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Cryogenic Feasibility of a Polyurethane Foam Insulated Testbeam Cryostat

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Polyurethane foam insulation is considered for insulation of the cryostat for the GEM calorimeter module testing. From the perspective of the cryogenics systems, foam insulation is feasible. Feasibility is based on the criteria of a total heat load to the internal cooling coils of 4000 W or less. Two sets of options were considered. In the first set, 4.5 inches of the insulation are applied resulting in the same overall dimensions as the vacuum vessel of the baseline design. This amount of insulation is acceptable provided that a liquid nitrogen cooled shield is also used. Total consumption of liquid nitrogen for this option is estimated to be 5800 liter / day with a cost of 408 $/ day compared to the baseline liquid nitrogen cost of 157 $/ day. The second set of insulation option considers that the vessel dimensions can be increased. In this case, 18 inches of insulation are applied along with a shield. The greater thickness of insulation would have a total heat load comparable to the baseline design and a liquid nitrogen cost of 182 $/ day.

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Introduction

The current baseline design for the GEM calorimeter module test uses a vacuum vessel around the inner cryostat to reduce the heat load [1]. The possibility of replacing the vacuum vessel with polyurethane foam insulation is considered. This option is evaluated based on the impact on the heat load to the cryogenics systems.

The insulation is considered to be blown in place polyurethane foam. Several options are considered. In the first set of options, the outer diameter of the vessel and insulation is maintained at the current dimension of 100 inches. The foam is considered to fill the region formerly occupied by the vacuum space. between the inner vessel an the outer diameter of the former vacuum enclosure. The foam insulation layer thickness is then 4.5 inches. In the second set of options, it is considered that the outer diameter of the assembly is not restricted to 100 inches. This would be the case if the foam insulation, beyond 4.5 inches, could be applied after the cryostat is located in its final position. In this second case, an insulation thickness of 18 inches is assumed.

To reduce the heat load to the cryostat, additional options are considered. These are: use of a shield within the insulation layer cooled by the cold nitrogen gas exhaust from the cooling coils, a shield using supplemental liquid nitrogen cooling, and use of active thermal intercepts on the cryostat supports. A nitrogen shield within the insulation layer cooled by the nitrogen exhaust from the coils within the cryostat offers the possibility of reducing the heat load to the vessel, by using the heat capacity of the exiting nitrogen vapor. The shield would be made from thin aluminum or copper sheet with attached cooling tubes. The window would not be covered. A shield of this type cooled with exhaust vapor can be expected to reduce the heat flux to the cryostat by 20 % compared to foam insulation without a shield [2]. Also considered is a shield with supplemental nitrogen cooling. In this option the shield is supplied directly with liquid nitrogen. Since the cryostat for the testbeam experiment will operate at liquid argon and liquid nitrogen temperatures, a shield directly cooled with liquid nitrogen offers the possibility of a "negative heat leak" in the sense that it is possible to run the shield colder than the cryostat itself. The other design modification that is considered to enhance the feasibility of foam insulation is the use of active thermal intercepts on the cryostat supports. In the current design using a vacuum vessel design, heat leak through the supports represents about a third of the heat load to the cooling coils. To minimize cost and improve reliability, the supports are not actively cooled. It is possible to reduce the heat load to the cooling coils by thermally intercepting the supports with liquid nitrogen. If the heat load is increased due to the elimination of the vacuum vessel in favor of foam, then thermal intercepting may be necessary to keep the total heat load within the capacity of the cooling coils.

Figure 1 shows the simplified schematic of the cryogenics system for a foam insulated vessel. A shield is included within the insulation. In the design shown the shield can be cooled using the nitrogen gas output of the condensing coils or using liquid nitrogen directly from the storage dewar.

Analysis

From the perspective of the cryogenics systems, the feasibility of using foam insulation depends on the net heat load to the internal cooling coils installed in the cryostat. Currently, the cooling coils already occupy the maximum amount of available space. For the current requirements, the total cooling load is estimated at 4100 W. The coils are sized to accommodate this requirement. The amount of space occupied by coils cannot be increased easily. The feasibility of various foam insulation scenarios is based on achieving the same total heat load to the cryostat as the current baseline of about 4000 W.

