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CRYOSTAT WITH FOIL AND MLI
STTR Phase I

Final Technical Report

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Peter K.F. Hwang[1], Chen-yu Guang[2]

1. Advanced Magnetic and Cryogenic, LLC, Macungie, PA 18062
2. Plasma Science and Fusion Center, MIT, Cambridge, MA 02139

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DEPARTMENT OF ENERGY

ABSTRACT

Induction cores are used to accelerate heavy ion beam array, which are built around the outer diameter of the cryostat housing the superconducting quadruple array. Compact cryostat is highly desirable to reduce the cost of the induction cores. Recent experiences in fabrication of a cryostat for single beam transport revealed that it is possible to reduce the spacing in the cryostat vacuum jacket by using low-emissivity thermal insulation material instead of conventional MLI. However, it is labor-intensive to install the new type of insulation as compared with using MLI.

It is promising to build a cost-effective compact cryostat for quadruple magnet array for heavy ion beam array transport by using low-emissivity material combined with conventional MLI as radiation insulation. A matrix of insulation designs and tests will be performed as the feasibility study and for the selection of the optimal thermal insulation as the Phase I work. The selected mixed insulation will be used to build prototype compact cryostats in the Phase II project, which are aiming for housing quadruple doublet array.

In this STTR phase I study, a small cryostat has been designed and built to perform calorimetric characterization of the heat load in a liquid helium vessel insulated with a vacuum layer with a nominal clearance of 3.5 mm. The vacuum clearance resembled that used in the warm-bore beam tube region in a prototype cryostat previously built for the heavy ion beam transport experiment. The vacuum clearance was geometrically restricted with a heater shell with the temperature controlled at near 300 K. Various combinations of radiation and thermal shields were installed in the tight vacuum clearance for heat load measurements. The measured heat loads are reported and compared with previous test result using a compact vacuum layer. Further developments of the thermal insulations used in the present study are discussed.

The compact cryostat with foil and MLI insulation may be used in the superconducting magnets for a wide range of applications including particle accelerators, fusion energy research, NMR, NMI, laboratory high field experiments and industrial magnets, compact feed through for general-purpose cryostat, etc.

Combination of low emissivity thermal insulation material with the conventional MLI has a great potential to build cost-effective compact cryostats for heavy ion fusion beam array transport and other more general-purpose applications.

INTRODUCTION

This STTR Phase I research project was motivated by the challenge of building a compact warm bore heavy ion beam transport line using superconducting quadruple magnets. To make the best used of the magnetic field, it is required to build a cryostat with a vacuum clearance in the warm bore region as tight as possible. It is a state of the art to minimize the heat load entering the cold mass bore, which preserves the performance of the superconducting magnets enclosed in a compact cryostat and maximizes the operation time with a minimal LHe budget.

A prototype cryostat housing a pair of NbTi superconducting quadruples for single beam High Current Experiment (HCX) project was constructed and tested[1]. The HCX prototype cryostat was an attempt to build a compact cryostat for single beam transport. One of the major purposes of the HCX cryostat was to investigate the feasibility of a compact vacuum jacket design for the warm bore beam tube. The radial spacing between the 4.5 K magnet bore and the room temperature beam tube was 3.5 mm, which was an ambitious design compared with allowing a 12 mm – 25 mm of vacuum clearance to accommodate commercial MLI.

Novel reflective foil[2] was used to cover the cold mass in the HCX cryostat. The reflective foil was made of 0.1 mm thick stainless steel foil, vapor-deposited with 1 micrometer thick of high purity aluminum on both sides of the foil. The nominal emissivity of the foil was no more than 0.02, 0.01, and 0.002 at respective temperature of 300 K, 77 K and 4.2 K.

In the HCX beam tube vacuum space, one layer of reflective foil was installed on the respective 4.5 K and 300 K surface. Two additional layers of dimpled foils were inserted in between the boundary layers. The dimples with an average height of 0.01" and an area density of ~ 4 dimples per squire inch were functioning as spacers to reduce the contact area between foils. In order to preserve the space in the vacuum jacket to accommodate sufficient layers of foil, no actively cooled thermal shield was used in this region.

