SSC-N-459
6/87

THERMAL PERFORMANCE OF CANDIDATE SSC MAGNET THERMAL INSULATION SYSTEMS

T. Ohmori*1, W.N. Boroski, J.D. Gonczy,
R.C. Niemann and M.K. Ruschman

Fermi National Accelerator Laboratory*2
Batavia, Illinois

T. Taira and K. Takahashi

Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI)
Yokohama, Japan

A. Yamamoto and H. Hirabayashi

National Laboratory for High Energy Physics (KEK)
Tsukuba, Japan

ABSTRACT

The thermal performance of three candidate thermal insulation systems for the SSC magnet cryostat has been evaluated experimentally in a heat leak test facility. The systems evaluated were multilayer insulation (MLI) blankets consisting of aluminized polyester film with fiberglass mat spacer, aluminized polyester film with spunbonded nylon spacer and aluminized dimpled perforated polyester film without spacer. Performance between 300 and 80 K with good and degraded insulating vacuum was studied. The inter-layer heat transfer coefficient h_{itl} and the effective thermal conductivity K_{eff} of MLI blanket were used to compare the different insulation systems and to predict the performance of the SSC magnet insulation.

INTRODUCTION

The proposed Superconducting Super Collider high energy physics research accelerator facility utilizes about 10,000 superconducting devices for particle beam acceleration and control. The magnet cryostats for these devices must have very low refrigeration loads in order to control the capital and operating costs of the refrigeration system. The insulation required for such a large number of magnet cryostats is extensive and thus the thermal performance of the insulation must be optimized to reduce the cost of materials and their installation.[1,2]

*1 Visiting scientist from IHI Co., Ltd. Isogoku, Yokohama 235, Japan
*2 Operated by Universities Research Assn. Inc., under contract with the U.S. Department of Energy

In operation, the magnet cryostat can experience good vacuum, e.g., 1.3 x 10^{-4} Pa (~10^{-6}Torr) when it is cooled down after installation, and also degraded vacuum, e.g., when it is heated during a magnet quench. These are important transient phenomena having different time constants and require study not addressed in this paper. Of equal importance is the steady-state thermal performance of the candidate insulation systems operating with good to degraded vacuum. In this series of measurements, the steady-state thermal performance of the MLI systems were studied in a heat leak test facility[3] between temperatures of 300 K and 80 K and pressures from 10^{-4}Pa to 1 Pa.

The reported studies address the MLI material properties and the fabrication and installation of the MLI blankets. Since heat transfer through an insulation blanket is inherently a function of the MLI material properties and the blanket layer density, accurate measurements of material properties and layer density are essential for obtaining reliable MLI thermal performance data and an optimum cryostat design. Careful measurements were therefore conducted on the physical dimensions of the installed MLI test samples as well as on the surface resistance of the aluminum layer on the polyester film substrate.

HEAT LEAK TEST FACILITY AND TEST METHODS

The heat leak test facility employs a heat meter[4] to measure the heat transfer through the insulation (Fig. 1). The heatmeter measurement is not affected by atmospheric pressure changes. This method is an improvement over boil-off calorimetry which requires special pressure control valving to measure the heat leak for a short period of time without the additional complication associated with a change in atmospheric pressure.

The sample MLI blanket is fabricated around the side and the bottom of a cylindrical cold plate constructed of OFHC copper. The cold plate is 394 mm in diameter and 305 mm in height. Thermal communication between the cold plate and the surfaces of the liquid nitrogen reservoirs, either by thermal radiation or by gas conduction, is limited to a negligible amount with the use of MLI in the space separating the surfaces. The MLI in this space is not shown in Fig. 1 so as not to be confused with the MLI pictured under test. A calibration heater embedded in the cold plate was employed and confirmed that no significant heatflux was bypassed around the heatmeater for both good and degraded vacuum conditions.

The insulating vacuum pressure (pressure of the space between insulation blanket and hot plate) was controlled by means of a turbo-molecular pump and an isolation valve. Vacuum levels higher than 8 x 10^{-3} Pa were obtained with a fully opened isolation valve and was measured with a an exposed ion gage. Degraded vacuum was controlled by closing the valve and was measured with a thermocouple gage. Degraded vacuum lower than 7 x 10^{-1} Pa was obtained by introducing nitrogen gas into the vacuum space. Hot plate temperature is controlled with an embedded heater and promotes the stability of the insulating vacuum. Control of the hot plate temperature is especially important to the study of MLI thermal performance in a degraded vacuum where the performance can be strongly dependent on insulating vacuum pressure.

