SSCL-Preprint-461

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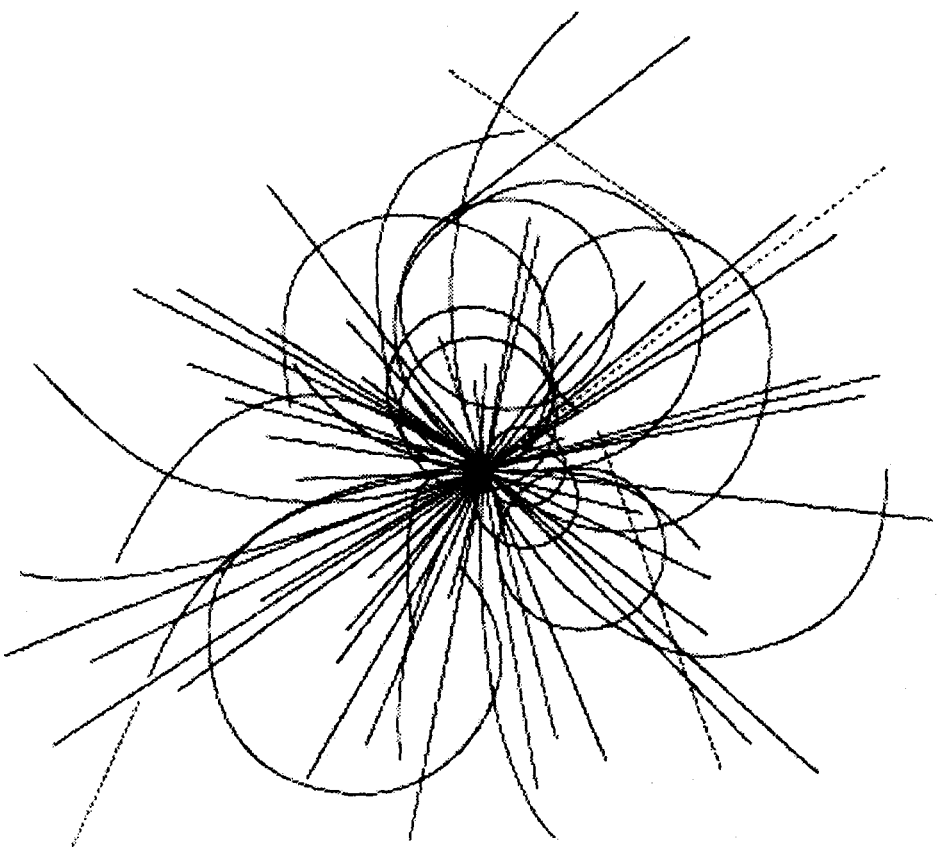
Analysis of Multilayer Insulation Between 80 K and 300 K



Superconducting Super Collider Laboratory

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To: All Preprint Recipients
From: Anita Lopez
Subject: Erratum to SSCL-PP-461
Date: July 28, 1993

Please find enclosed a corrected version of page 4. A correction was made in figure 4 (it had also been reversed with figure 3). Please replace the incorrect page 4 with the new version of pages 3 and 4.

We are sorry for any inconvenience this may have caused and appreciate your help in this matter. If you have any questions, please feel free to give me a call.

Anita Lopez
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performed using a thermal analyzer code (DYSIM) developed in-house.

LABORATORY TEST RESULTS

Some laboratory temperature and heat transfer measurements of MLI have been performed by Boroski[4,5,6] at FNAL. Details of his apparatus and procedure are discussed in the references cited. Some of his data for a 32-layer blanket are given in Table 2 for a range of insulating vacuum pressures. Results of predictions for high and low insulating vacuum pressures are shown in Figures 1 through 3. The analysis assumes that the heat is transferred