For the reason of not to degrade the emissivity of the foil by the outgassing from the commercial MLI, as recommended by the foil inventor / vendor, the cold surfaces in the vacuum space were covered with the same foil material. Except for the magnet bore, active thermal shield in the form of LN reservoir or copper sheath cooled with LN trace was used between the second and the third layers of foil.

The HCX cryostat test results showed that the heat load in the LHe bath was higher than design calculation based on published emissivity data especially in the worm bore beam tube region. Due to the complicated geometry and heat sources in the HCX cryostat, it was difficult to characterize the heat load entering the cold mass in the beam tube region.

In this project, a small cryostat has been designed and built as a common platform to test the heat loads in a simple cylindrical LHe vessel. The LHe vessel could be covered with

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[1] Gung, C., etc., "Construction and Test of HCX Quadruple Doublet for Heavy Ion Bean Transport Experiments", IEEE Trans. Appl. Superconductivity, Vol. 15, p. 1171-1174, 2005.

[2] Gotoh, M., Momose, T., Ishimaru, H., Larin, M.P., "Liquid helium cryopumps with low emissivity Al film coating and low helium consumption", J. Vac. Sci. Technol. A13 (5) Sep/Oc 1995, p. 2579.

various combinations of radiation insulations and heat shields used in a tight vacuum clearance, which simulated that in the HCX beam tube region. The purposes were to compare the performances of the novel foil vs. commercial MLI, as well as investigate the feasibility of using an active thermal shield in a tight vacuum clearance in the warm bore region defined in a practical HCX cryostat. Heat load entering the LHe bath covered with 4 layers of reflective foils without active thermal shield was tested and compared with the previous results in HCX cryostat experiments. The best combination of insulation and thermal shield with the lowest heat load in the cold mass will be used to shield the magnet bore in the Phase II cryostat.

DESIGN AND FABRICATION OF THE TEST CRYOSTAT

Fig. 1 shows the sketch of the Phase I cryostat. The dimension of the LHe vessel was the same as that of the cold magnet bore used in the previous HCX test[3]. In order to reduce the longitudinal conductive heat load from room temperature, a thin wall stainless steel tube with 0.75" dia x 0.01" wall, was used as a vent tube to connect the LHe vessel to the top flange. The conductive heat load along the thin wall vent tube into the LHe bath was estimated orders of magnitude less than 0.1 mW.

The cryostat was designed with a removable vacuum vessel flange. Both liquid helium and liquid nitrogen vessels were welded to the top flange. The cylindrical surface of the LHe vessel was the area for testing various insulations and thermal shield. Autocad drawings for manufacture were generated.

The cryostat was fabricated by a local welding and machine shop, AES. Care was taken in the welding of thin vent tube. Two layers of aluminum foils were used to wrap around the vent tube region and they are tied with stainless steel wire. This technique was a design with an aim to eliminate or reduce the out-gassing issue.

The upper end of the thermal shield in-between the radiation insulations for 4.5 K and 300 K surfaces were sandwiched between a the copper ring brazed to the bottom of the LN vessel, and the mating copper clam shells. The lower end of the thermal shield was connected to a heavy copper disk below the bottom flange of the LHe vessel, which was cooled by a circular loop of LN trace. The insulations and the thermal shield installed in the test zone were both demountable.

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[3] Gung, C.Y., Manahan, R., Martovetsky, N., "HCX quadruple prototype cryostat statement of work, rev. 2", August 2, 2002.

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1/2" quick disconnect welded to ¾" Tee for LHe transfer line.
Remove transfer line with Tee and LHe sensor during test.