The heat flux through the foam insulation is calculated based on the effective or apparent thermal conductivity of the insulation. The apparent thermal conductivity is an experimentally measured parameter that includes all heat transfer mechanisms such as convection within the cells of the foam. The effective thermal conductivity of polyurethane between 300 K and 77 K is 33 mW/m-K [3]. The effective thermal conductivity depends a number of factors including the type of gas used to expand the foam, thermal conditions at time of application, foam density, and aging. To ensure conservative heat load estimates, the calculations were based an effective conductivity of 50 mW/m-K. It is assumed that the cryostat is operating with liquid argon in the bath boxes at a temperature of 87 K. The effective conductivities of most foam, fibrous and gas-filled cryogenic insulations such as perlite, rock wool, and fiber glass fall within the range of 25 to 50 mW/m-K. The results reported for polyurethane are then applicable to these other types of insulation.

Results

The results of the analysis of polyurethane foam insulation are summarized in Table 1. The baseline case shown in Table 1 assumes a vacuum vessel around the cryostat, 30 layers of multilayer insulation in the vacuum space, and a vacuum pressure of 5×10^{-3} Torr. The thermal radiation heat load is 650 W, and the total heat load from all sources, including the preamplifiers, is 4161 W. The baseline liquid nitrogen consumption is 2240 liter/day. At a liquid nitrogen cost of $0.07/liter the baseline operating cost is $157 per day.

The first set of options assumes 4.5 inches of foam insulation on the cylindrical portion of the vessel and 2 inches on the ends. These thicknesses of insulation preserves the current outer dimensions of the assembly. The second

row of Table 1 shows the calculated heat load using just foam insulation. The heat leak to the vessel increases by 7300 W to a total of more than 10,000 W. This is beyond the capability of the cooling coils and is not a feasible option. The next option considers that a shield, cooled by the cooling coil exhaust, is added within the insulation. In this case the total heat load is reduced to 9300 W. This is still beyond the range of the coils. The fourth option listed in Table 1 considers that thermal intercepts are used on the supports reducing the heat leak to the vessel by 1000 W. This still results in a heat load to the cooling coils of 8300 W exceeding the accepted limit.

There are two options using only 4.5 inches of insulation for which foam insulation is feasible. If supplementary liquid nitrogen is used to cool the shields, the heat load to the vessel can be maintained at about 4100 W, within the capabilities of the cooling coils. The analysis assumed that sufficient liquid nitrogen is supplied to the shield such that the conduction heat leak to the vessel through the foam insulation is no more than that which would result for the case of thermal radiation through a vacuum vessel. The total heat leak to both shield and coils is still a factor 2.6 greater than the baseline case. Including both the shield and the internal coils, the total liquid nitrogen consumption is 5800 liter/day at an operating cost of $408 per day. The option which includes a supplemental nitrogen supply to the shields and active thermal intercepts on the supports is also feasible with 4.5 inches of foam insulation. In this case the total heat load is approximately unchanged, but the amount handled by the internal coils is estimated to reduced by 1000 W by using intercepts.

Several options were considered based on 18 inches of insulation on all sides of the vessel. The feasibility of these options is also shown in Table 1. Adding the insulation alone reduces the heat flux through the insulation to 1650 W and the total heat load to 5100 W, close to the acceptable range. If a vapor cooled shield and active thermal intercepts are used then the total heat load is reduced to 3800 W. This is a feasible option. The nitrogen consumption in this case is 2600 liters per day resulting in a liquid nitrogen operating cost of $182 per day. This is close to the operating cost of the baseline design incorporating a vacuum vessel. The use of supplemental liquid nitrogen in the shield is not required if the insulation thickness can be increased to 18 inches. If supplemental nitrogen is used, the heat load to the internal coils can be reduced to about 3000 W. This option may be useful if the heat load inside the cryostat from other source such as the preamplifiers increases beyond current design estimates.

This analysis has identified several approaches in which the GEM testbeam cryostat can be operated using foam insulation rather than a vacuum vessel. One approach preserves the baseline dimensions of the outer vessel, using 4.5 inches of insulation combined with a liquid nitrogen cooled shield. In this case total nitrogen consumption increases by a factor of 2.6 and liquid nitrogen operating cost increases to 408 $/day compared with 157 $/day for the

baseline design (based on $0.07/liter). If the overall dimensions of the final assembly can be increased, then 18 inches of insulation can be added to the cryostat. In this case operation with a nitrogen cooled shield results in a total heat leak that is comparable to the baseline case. The liquid nitrogen costs for this option are about 200 $/day.

Installation

The feasibility of foam insulation also depends on the ability to apply the insulation to the vessel. Since the use of foam insulation is an established technique, no fundamental problems are expected with installation. To prevent degradation of insulation properties a plastic coating such as Mylar is recommended [3]. A possible procedure for installing the insulation and shield is outlined in the following sequence of steps:

Cover vessel with plastic or an insulating liner and seal. Air should not be able to get to vessel metal. The seal could be painted with rubber or epoxy base paint.