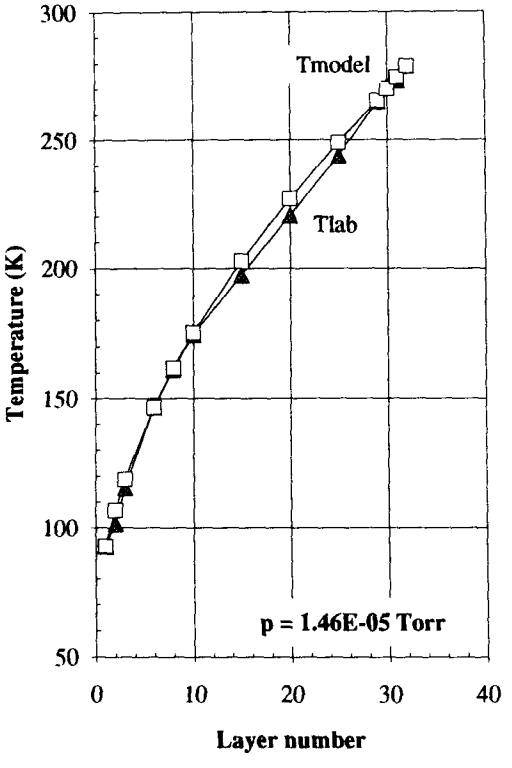

Fig 1. Laboratory results and model prediction for MLI temperature distribution

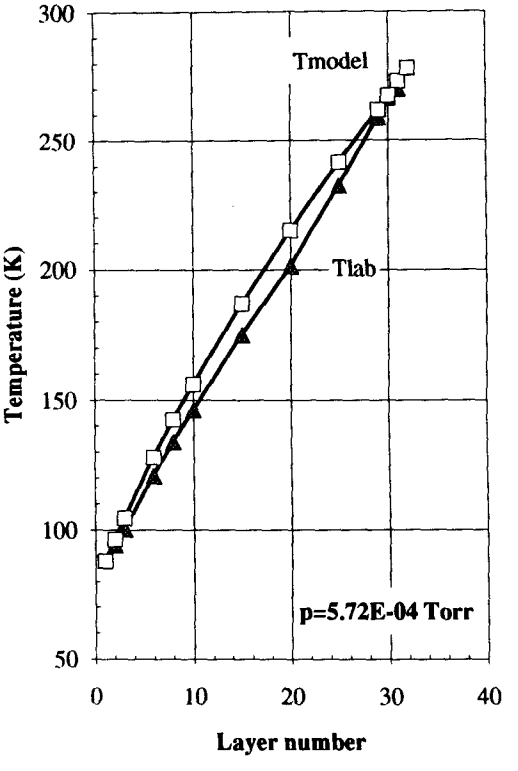

Fig 2. Laboratory results and model prediction for MLI temperature distribution

through the MLI by radiation, spacer conduction, and gas conduction. The gas is assumed to be nitrogen. The temperature predictions agree in most cases to within 5% of the measurements. The predicted and measured heat flux through the MLI as a function of pressure is shown in Figure 4. For the three high-insulating vacuum conditions, the heat flux predictions are close but slightly lower than the measured values. At P_{ins}=5.72 x 10^{-4} Torr, the heat transfer is 39% lower than the measurements. For the last point with P_{ins}=6.44 x 10^{-3} Torr, the predicted heat transfer is about 14% higher than the measurement. These data provide a means for determining the accuracy of the DYSIM predictions of heat transfer.

EXPERIMENT TEST RESULT

A schematic of the five dipole string test (ER Test) at FNAL is presented in Figure 5 and a summary of some measurements is provided in Table 3. The ER string test data was taken for a 64-layer MLI blanket installed between the 80 K shield and the 300 K vacuum vessel of a magnet. It was constructed from two 32-layer blankets separated by a doublespacer layer. The temperature of the 80 K shield at several locations along the string is shown in Figure 6. A typical set of temperature data through the MLI blanket for the ER string test is shown in Figure 7. All of this data was taken November 6, 1991. The