3/4" SST Tee

9 pin electrical connector plugged in 1/2"
quick disconnect fitting for LHe level sensor

KF 16 connection

2 x 9 pin hermetic electrical connectors in ½" quick
disconnect, for 5~7 two-wire CLTS, in vacuum space

3/4" SST Tee

8" OD nonrotatable SST conflat flange
for 6" tube, bolt hole: clearance

LN thermal intercept bonded to upper GHe vent tube

Upper GHe vent tube, 075" OD x 0.065" wall

Lower GHe vent tube, 0.75" OD x 0.010" wall

Upper LN vessel, annular jacket, 304 LN,
2.88 ID x 4.5 OD x 11.5 H x 0.065 wall

Vacuum vessel, 304 SST, 5.75 ID x 6.0 OD

LHe vessel, 316 SST, 2.1 ID x 2.25 OD x 16.86 H,
Test volume: 0.96 liters

LHe level probe, 16" x 0.25 dia., fastened to a G-10 strip

Test zone: 3.5 mm (0.138") radial build from LHe vessel
for thermal insulation / shield, 2.25 ID x 2.526 OD x 15 H.

Test zone: outer sleeve for dimension control,
2.526 ID x 0.002~0.003 wall x 15 H;
formed by SST shim stock with spot welded axial seam

LN inlet / outlet tubes for cooling bottom shield, insulated in
pair in 10 layers of MLI, SST tube, 0.25 OD x 0.035 wall

SST threaded rod for position control of the bottom
thermal shield, 1/16 dia x 20 H, 1 piece

Cu disk 3.5 dia. X 0.5 thick, 1 piece,
top: machined OD to 3.0 dia. X 0.25 deep,
bottom: 3.0 dia. round groove, groove: 5/16 dia. X 5/32 deep,
through hole for 8-32 bolt, bolt circle: 2.0 dia., 6 places

G-10 plate, 3.5 dia. X 0.125 thick, 1 piece,
through hole for 8-32 bolt, bolt circle: 2.0 dia., 6 places

GHe vent, 0.75" Tee x 0.065" wall

Vacuum insulation, 1.5 x 0.063 wall, SST tube

LN inlet / outlet, 2 places, 0.25 OD x 0.035
wall SST tube

Vacuum insulation, 1.0 x 0.063 wall, SST tube

CPC Cryolab vacuum
seal off valve, 1" dia.