CANDIDATE INSULATION SYSTEMS

The three candidate MLI systems evaluated were insulation blankets consisting of (1) double aluminized Mylar (DAM) films with fiberglass mat (FGM) spacers (FGM/DAM), (2) double aluminized Mylar films with Cerex spunbonded nylon (CSN) spacers (CSN/DAM) and (3) dimpled and perforated (DP) double aluminized Mylar films without spacers (DP-DAM). The blanket structures are as follows and their geometry is illustrated in Fig. 2:

1) FGM/DAM -- The MLI test sample consists of one blanket of FGM/DAM. The blanket construction is a stacked assembly of alternating DAM and FGM layers stacked to a height of 11 layers of DAM films (Scharr; DAM 25.4 μmt) and 10 layers of polyester bonded fiberglass mat spacers (Nicofibers Inc; SURMAT 254 μmt, fiber diameter is 18 to 21 μm). The fiber glass mat binder adheres to DAM film so that the blanket structure requires no materials to fasten the layers to each other.

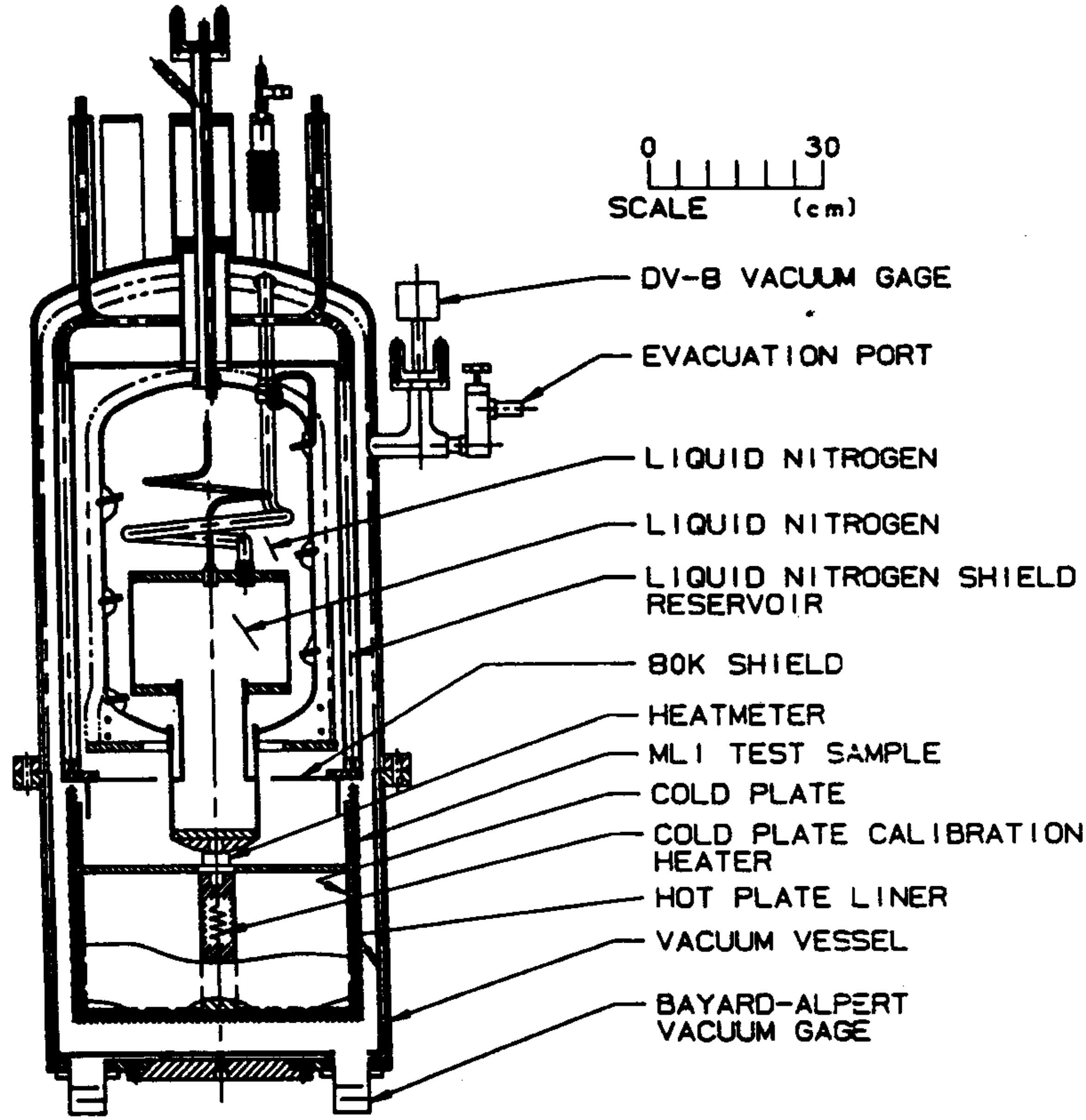


Fig. 1. Heat leak test facility showing MLI test geometry for 300 K - 80 K

2) CSN/DAM -- The MLI test sample consists of two blankets of CSN/DAM. Each blanket is comprised of 13 layers of DAM (Scharr; DAM 25.4 μmt) alternately stacked with 12 spacer layers each having two sheets of CSN (James River Corp.; CEREX 81.3 μmt, 6/6 nylon fibers 21 μm in diameter). The MLI layers were secured together by 16 nylon tag-pins through the blanket.
3) DP-DAM -- The MLI test sample consists of two blankets of DP-DAM. Each blanket contains of 10 layers of DP-DAM (IHI; Dimple 12 μmt; 2 μm diameter perforations for every 100 x 100 μm area) and three DAM layers. The DAM layers are located at the outer most blanket surfaces and in the middle of the blanket. The blanket employs 6 nylon tag-pins to secure the MLI layers.

The layer density of blanket as averaged from the side and bottom parts of the cold plate is listed in Table 1.

Surface resistance of the aluminum coating on the polyester film was measured on sample films by the four electrode method in order to avoid measurement errors

Table 1. Total Thickness H of MLI Blanket Sample

Test Sample	Blanket thickness H (mm) H_s, mm side of cold plate *1	H_b, mm bottom of cold plate *2	H, mm mean value *3	N layers	N/H layers /mm	Note