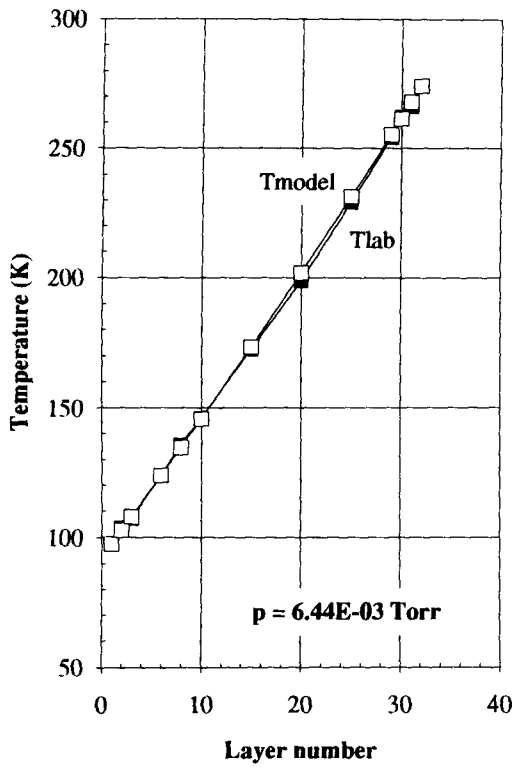

Fig 3. Laboratory results and model prediction for MLI temperature distribution

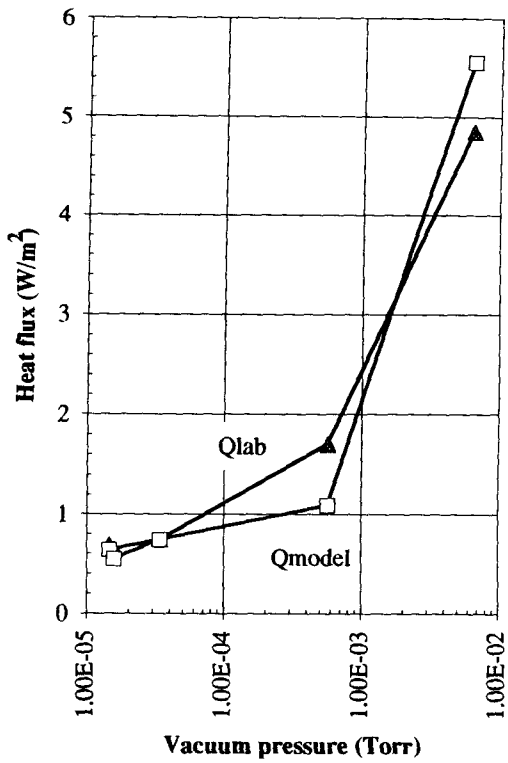

Fig 4. Laboratory results and model prediction for MLI heat flux

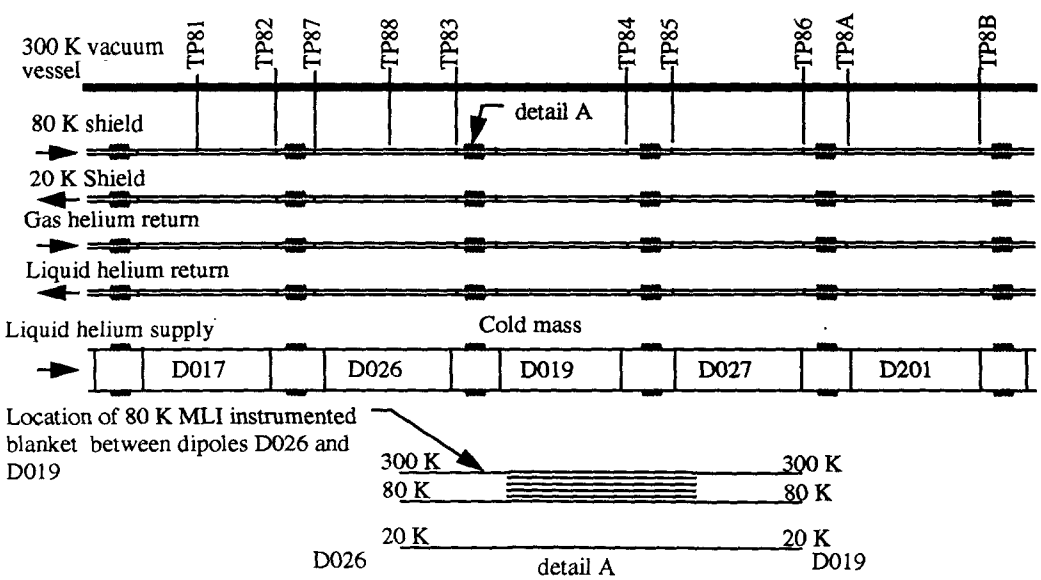

Figure 5 - Schematic of five dipole sting test at FNAL (ER TEST) showing relevant sensor placement[7,8]

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Analysis of Multilayer Insulation Between 80 K and 300 K*

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July 1993

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ANALYSIS OF MULTILAYER INSULATION BETWEEN 80K AND 300K

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ABSTRACT

A model has been developed that can be used to determine the temperature distribution and heat transfer through a multilayer insulation (MLI) blanket. Predictions from the model were compared with a series of temperature measurements made during laboratory experiments and during a test of five superconducting magnets (dipoles) installed in a string and tested at Fermi National Accelerator Laboratory, FNAL (ER Test).

INTRODUCTION

Multilayer insulation (MLI) will be used in many cryogenic components of the Superconducting Super Collider (SSC), such as over the 80 K shield in the magnet cryostats and in cryogenic transfer lines. Therefore it is necessary to have the ability to analyze the heat transfer through MLI blankets under the operating conditions expected in the collider components. A model has been developed based on current 32- and 64-layer MLI blankets.

The model was used to analyze both laboratory experiments and measurements on MLI blankets installed in the FNAL ER string test under different vacuum pressures. The agreement between the predictions and the measurements indicates that the modelling approach can be used in design of multilayer insulation for the 80 K to 300 K temperature range. The paper describes briefly the experimental set-up and the model formulation and provides data comparisons with predictions. The differences between the measured and predicted temperatures and heat fluxes are small for low pressures, but they become larger at higher pressures due to inadequate gas conduction models at these pressures.

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1. Guest Collaborator from JINR/Laboratory of High Energy, Dubna, Russia
2. Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486

THEORETICAL FORMULATION

The solution of the temperature distribution in a MLI blanket can be determined by an energy balance for n layers of the total N layers in the blanket. There are three simultaneous modes of heat transfer within the blanket: solid conduction, thermal radiation, and gas conduction.

Heat conduction occurs between the polyethylene-terephthalate (PET) spacer located between two double aluminized mylar (DAM) reflective layers and is described by:

$$Q_{solid} = kA\frac{dT}{dx} \ .$$

The thermal radiation was modelled assuming infinite parallel specularly reflecting surfaces. For n parallel surfaces the net heat transfer can be expressed in terms of the temperatures at the two outer surfaces, the number of intervening surfaces, and the emissivity of the surfaces by the following equation:[1]

$$Q_{rad} = \frac{\sigma\,(T_1^4 - T_2^4)}{(n+1)\,(\frac{2}{\varepsilon} - 1)} \ .$$

The emissivity used is a function of temperature for the DAM layers. In the application of the equation, the emissivity is based on the average of the two outer surface temperatures used to calculate the radiation heat transfer.