8.31

3.00

2.06

2.00

2.00

1.50 2.00

1.00

5.00

11.50
LN jacket
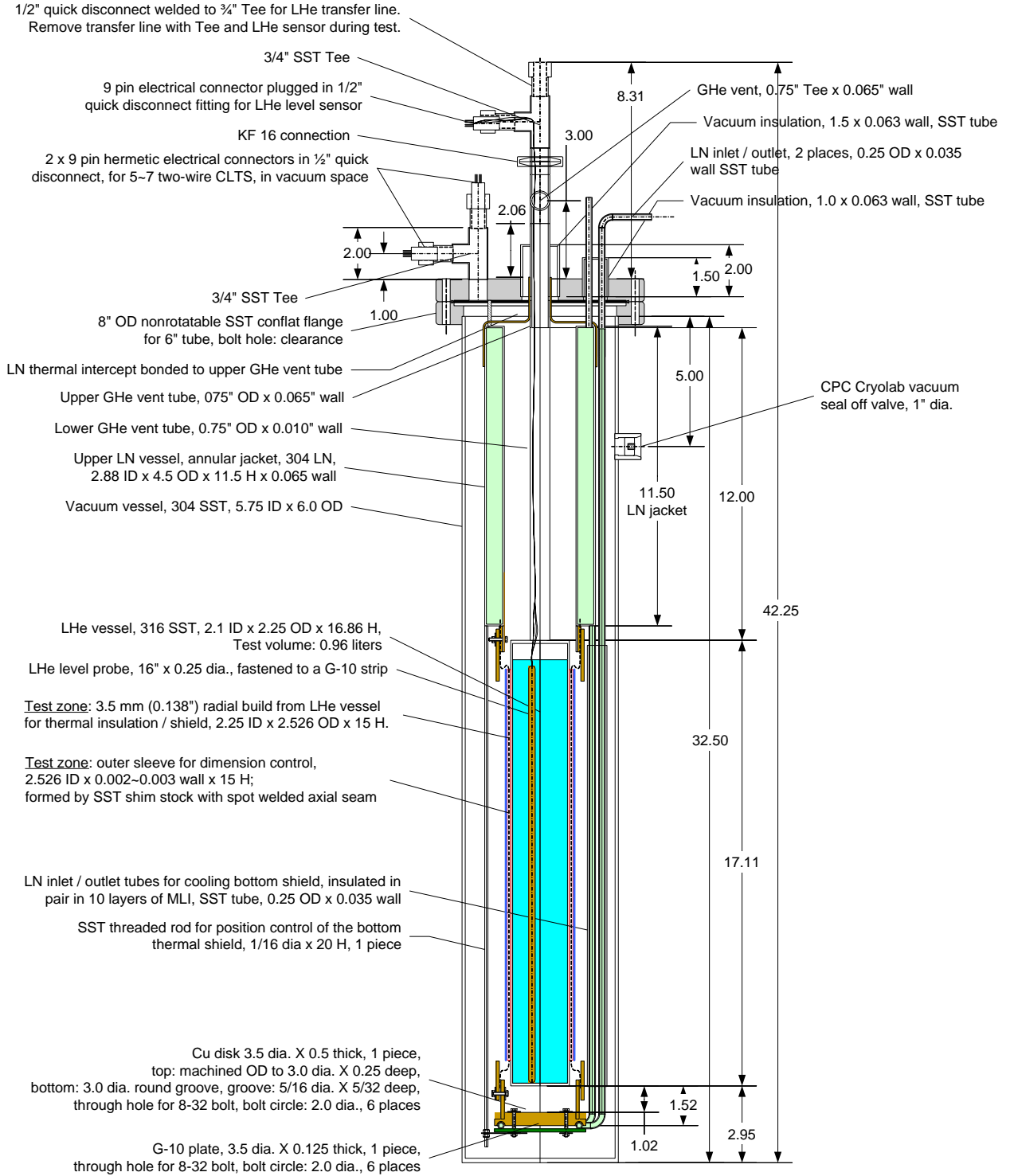
12.00

42.25

32.50

17.11

1.52

1.02

2.95

Fig. 1 Cryostat designed for testing various thermal insulations.

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THERMAL INSULATION

Fig. 2 shows the design of the test insulation in the cryostat as well as in the test zone. The top flange of the LHe vessel was covered with a few layers of crumpled aluminum foil. The bottom flange of the LHe vessel was insulated by 10 layers of aluminum foil stacked up on the copper disk ~ 1" underneath the LHe vessel.

Fig. 3 shows the cross section view of the combination and the arrangement of the insulations and the thermal shield used in different tests. In all cases, the 0.012" thick aluminum foil (item #3) used as the conduction cooled thermal shield limited the outer diameter of the 4.5 K insulation within 2.368". A cryogenic linear temperature sensor (CLTS) was installed at the midplane of the thermal shield to monitor the temperature. Likewise, the outer heater shell (item #5), a 0.012" thick aluminum sheet, installed with a heater and a CLTS for regulating the shell temperature at ~ 300 K, was used to restrict the overall test zone diameter within 2.486". The radial clearance between the outer surface of the LHe vessel at 4.5 K and the heater shell at ~ 300 K was kept at 0.118" or ~ 3 mm, which reproduced the tight vacuum clearance in the warm bore region of the HCX cryostat experiment. The only difference was that the warm and cold surfaces in the present cryostat were opposite to those in the magnet bore in the HCX cryostat.

Case 1: MLI with Thermal Shield

As described above, the emissivity of the aluminum coated stainless steel foil was no more than 0.02, 0.01, and 0.002 at respective temperature of 300 K, 77 K and 4.2 K. The emissivity of the foil is equivalent to 10 layers of highly polished aluminum at 4.5 K, and ~ 5 layers at 77 K. To compare the performances of the MLI and the foil, we installed 5 layers of MLI in the region between the LHe vessel and the thermal shield, and 10 layers between the thermal shield and the room temperature heater shell in the first test with MLI. It is understood that this high packing density of MLI contradicted with the statistical rule of thumb density of 30-40 layers / inch, which has a minimal heat transferring. However, the purpose of the first test setup was to compare the performances of various insulation concepts used in a tight vacuum clearance between liquid helium and room temperature walls.