FGM/DAM	5.4	10.0	6.5	11	1.7	*1: Surface area $S_s = 0.377\ m^2$
CSN/DAM	9.1	8.0	8.9	26	2.9	*2: Surface area $S_b = 0.123\ m^2$
DP-DAM	6.4	3.6	5.7	26	4.6	*3: $H = (S_s H_s + S_b H_b)/S$; * $S = S_s + S_b$

due to variations in electrode contact resistance with the sample. The electrodes are constructed of copper with a width of 100 mm. The data obtained represent the resistance of a 100 x 100 mm area. The distributions of surface resistance along the transverse direction of the original roll film at 23.5°C are shown in Fig. 3 for both DAM and DP-DAM. To obtain a good reflective surface for thermal radiation, the electrical resistance of the aluminum layer is recommended to be less than 1Ω.[5] The resistances of both sides were measured at two positions 9.14 m apart. Scharr DAM has a resistance of less than 1Ω for both surfaces. DP-DAM film has an average resistance 1Ω for the convex side, and 2.7Ω for the concave side.

HEAT TRANSFER ANALYSIS OF MLI

Figure 4 illustrates the MLI blanket installed on the cold boundary (temperature: T_{cold}) and surrounded by the hot boundary (temperature: T_{hot}). The heat transfer through the MLI blanket in the direction normal to the layers is described as the summation of radiative and conductive contributions.[6,8] For adjacent i-th and i-1-th reflective layers, net heat flux q (W/m^2) is,

$$q = \sigma(T_i^4 - T_{i-1}^4)/(1/\epsilon_i + 1/\epsilon_{i-1} - 1) + h(T_i - T_{i-1}) \quad (1)$$

where ϵ is the emissivity, T is the temperature of reflective films, and h is effective heat transfer coefficient of the conductive contribution between the reflective films. i and i-1 denote the i-th and i-1-th reflective films. If the number of reflective films N is large, the warm surface temperature T_N of the insulation is almost equal to the hot boundary temperature T_{hot}.[9] If the heat transfer coefficients for each space and the emissivity of each reflective films are regarded as constant, the net heat transfer q is described by Eq. (2) by adding N sets of Eq. (1) for each insulation effective. Thus,

$$Nq = \sigma(T_{hot}^4 - T_{cold}^4)/(2/\epsilon - 1) + h(T_{hot} - T_{cold}) \quad (2)$$