The gas conduction is modelled using the approach described in Corruccini.[2] The gas conduction is a function of the space between layers of DAM, which is given by the spacer thickness, the pressure of the gas, the temperatures between the two surfaces, and the thermal accommodation coefficient. The resulting equation applied is given as:

$$Q_{gas} = \frac{\bar{k}d\,(T_1 - T_2)}{\left(d + \sum_{i=1}^{2} \frac{k_i}{p_{ref}} \left(\frac{2-\alpha}{\alpha}\right) \left(\frac{\gamma_i - 1}{\gamma_i + 1}\right) \sqrt{\frac{2\pi M T_i}{R}}\right)} \ ,$$

where the accommodation coefficient was assumed to vary linearly from 1.0 at 80 K to 0.8 at 300 K based on values taken from Scott[3] for air. In the analysis the PET spacer thermal conductivity, the DAM emissivity, and the accommodation coefficient are all functions of temperature. The properties were determined by linear interpolation between the values given in Table 1.

MODELING OF MLI

The 32-layer blanket was divided into N-1 sections with N nodes. Each section of the model could contain several layers. For the results presented here, each node was located at a layer where a temperature measurement was made in order to provide an accurate comparison of the predicted and measured temperatures.

For the boundary conditions, the measured temperatures at the 300 K side and the 80 K shield side were specified using measured values. The model will then solve for the temperature distribution and the heat transfer through the blanket by performing an energy balance with the three heat transfer modes previously described. The calculations were

Table 1. Temperature dependence of DAM emissivity and spacer thermal conductivity

	80 K	190 K	300 K
ε	0.0390	0.0410	0.0429
k (W/m/K)	$8.618 * 10^{-6}$	$2.510 * 10^{-5}$	$2.510 * 10^{-5}$

performed using a thermal analyzer code (DYSIM) developed in-house.

LABORATORY TEST RESULTS

Some laboratory temperature and heat transfer measurements of MLI have been performed by Boroski[4,5,6] at FNAL. Details of his apparatus and procedure are discussed in the references cited. Some of his data for a 32-layer blanket are given in Table 2 for a range of insulating vacuum pressures. Results of predictions for high and low insulating vacuum pressures are shown in Figures 1 through 3. The analysis assumes that the heat is transferred