The same setup, except with 2 layers of MLI installed between the LHe vessel wall and the thermal shield, was tested in a later shot to compare the effect of reduced packing density, which was in line with the recommended usage.

The MLI used in these tests was Cryolam in Crinkleform manufactured by MPI, which is a two-sided aluminized film with a non-woven, non-outgassing spacer bonded together for applications requiring layer separation.

Case 2a: Foil without Thermal Shield

The second type of test was designed to test the heat load to the LHe bath insulated with the novel foil with low-emissivity. As installed in the warm bore vacuum space in the previous HCX quadruple magnet, four layers of foils were used without an active thermal shield. The foil against the LHe vessel was made with dimples as the spacer to the neighboring layer. The outer most layer was spot-welded with small spacer against the near room temperature heater shell. No spacers were installed on two intermediate layers.

Case 2b: Foil with Thermal Shield

Same foils used in case 2a were used in this test. The difference was that a thermal shield was installed between the second and the third foil. The purposes are to evaluate the feasibility of accommodating an additional layer of material as thermal shield in a tight vacuum clearance, and to test the improvement in the heat load by this actively cooled thermal shield.

Case 3: Mixed Foil and MLI with Thermal Shield

The third test was an attempt to improve the thermal performance of the cryostat by replacing the foils between the thermal shield and the heater shell with MLI. Since the emissivity of the foil at room temperature was slightly better than highly polished aluminum, it was interesting to find out whether the heat load into the LHe vessel can be reduced by using more layers of MLI between ~ 77 K and 300 K. In order to isolate the outgassing of the MLI from the foil, 10 layers of MLI were enclosed in a separated vacuum bladder made of 0.01" thick stainless steel sheets.

In the initial plane in making the cylindrical bladder, two stainless steel sheets are pre-rolled into cylinders then welded together with the MLI enclosed inside. A small opening along the edge is welded to a pump out tube. The tube is sealed with epoxy after the bladder is evacuated. The practical experiences with bladder fabrication and application will be discussed in a later section.
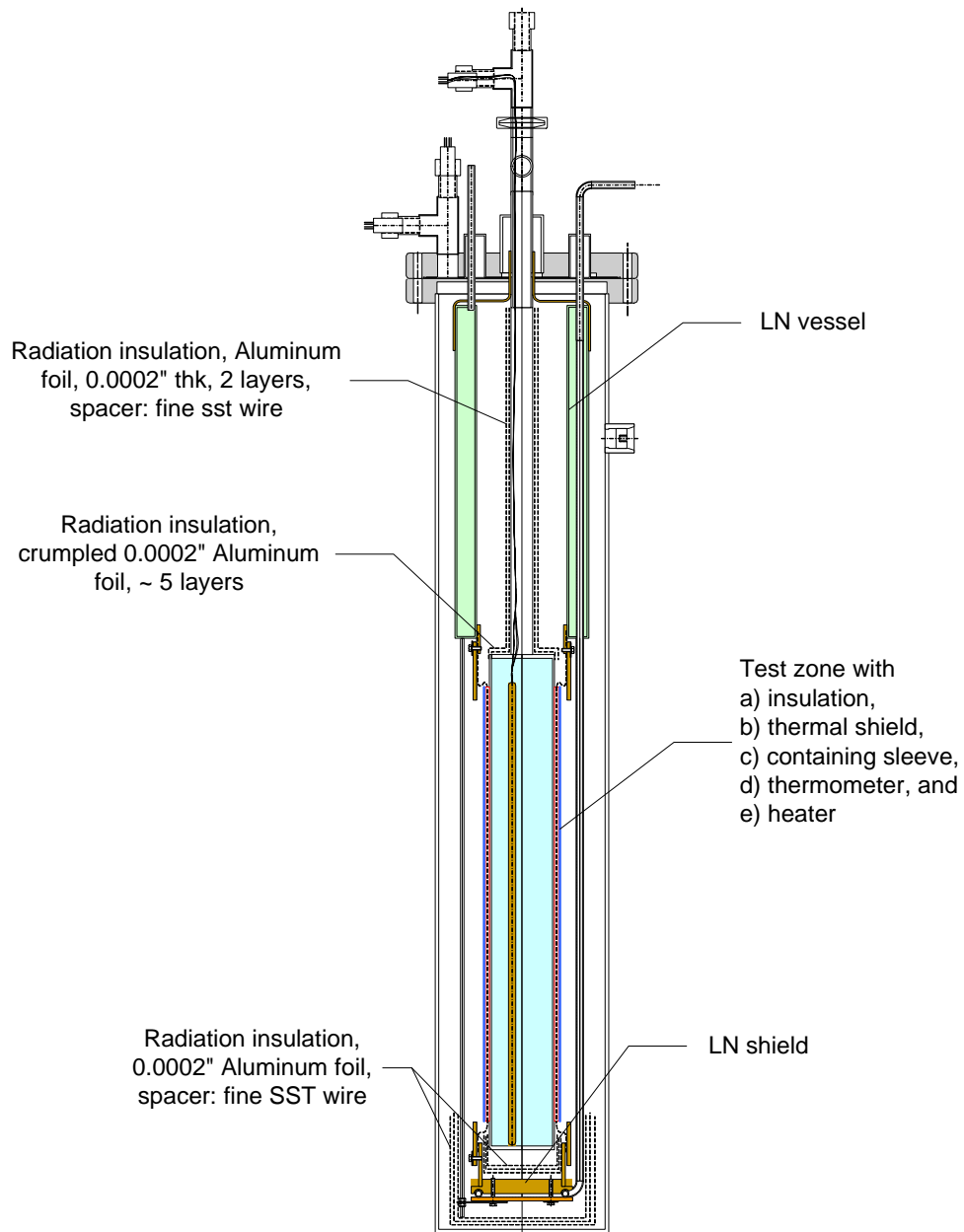
Radiation insulation, Aluminum
foil, 0.0002" thk, 2 layers,
spacer: fine sst wire