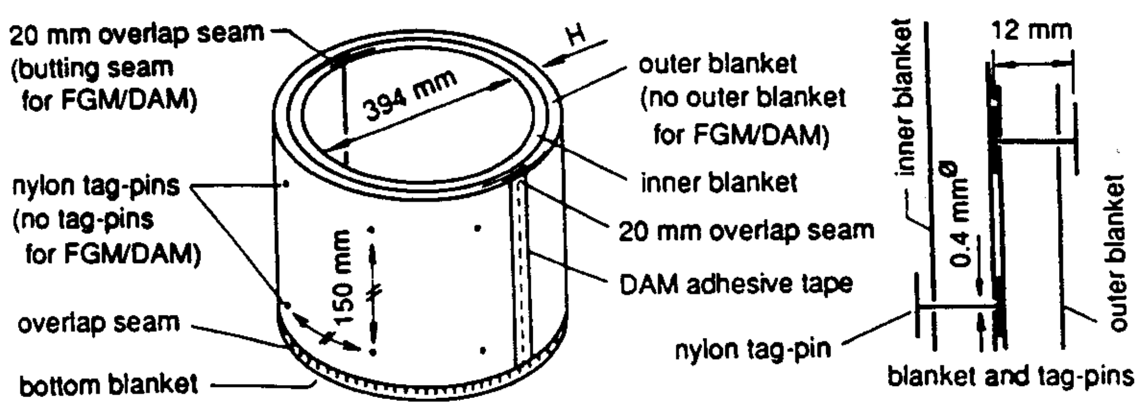
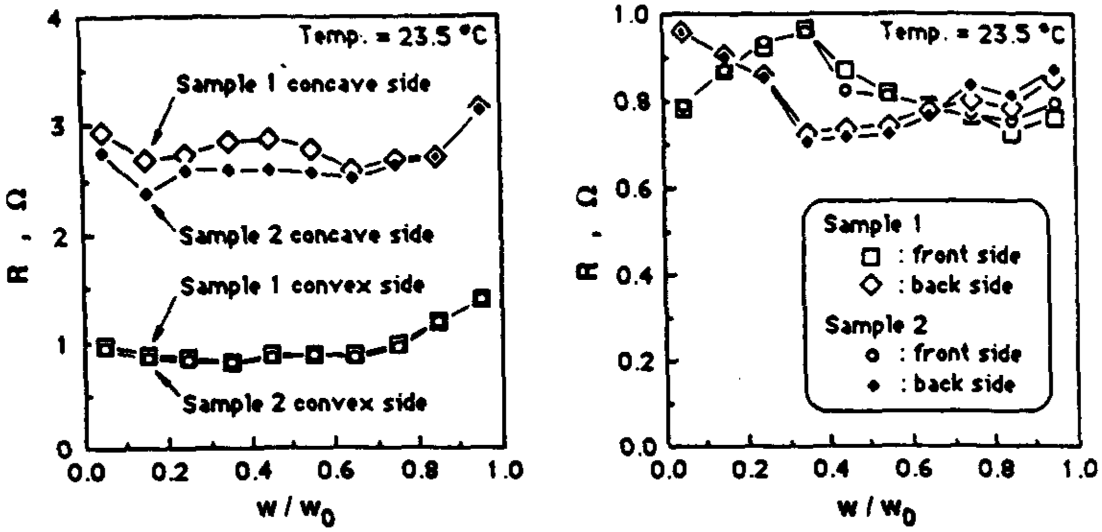


Fig. 2. Geometry of MLI blanket test sample for the heat leak test facility.



(a) DIMPLE (w_0 = 1000 mm)   (b) DAM (w_0 = 1067 mm)

Fig. 3. Surface resistance of aluminized polyester film.

By using the inter-layer heat transfer coefficient h_{itl} (W/m^2K) between adjacent reflective films, Eq. (2) is written as,

$$Nq = h_{itl}(T_{hot} - T_{cold}) \tag{3}$$

$$h_{itl} = 4\sigma \overline{T^2}\,\overline{T} \;/\; (2/\epsilon - 1) + h \tag{4}$$

where $\overline{T^2}$ is the mean square temperature defined as $(T_{hot}^2+T_{cold}^2)/2$ and $\overline{T}$ is the mean temperature defined as $(T_{hot}+T_{cold})/2$. The emissivity ϵ is the radiative property of the reflective film. The heat transfer coefficient h is a parameter which describes the fabrication condition of the MLI blanket, for example, layer density N/H or compression of the blanket. If MLI blankets are fabricated with the same materials and have the same fabrication conditions, Nq and h_{itl} become identical for the same boundary temperatures even if the total number of reflective films N is different. Then the net heat transfer q is inversely proportional to N.