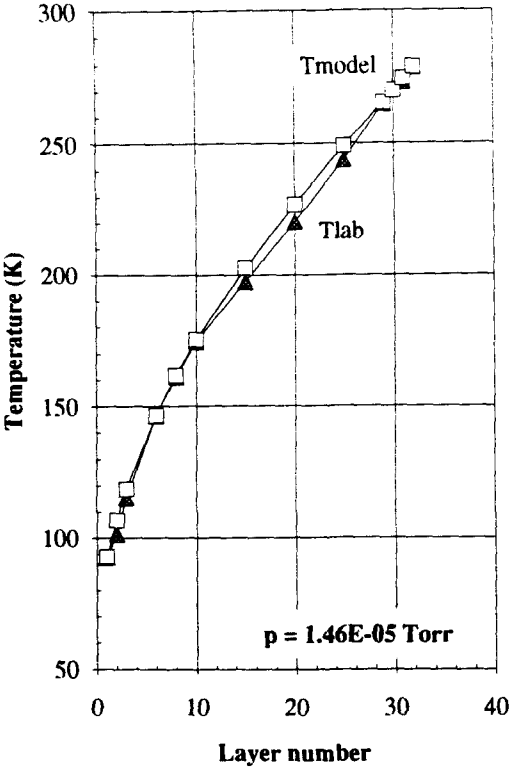

Fig 1. Laboratory results and model prediction for MLI temperature distribution

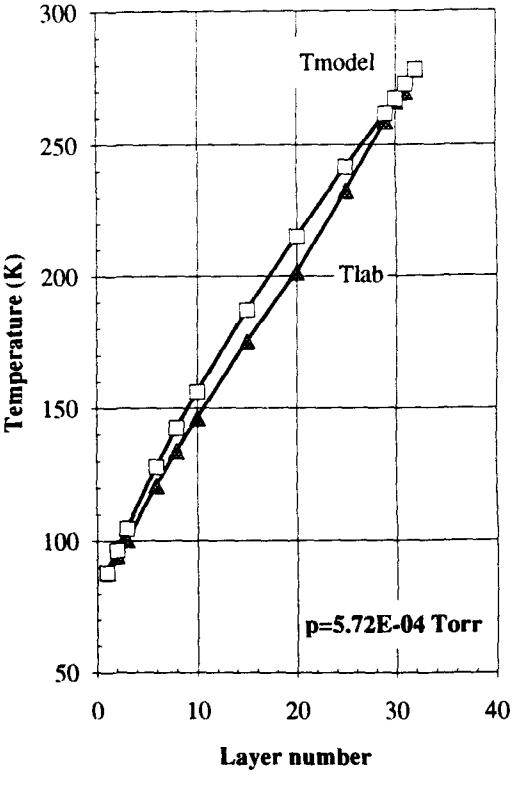

Fig 2. Laboratory results and model prediction for MLI temperature distribution

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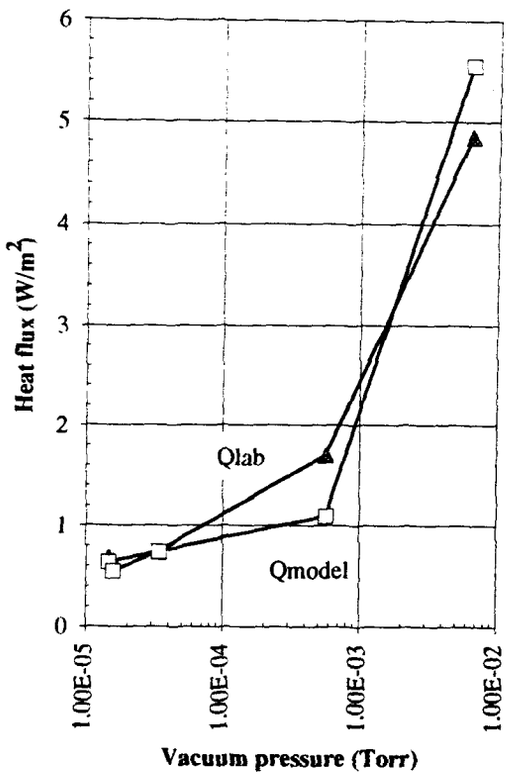

Fig 4. Laboratory results and model prediction for MLI heat flux

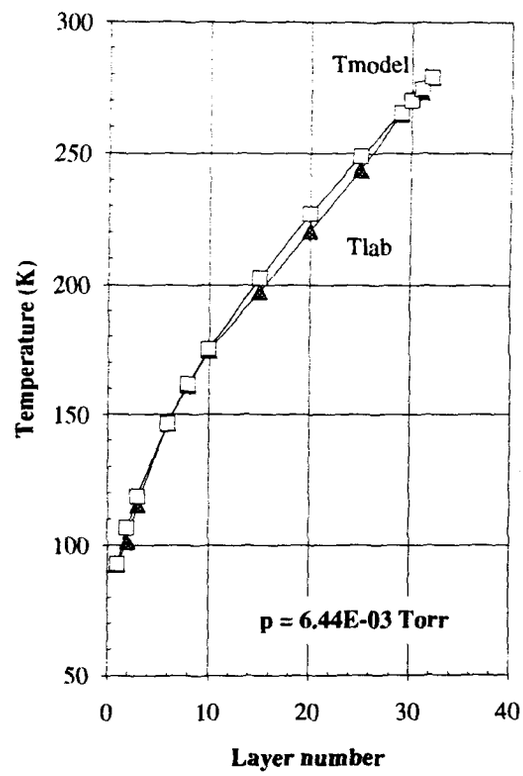

Fig 3. Laboratory results and model prediction for MLI temperature distribution

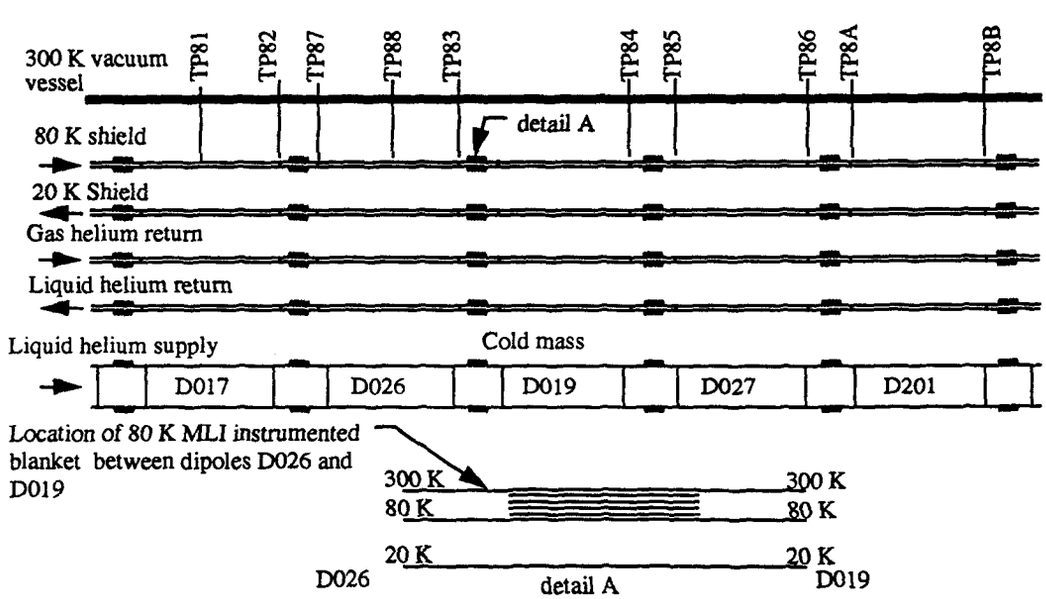

Figure 5 - Schematic of five dipole sting test at FNAL (ER TEST) showing relevant sensor placement[7,8]

Table 2. Laboratory measured MLI data of Boroski [4,5]

Test	Pressure (10^5Torr)	Warm Temp (K)	Cold Temp (K)	Heat Leak (W)	Heat Flux (W/m^2)
1	1.46	285.4	79.8	0.343	0.686
2	1.34	270.0	79.6	0.320	0.640
3	1.44	270.1	80.2	0.323	0.646
4	1.59	296.9	79.6	0.324	0.628
5	3.41	299.7	79.9	0.370	0.741
6	38.60	285.2	82.5	0.755	1.510
7	34.00	285.3	83.0	0.757	1.514
8	57.20	285.2	83.1	0.850	1.700
9	644.0	285.1	93.23	2.428	4.855

experimentally measured temperature distribution by layer number through the MLI blanket is given in Figure 8.