LN vessel

Radiation insulation,
crumpled 0.0002" Aluminum
foil, ~ 5 layers

Test zone with
a) insulation,
b) thermal shield,
c) containing sleeve,
d) thermometer, and
e) heater

Radiation insulation,
0.0002" Aluminum foil,
spacer: fine SST wire

LN shield

Fig. 2 Installation plan of the radiation insulation in the cryostat and the test zone.

TEST ZONE, CROSS SECTION VIEW

Ø2.250, OD, LHE VESSEL

#1
Ø2.299, OD OF 4K INSULATION

#2
Ø2.309, INSULATION IN 4 K - 77 K

#3
Ø2.368, THERMAL SHIELD

#4
INSULATION IN 77 K - 300 K

#5   HEATER SHELL
1) Ø2.486, ID, AL FOIL, 0.012" THICK; &
2) OVER-WRAPPED W/ FLEXIBLE HEATER
   W/ KAPTON INSULATION

TESTS WITH MLI ONLY

#1	MLI WITH SPACER, 5 LAYERS
#2	N/A
#3	ALUMINUM FOIL, 0.012" THICK, CONDUCTIVELY COOLED
#4	MLI WITH SPACER, 10 LAYERS
#5	AS SHOWN

TESTS WITH REFLECTIVE STAINLESS STEEL FOIL ONLY

#1	REFLECTIVE FOIL WITH DIMPLES, 1 LAYER
#2	REFLECTIVE FOIL, 1 LAYER
#3	ALUMINUM FOIL, 0.012" THICK, CONDUCTIVELY COOLED
#4	REFLECTIVE FOIL W/ SPOT WELDED SST SPACERS, 2 LAYERS
#5	AS SHOWN

TEST WITH MIXED MLI AND REFLECTIVE STAINLESS FOIL

#1	REFLECTIVE FOIL WITH DIMPLES, 1 LAYER
#2	REFLECTIVE FOIL, 1 LAYER
#3	ALUMINUM FOIL, 0.012" THICK, CONDUCTIVELY COOLED
#4	MLI (10 LAYERS) ENCLOSED IN A STAINLESS VACUUM BLADDER, INNER WALL WRAPPED AGAINST LN COOLED ALUMINUM FOIL
#5	AS SHOWN

Fig. 3 Installation of the thermal shield and insulation.