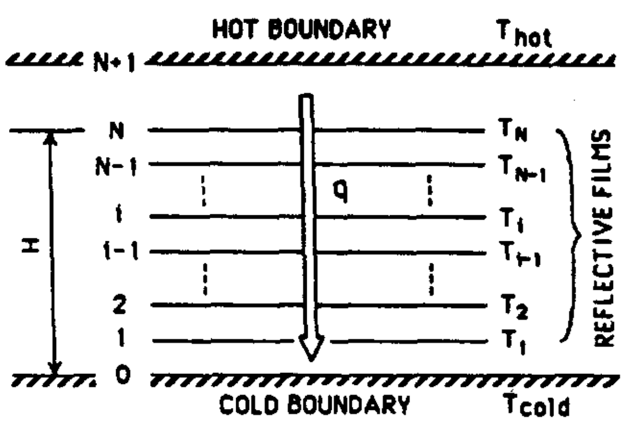


Fig. 4. Heat transfer through the MLI blanket.

The net heat transfer q is also evaluated by using the effective thermal conductivity of the MLI blanket K_{eff}, which is related to h_{itl} by the layer density N/H.

$$q = (K_{eff}/H)(T_{hot} - T_{cold}) \qquad (5)$$

$$K_{eff} = h_{itl} \;/\; (N/H) \qquad (6)$$

Figure 5(a) shows the thermal performance of crinkled MLI for 3×10^{-5} Pa to 0.2 Pa cryostat vacuum pressure as measured in a vertical cylindrical calorimeter[7] for different total number of layers, but maintaining the layer density, N/H,