Two sets of predictions are shown in Figures 9 and 10. The first one assumes that there is no contact resistance between the double spacer layer and the first or second 32-layer MLI blanket. The second calculation, which fits the data better, assumes that the contact coefficient is 1.0×10^{-4} W/m^2 K. The predicted heat transfer for these two cases is 0.271 W/m^2 and 0.256 W/m^2, respectively. Figure 10 shows detailed results across the double spacer layer.

Using the two models for the 32- and 64-layer MLI blankets, the heat flux as a function of pressure was determined assuming the hot and cold sides to be at 300 K and 80 K respectively, and only nitrogen gas for the gas conduction. These results are shown in Figure 11. The heat transfer across the 32-layer blanket is approximately twice that for the 64-layer blanket for pressures less than $P_{ins} = 1 \times 10^{-4}$ Torr. For higher pressures the heat

Table 3: Summary of 1991 FNAL experimental data (ER Test) [7,8]

DATE		10/1	10/23	10/24	10/25	10/26	10/27	11/2	11/3	11/4	11/5	11/6
$P_{ins}*10^4$ (Pa)		4.00	8.00	8.00	8.00	11.0	8.00	8.00	8.00	8.00	8.00	8.00
$P_{ins}*10^6$ (Torr)		3.00	6.00	6.00	6.00	8.00	6.00	6.00	6.00	6.00	6.00	6.00
Average 80 K Shield T (K)		78.7	109.4	108.8	108.9	82.9	82.5	108.8	105.4	106.0	80.4	80.1
Start Time End Time		00:00 10:00	08:00 10:00	18:00 20:00	15:00 17:00	20:00 21:00	01:00 03:00	17:00 19:00	07:00 09:00	05:00 08:00	03:00 04:00	05:00 10:00
Sensor	Layer	Temperature (K)										
11	2	106	134		139		116	139	137	135	115	111
12	6	123	144		156	141	140	156	155	153	139	134
13	11	143	158									
14	16	160	170	173	178	172	171	178	177	174	169	163
15	21	174	181	185	188	184	183	187	187	184	180	175
16	26	186	191	195	196	194	193	195	194	192	189	184
17	32	198	202	205	206	204	203	203	202	200	198	194
32	34	223	226	228	228	227	226	224	223	221	220	217
31	38	236	238	240	240	239	238	235	234	232	231	230
22	43	243	244	246	247	246	245	241	240	238	238	236
21	48	249	249	251	252	251	250	246	244	242	242	242
20	53	260	260	262	262	260	260	255	253	251	252	252
19	58	271	270	272	271	270	269	264	262	261	262	263
18	64	276	274	276	276	274	273	267	265	264	266	267