ASSEMBLY OF TEST CRYOSTAT

Fig. 4 demonstrates the installation of the insulation, which was MLI in the photos, and the thermal shield against the LHe vessel. Fig. 4(a) shows an annular LN upper vessel welded to the top flange, and an LHe vessel with a smaller cylinder located below the LN vessel. The LHe vessel is welded to the lower end of a GHe vent tube made of a 0.75" dia. x 0.01" thick stainless steel tube, and is surrounded by the LN vessel. The upper end of the GHe vent tub is welded to the top flange of the vacuum vessel and is thermally anchored by copper braids brazed to the LN vessel. The vent tube was the only structure to carry the dead weight of the LHe vessel. An LN trace loop and a copper ring for conductive cooling is connected to the bottom of the LN vessel. Fig. 4(b) shows the inner insulation wrapping over the LHe vessel.

(a)   (b)   (c)   (d)   (e)
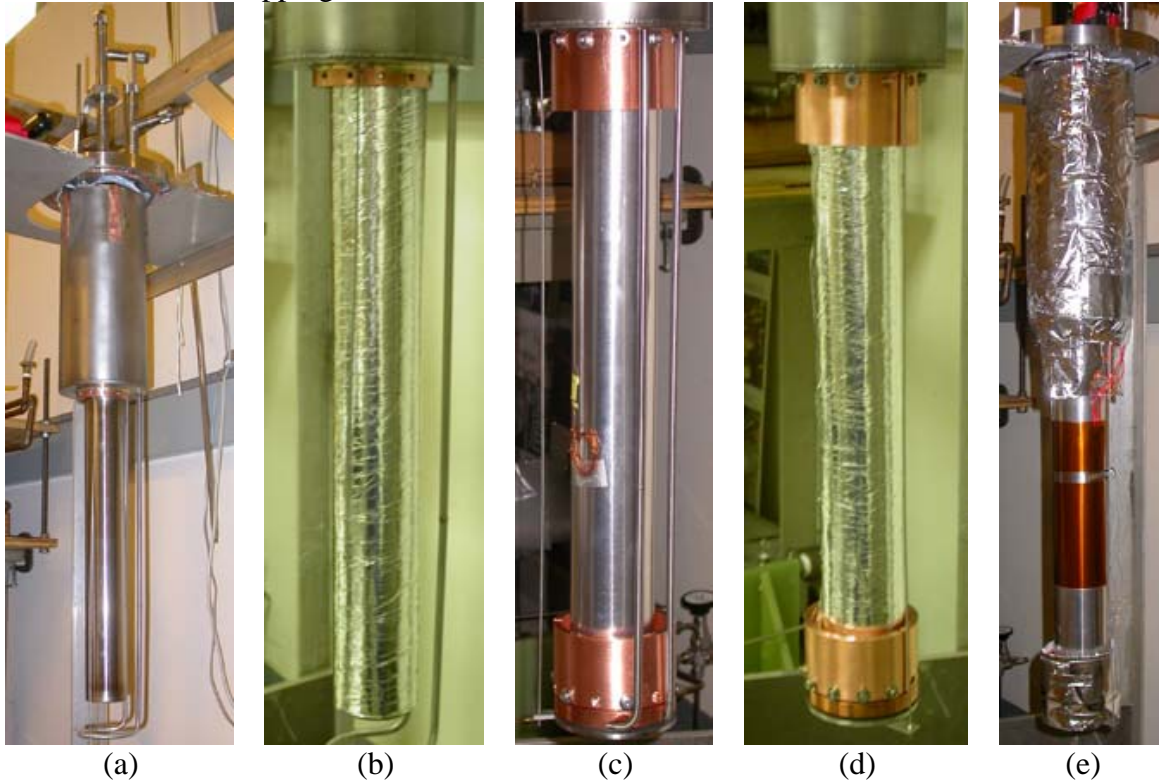
Fig. 4 In-vessel test setup. (a) The LHe (lower) and the LN (upper) vessels both were welded to the removable top flange. (b) The inner insulation wrapped over the LHe vessel. (c) Conductively cooled thermal shield wraps over the inner insulation, which was an aluminum sheath bent into tubular shape, with both ends anchored to the 77 K surfaces. (d) The outer insulation wrapped over the thermal shield. (e) The aluminum heater shell wrapped over the outer insulation, which was attached with a Kapton insulated flexible heater pad and a CLTS to regulate the temperature to ~ 300 K during cold test.

