 1974.
7. McIntosh, G. E., "Layer by Layer MLI Calculation Using a Separated Mode Equation," Cryogenic Technical Services Inc., Boulder, CO. US Patent 5590054
8. McIntosh, G.E. "Layer by Layer MLI Calculation Using a Separated Mode Equation" *Advances in Cryogenic Engineering*, Vol. 39, Plenum Press, NY
9. "Cryogenic Research at MSFC" *Research Achievements Volume IV Report No. 2* NASA TM X-64561, 1971.
10. Fredrickson, Special Report #1
11. Spradley, I.E., Nast, T.C., Frank, D.J. "Experimental Studies of Multilayer Insulation at Very Low Temperatures" *Advances in Cryogenic Engineering*. Vol. 35A. 1990. Pg. 477-486
12. Stochl, R.J., Dempsey, P.J., Leonard, K.R., and G.E. McIntosh, "Variable Density MLI Test Results" *Advances in Cryogenic Engineering* Vol. 41, Plenum Publishers, NY, 1996. pg. 101-107.
13. Martin, J. J. and Hastings,L . J, "Large-scale Liquid Hydrogen Testing of a Variable Density Multilayer Insulation With a Foam Substrate," NASA-TM-2001-211089, June, 2001.
14. Mills, G.L. and

15. Johnson, W.L., Sutherlin, S.G., and S.P. Tucker, "Mass Optimization of Cryogenic Thermal Insulation Systems for Launch Vehicles" presented at AIAA Space 2008, San Deigo, CA. Sept. 9-11, 2008.
16. Hedayat, A.; Hastings, L. J.; Brown, T. "Analytical Models for Variable Density Multilayer Insulation Used in Cryogenic Storage " Advances in Cryogenic Engineering (2002), 47B, 1557-1564.
17. Chorowski, M., Grzegory, P., Parente, Cl., and G. Riddone, "Optimisation of Multilayer Insulation – an Engineering Approach" Presented at the 6th IIR International Conference "Cryogenics 2000", October 10-13, 2000, Praha, Czech Republic.