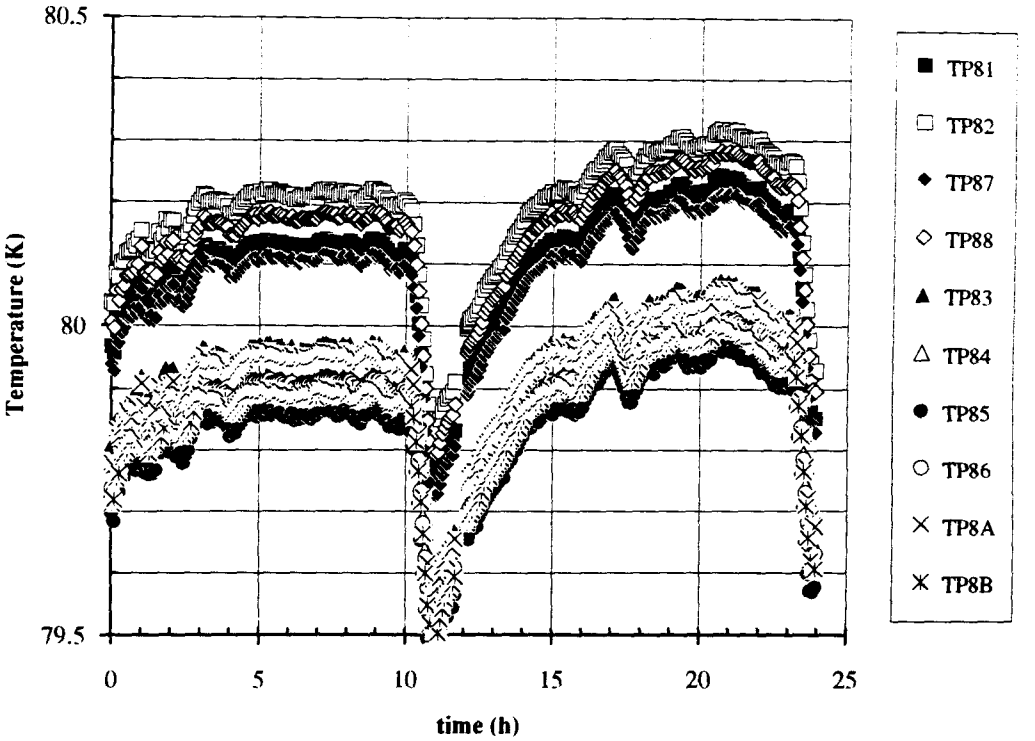

Fig 6. Experimental results for 80 K shield temperature distribution

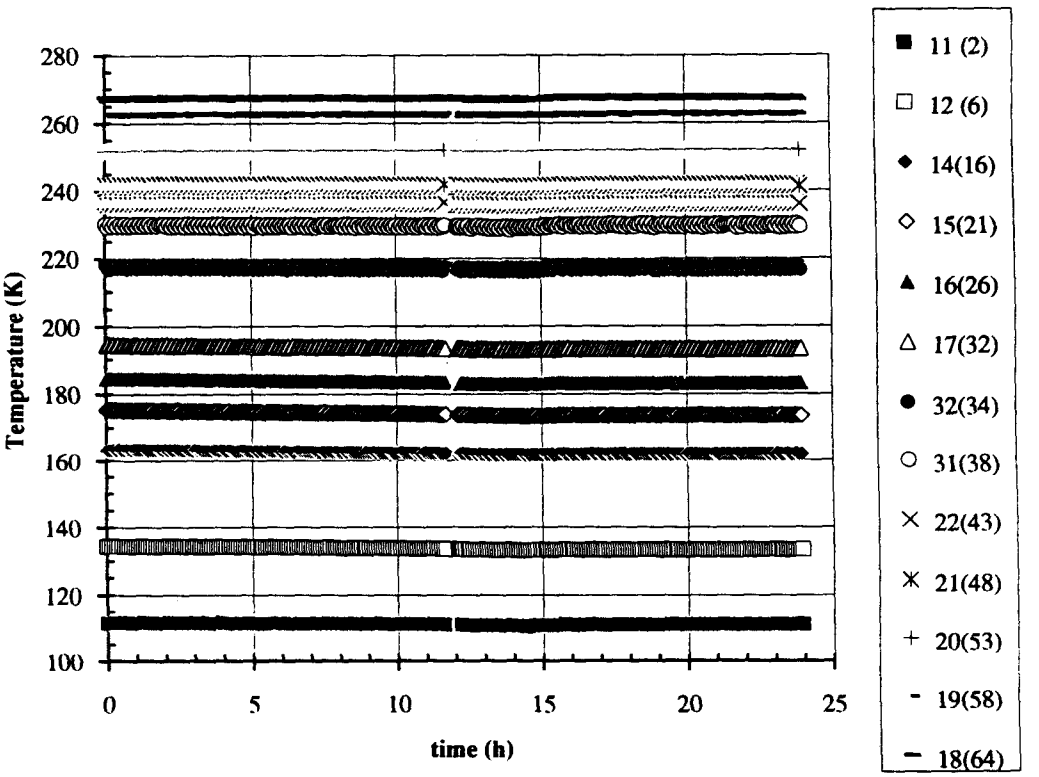

Fig 7. Experimental results for MLI temperature distribution

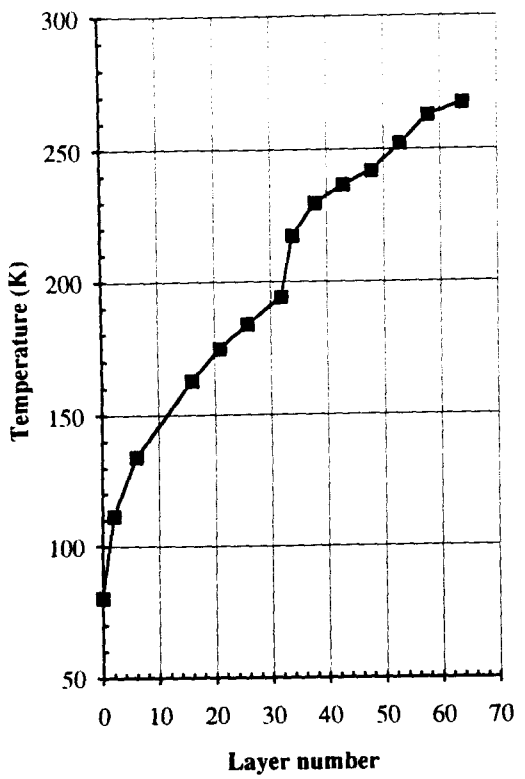

Fig 8. Experimental results for MLI temperature distribution

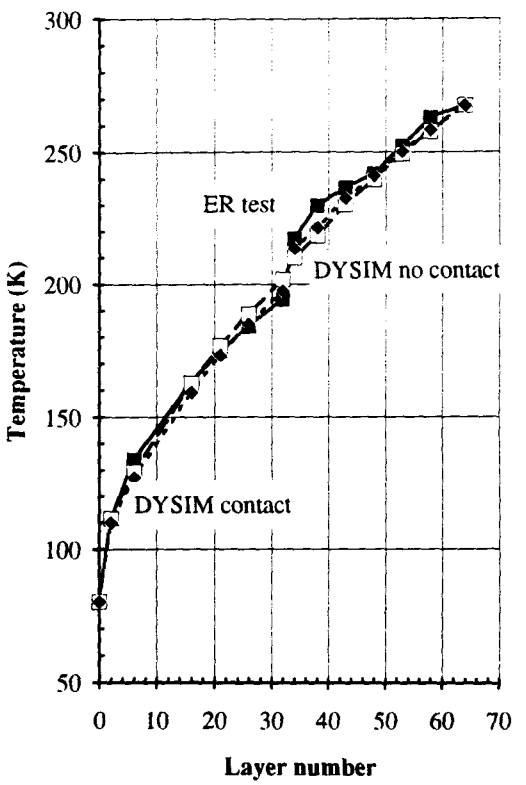

Fig 9. Experimental results and model prediction for MLI temperature distribution