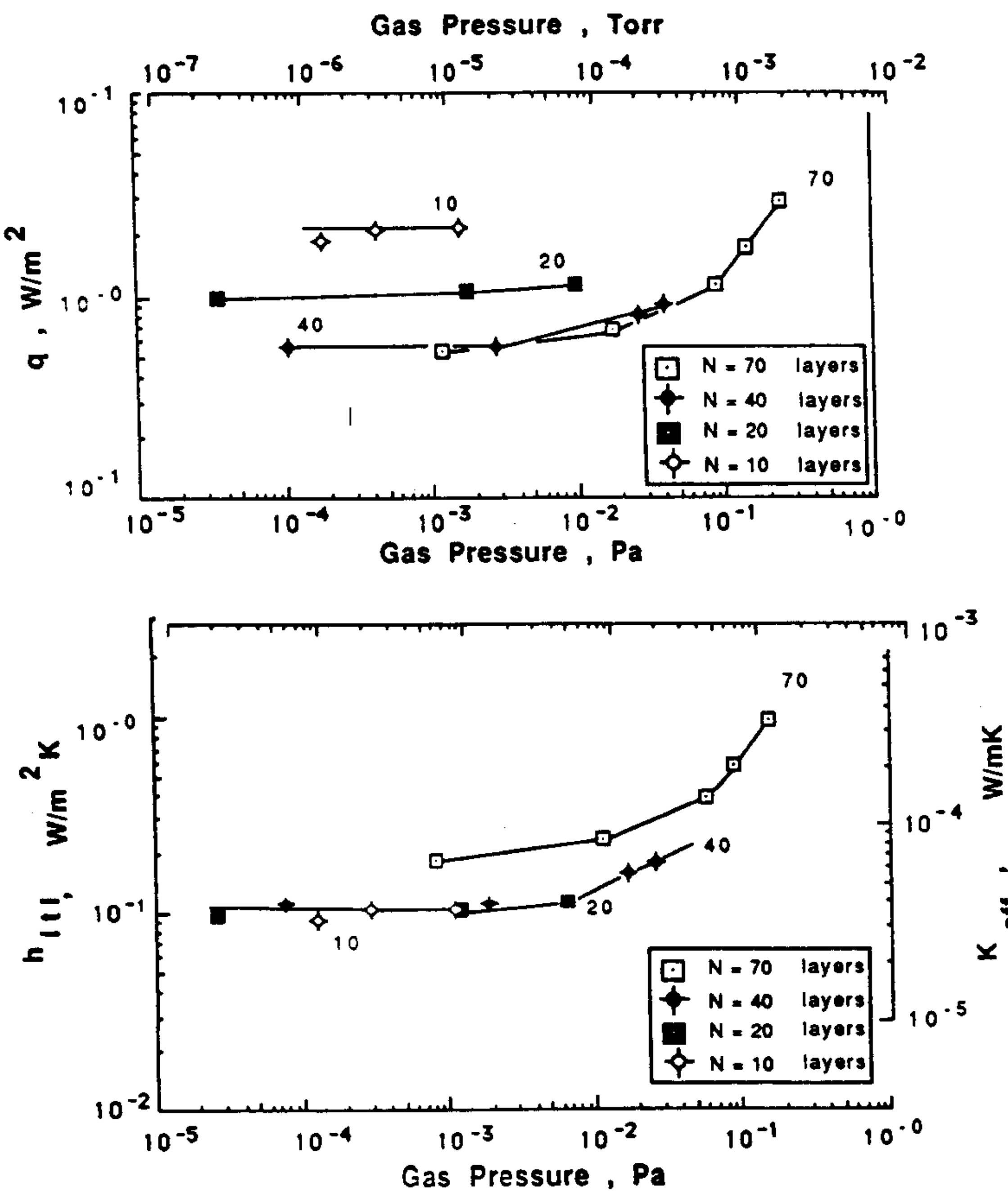


Fig. 5. Thermal performance of crinkled MLI without spacer.

identical at 2.8 layers/mm.[10] If the thermal performance of the MLIs are expressed in terms of h_{itl} or K_{eff}, the results for the different number of layers, i.e., 10, 20, and 40 lie on the same curve as shown in Figure 5(b). The data for 70 layers has a higher heat transfer coefficient than the others. The guard reservoir height L of 400 mm is designed to avoid lateral heat transfer from the cryogen fill/vent ports to the main reservoir. The thickness of this insulation H is 25 mm so that the ratio L/H is 16 for this case.[7] The higher heat flux for N=70 is felt to be due to the compression of the insulation. However, from the data between N=10 and 40, the proportionality of heat flux to N^{-1} is very good. It can be said that h_{itl} and K_{eff} become constant and are characteristic properties of thermal insulation performance for MLI.

If the total number of layers N is small, the space between the hot boundary and the outermost surface of MLI contributes to the insulation performance. Then the left side of Eq. (2) must be (N+1)q. In this situation, the characteristic properties of thermal insulation performance are h_{itl} (or (N+1)q) and N/H.

$$(T_{hot} = 285 \text{ K}, T_{cold} = 77 \text{ K}, N/H = 2.8 \text{ mm}^{-1})$$

TEST RESULTS AND DISCUSSION

Thermal performance data between 300 K and 80 K for candidate MLI blankets are listed in Table 2 and are shown in Fig. 6. The values for h_{itl} and K_{eff} remain essentially constant under good vacuum condition and increase significantly under degraded vacuum condition; i.e., $>10^{-2}$ Pa. The performance difference between each blanket decreases in the degraded vacuum region. For the entire range of vacuums studied, DP-DAM has the lowest h_{itl} and K_{eff}.

The best vacuum recorded was 1.8×10^{-4} Pa for DP-DAM, 1.1×10^{-3} Pa for FGM/DAM and 1.2×10^{-3} Pa for CSN/DAM. Cryostat vacuum better than 1.33×10^{-4} Pa (10^{-6} Torr) could not be attained, because FGM/DAM blankets are employed for the liquid helium and liquid nitrogen reservoirs of the facility. After filling the reservoirs with liquid nitrogen, the vacuum improved to better than 1.33×10^{-3} Pa (10^{-5} Torr) in 50 hours for DP-DAM, 280 hours for FGM/DAM and 400 hours for CSN/DAM. The FGM/DAM insulation recorded better vacuum with faster evacuation speeds than CSN/DAM because the former has fewer layers to evacuate than does the CSN/DAM.

The inter-layer heat transfer coefficient h_{itl} for DP-DAM was also measured between 293 K and 78 K by the vertical cylindrical calorimeter and was evaluated as 5.95×10^{-2} W/m^{2}K for a sample without tag-pins.[5] The layer density of the sample is 4.02 layers/mm and rather small. The results are better by factor of 1.17 than the results obtained by the heat leak test facility because DP-DAM has 6 tag-pins and 6 flat films of DAM. From the analysis of conduction heat transfer through the nylon tag-pin, the total heat flux increase by 6 tag-pins is estimated to be 5.3% for DP-DAM. The total heat flux increase by the 16 tag-pins for CSN/DAM is estimated to be 4.5% which is smaller than in the DP-DAM insulation because the blanket is thicker than the DP-DAM insulation.