Install a wire frame with a standoff at the distance of shield from vessel.

Apply first layer of foam to just beyond the height of the wire frame. After drying, trim foam.

Install shield as sheets of metal, tack in places.

Attach cooling coils to shield.

Shield surfaces should be thermally insulated in a manner similar to vessel.

Apply second wire form to desired final outer diameter.

Apply second layer of foam. Trim.

Cover with plastic, or spray rubber.

Attach hoses for purge gas.

Other Issues

Thermal Contraction

The considerable thermal contraction of foam insulation must be considered in the application procedure.

Condensation of Oxygen

Foam insulation is not compatible with liquid oxygen due to flammability considerations. Steps must be taken to insure that atmospheric oxygen does not condense anywhere on the vessel exterior or on the insulation. The insulation should be purged with dry nitrogen during operation. The nitrogen could be the shield exhaust gas resulting in no additional operating costs. The thermal design of the vessel should be such that the potential for temperatures close to 90 K is minimized. Oxygen condensation will be an issue when the vessel will be operated at liquid argon temperatures and when liquid nitrogen is applied to the shield and support intercepts.

Cryostat Supports

Cryostat supports would extend through the foam insulation. Steps would have to be taken to minimize heat leak through the supports. The likely approach is to thermally intercept the supports using the cold nitrogen gas in the shield cooling circuit or liquid nitrogen.

Beam Window

The beam window will not be covered with the shield. Order of magnitude estimates indicate that the window can probably be covered with foam insulation. An estimate for the beam window design is a 0.2 inch thickness of beryllium [4]. Using a radiation length of 35.3 cm for beryllium [6], the window will be about 0.014 radiation lengths. The radiation length of polyethylene foam is not readily available and is estimated from the radiation length of polystyrene [5]. For polystyrene at a density of 1.03 gr/cm^3, the radiation length is 42 cm [6]. The density of polyethylene is 0.011 gr/cm^3 [3]. Scaling the radiation length by density and assuming a 4.5 inch thickness of foam insulation, results in 0.003 radiation lengths for the insulation. This is about 20 % of that for the window itself. The acceptability of this will have to be determined by the physicists. If foam over the window is unacceptable and alternative would be to use a vacuum break out over the window area. The issue of the

beam window will have to be addressed in more detail if foam insulation is used, but no insurmountable problems exist.

Summary

Polyurethane foam insulation is considered for insulation of the cryostat for the GEM calorimeter module testing. From the perspective of the cryogenics systems, foam insulation is feasible. Feasibility is based on the criteria of a total heat load to the internal cooling coils of 4000 W or less. Two sets of options were considered. In the first set, 4.5 inches of the insulation are applied resulting in the same overall dimensions as the vacuum vessel of the baseline design. This amount of insulation is acceptable provided that a liquid nitrogen cooled shield is also used. Total consumption of liquid nitrogen for this option is estimated to be 5800 liter/day with a cost of 408 $/day compared to the baseline liquid nitrogen cost of 157 $/day. The second set of insulation option considers that the vessel dimensions can be increased. In this case, 18 inches of insulation are applied along with a shield. This greater thickness of insulation would have a total heat load comparable to the baseline design and a liquid nitrogen cost of 182 $/day.

Several other factors were considered in determining feasibility. Assembly of the insulation is based on the polyurethane being foamed in place using established techniques. Steps must be taken to inhibit degradation of the insulation over time, and to prevent possible liquid oxygen condensation on the cryostat assembly. Assembly must accommodate the thermal contraction of the foam at operating temperatures. With foam insulation the heat load through the cryostat supports becomes significant and active thermal intercepts would be required. The potential of oxygen condensation on the vessel, shield, or support intercepts must be eliminated. The method of insulating over the beam window will require further work.

References

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[6] M. Aguilar-Benitez et al., *Particle Properties Data Booklet*, North Holland, (1990).