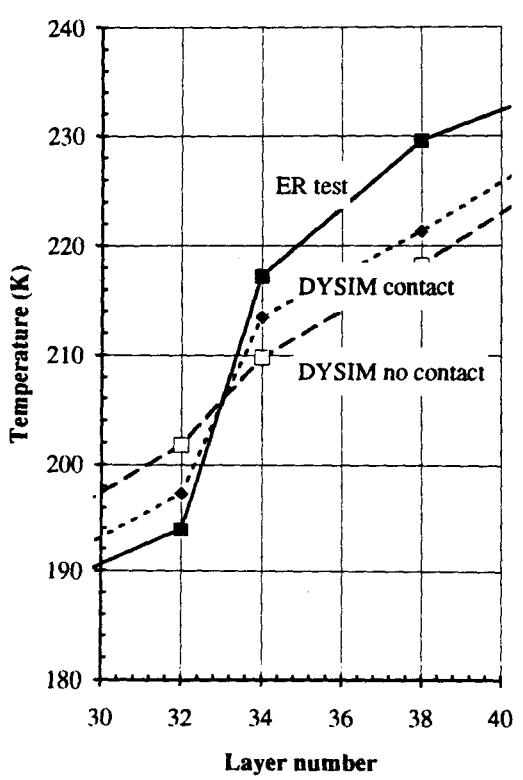

Fig 10. Experimental results and model prediction for MLI temperature distribution

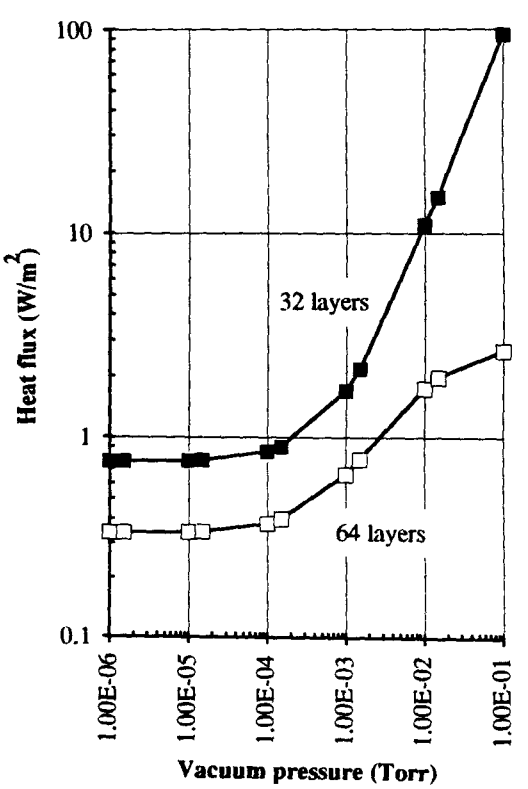

Fig 11. Model prediction for MLI heat flux with 32 and 64 layers

transfer increases rapidly for the 32-layer blanket. For the 64-layer blanket the rise in heat transfer is not as severe over the same pressure range

CONCLUSIONS

An analysis of the 32- and 64-layer MLI laboratory and experimental data has been performed. There is favorable agreement of the predicted and measured temperatures. The predicted heat fluxes for the laboratory data are in close agreement at low pressures, but the difference becomes large at high pressures due to inadequate gas conduction models and insufficient data on the gas pressure between the MLI layers.

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NOMENCLATURE

- A - area (m^2)
- d - distance between two surfaces for gas conduction calculation (m)
- k - thermal conductivity (W/m/K)
- $\bar{k}$ - average thermal conductivity (W/m/K)
- M - molecular weight
- n - number of layers between two nodes
- N - total number of layers in MLI blanket
- P_{ins} - insulating vacuum pressure (Torr)
- P_{ref} - reference insulating vacuum pressure (Torr)
- Q_{solid} - heat transfer through spacer material by conduction (W)
- Q_{gas} - heat transfer by gas conduction (W)
- Q_{rad} - heat transfer by radiation (W)
- R - universal gas constant (J/mol/K)
- T - temperature (K)
- x - spacial coordinate through the thickness of the MLI blanket (m)
- α - thermal accommodation coefficient for nitrogen used in gas conduction
- γ - ratio of specific heats for nitrogen gas (J/g/K)
- ε - surface emissivity of double aluminized mylar
- σ - Stefan-Boltzmann constant (5.729×10^{-8} $W/m^2/K^4$)