Table 2. Candidate Thermal Insulation Systems for The SSC Magnet 80 K Shield*

Insulation	Data obtained in the heat leak test facility (T_{hot} = 300 K, T_{cold} = 80 K)					Design 80 K insulation system		
System	H	N/H	Nq	h_{itl}	K_{eff}	N_t	H_t	w_t
	mm	mm^{-1}	W/m^2	W/m^{2}K	W/mK	layers	mm	kg/m^2
FGM/DAM	6.5	1.69	26.7	0.122	7.19×10^{-5}	44	26.0	3.37
CSN/DAM	8.9	2.93	35.8	0.163	5.55×10^{-5}	59	20.1	3.27
DP-DAM	5.7	4.55	15.9	0.0722	1.59×10^{-5}	26	5.7	0.452

* Insulation heat leak budget for 80 K shield = 0.61 W/m^2

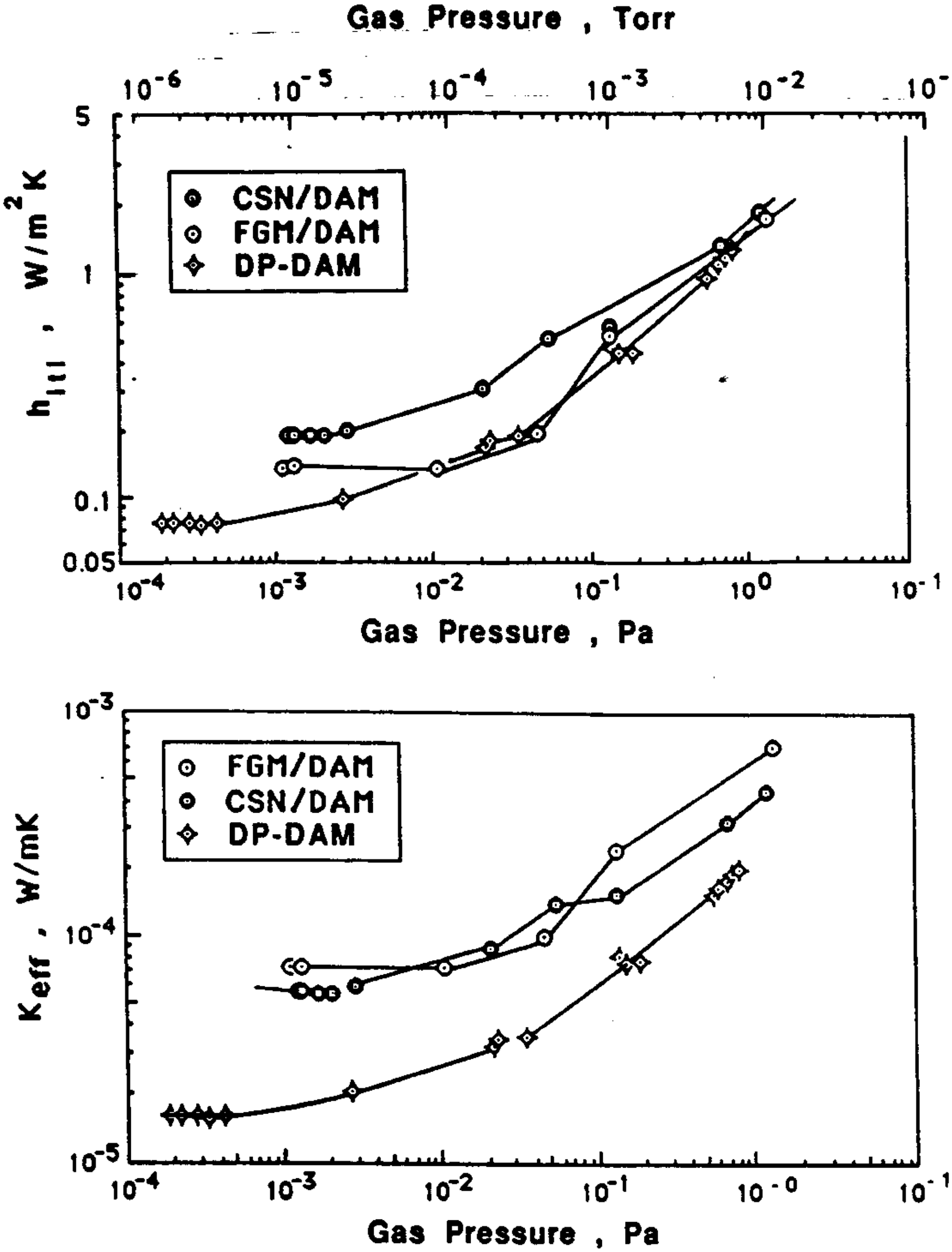


Fig. 6. Thermal performances of candidate insulation systems.

The three candidate thermal insulation systems as designed for the SSC magnet cryostat 80 K shield are listed in Table 2. From the data obtained in the heat leak test facility, the total number of reflective layers N_t of the insulation system which has the same layer density as the MLI blanket test sample required to meet the 80 K heat leak budget, and the corresponding thickness H_t and specific weight w_t are as estimated in Table 2.