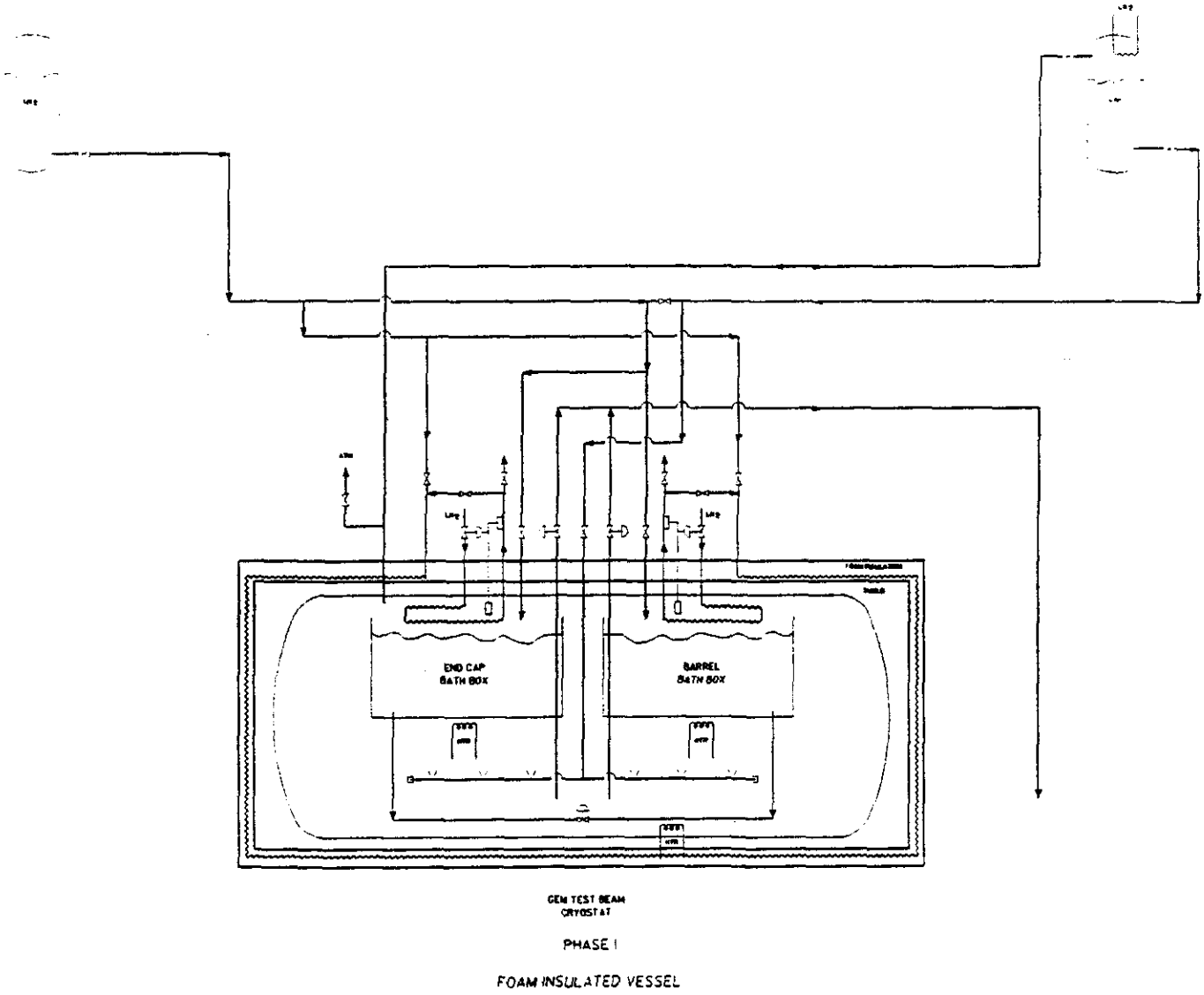

Figure 1. Simplified Cryogenics System Schematic.

Table 1. Summary of Foam Insulation Options.

Option	Vessel Insul. Heat Load (W)	All Other Heat Loads (W)	Heat Load to Internal Coils (W)	Heat Load to Shields/Intcpt (W)	Heat to LN2 Total Load (W)	LN2 Used (liter/day)	LN2 Cost@ $0.07/liter ($/day)	Feasible
Baseline (vacuum vessel + MLI)	650	3511	4161	0	4161	2243	157	yes
4.5" foam, no shield	7300	3511	10811	0	10811	5827	408	
4.5 " foam, vapor shield	5835	3511	9346	0	9346	5037	353	
4.5" foam, vapor shld, intercepts	5835	2500	8335	1000	9335	5032	352	
4.5" foam, supl. LN2, no intercepts	600	3511	4111	6700	10811	5827	408	yes
4.5" foam, supl. LN2, intercepts	600	2500	3100	7700	10800	5821	407	yes
18" foam, no shield	1650	3511	5161	0	5161	2782	195	
18" foam, vapor shield	1320	3511	4831	0	4831	2604	182	
18" foam, vapor shield, intercepts	1320	2500	3820	1000	4820	2598	182	yes
18" foam, supl. LN2, no intercepts	600	3511	4111	1050	5161	2782	195	yes
18" foam, supl. LN2, intercepts	600	2500	3100	2050	5150	2775	194	yes