The total number of layers N_t is a measure of material and assembly cost of MLI blanket. DP-DAM has the lowest N_t with FGM/DAM second and CSN/DAM third. This ordering is similar to that for the parameter h_{itl}. The material costs for CSN/DAM and FGM/DAM are at present less than DP-DAM, but the fabrication cost of a blanket for the former is higher than DP-DAM.

The total thickness H_t must be smaller than the available installation space in order to avoid mechanical compression of the insulation. DP-DAM has the smallest H_t while CSN/DAM is second and FGM/DAM is third. This ordering is similar to that for the effective thermal conductivity K_{eff}. The installation space for the 80 K and 20 K thermal insulation is especially restricted in the interconnection region between adjacent magnets because the cold mass and other cryogenic pipings are connected by bellows. If a FGM/DAM system is employed, it can encounter high blanket compression which increases the heat leak. The half cell of the magnet string, which consists of 5 dipole magnets, 1 quadrupole magnet and 1 spool piece,[11] has mobile pumping systems at its ends. The vacuum pumpout space around each insulated assembly can only be assured continuity by using thin insulation.

The specific weight w_t of the insulation blanket must be small in order to avoid self-compression of the insulation due to its weight; particularly on a horizontal cylindrical shield. DP-DAM is the lightest blanket because the N_t is the smallest and the insulation requires no spacer material.

The inter-layer heat transfer coefficient h_{itl} of DP-DAM without tag-pins between 78 and 4.2 K measured by the cylindrical calorimeter is 7.93×10^{-3} W/m^{2}K.[5] The thermal insulation system of DP-DAM for the 20 K shield is designed to meet the heat leak budget of 0.075 W/m^2. This system has 22 dimpled layers with a total thickness of 5.5 mm($N/H = 4.02\text{mm}^{-1}$). The CSN/DAM system can be considered as potential material for the 20 K shield, only if its thermal performance h_{itl} and K_{eff} between 80 and 20 K are much better than that for the DP-DAM system.

CONCLUSIONS

The thermal performances from 300 to 80 K of three candidate insulation systems were evaluated and compared experimentally. DP-DAM has the lowest inter-layer heat transfer coefficient h_{itl} between adjacent reflective films and the lowest effective thermal conductivity K_{eff} between 300 and 80 K both in good and degraded insulating vacuum. The insulation system for the SSC 80 K shield utilizing DP-DAM has the smallest total number of layers and the smallest total thickness.

The thermal insulation system for the 20 K shield can be designed with DP-DAM using the data obtained with the cylindrical calorimeter. As the heat transfer mechanism through MLI between 80 and 20 K is different from that between 300 and 80 K, performance studies of CSN/DAM and DP-DAM will be continued in this temperature region.

REFERENCE

1. R.C. Niemann, et al, The cryostat for the SSC 6T magnet option, in: "Adv. Cryo. Engr.," Vol. 31, Plenum Press, New York (1985), p. 63.
2. R.C. Niemann, et al, Superconducting super collider magnet cryostat, in: "6th Intersociety Cryogenic Symposium," Miami, Florida, Nov. 2-7, 1986.
3. J.D. Goncsy, et al, Heat leak measurements facility, in: "Adv. Cryo. Engr.," Vol. 31, Plenum Press, New York (1986), p. 1291.
4. M. Kuchnir, et al, Measuring heat leak with a heat meter, in: "Adv. Cryo. Engr.," Vol. 31, Plenum Press, New York (1986), p. 1285.
5. T. Ohmori, et al, Multilayer insulation with aluminized dimpled polyester film, in: "Proc. Eleventh Intl. Cryo. Engr. Conf.," Butterworth, Guilford, UK (1986), p. 567.
6. C.L. Tien and G.R. Cunnington, Cryogenic insulation heat transfer, in: "Adv. in Heat Transfer," Vol. 9, Academic Press, New York (1976), p. 39.
7. ibid, p. 403.
8. N. Inai, Trans, Japan Soc. Mech. Eng., Ser.B, 43:217 (1977), P.217,
9. Q.S. Shu, et al, Heat flux from 277 to 77 K through a few layers of multilayer insulation, Cryogenics, 26:671 (1986).
10. T. Ohmori, et al, Thermal performance of evacuated multilayer insulation, in: Proc. 27th Meeting of Cryogenic Association of Japan, Tokyo (1981), p. 60, Cryogenic Association of Japan.
11. SSC Central Design Group, Superconducting Super Collider Conceptual Design, SSC-SR-2020, March 1986, p. 331.