Fig. 4(c) is the conductively cooled thermal shield, wrapping over the inner insulation, and thermally anchored to the LN vessel in the top end and to the bottom copper disk in the lower end. The copper clam shells in both ends are used to hold the thermal shield against the 77 K surface. Fig. 4(d) is the outer insulation wrapping around the thermal shield. As shown in Fig. 4(e), the heater shell made of 0.012" thick aluminum sheet

wraps over the outer insulation. The aluminum shell is attached with a Kapton insulated flexible heater pad and a CLTS to control the temperature at ~ 300 K.

Except for testing with bladder containing MLI, the same thermal shield was used in all tests to maintain the same test clearance between the LHe vessel and the thermal shield. The same heater shell was used as well to control the overall radial clearance.

As mentioned before, the emissivity of the novel reflective foil is similar to that of MLI at near room temperature. It is possible to evaluate the heat load in the cold mass by replacing the 2 layers of 0.005" thick foil between the heater shell and the thermal shield with multiple layers of 0.0002" thick MLI. Fig. 5(a) shows the bladder made of 0.010" thick stainless steel sheath for containing 10 layers of MLI and for isolating the outgassing from the foil.

Fig. 5(b) shows the installation of the foils (2 layers) between 4K and the thermal shield, the thermal shield connection to the copper rings, and the bladder contain MLI as insulation between the thermal shield and the 300 K shell. Due to the stiffness of the bladder, an oversize thermal shield was used to remove the heat from the in-board wall of the bladder. Also, leaks developed along the welded circular edges when it was bent to a smaller diameter to conform to the original thermal shield. The stainless steel tube used as pump out port was routed to near the pump out port of the test vessel. The cryostat was continuously evacuated with a turbo pump throughout the cold test to reduce the amount of outgas cryo-pumped to the foil surfaces. The effect of the MLI outgassing on the foil was reduced, but not strictly isolated.

Fig. 5(a) Stainless steel bladder with 0.01" thick wall containing 10 layers of MLI.
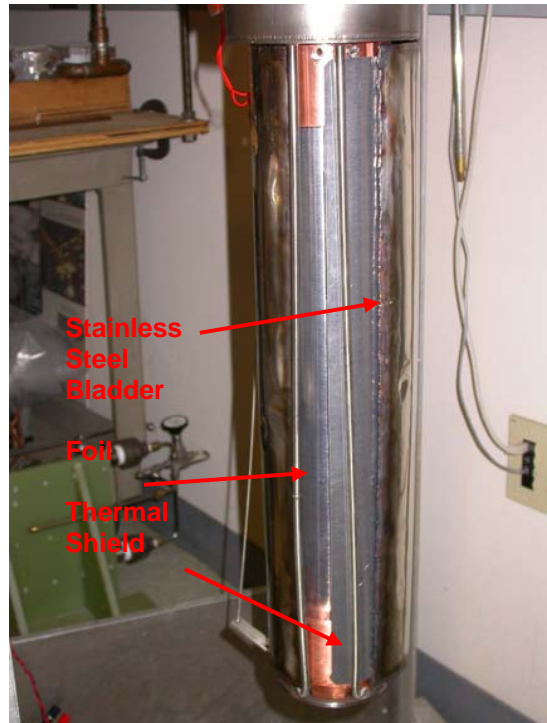
Fig. 5(b) Installation of the foil, thermal shield, and the bladder to the test cryostat.

INSTRUMENTATION

Two cryogenic linear temperature sensor (CLTS) made by Vishay Micro-Measurement were used in the vacuum space. One was installed on the thermal shield and the other was installed on the outer aluminum heater shell along with a Kapton insulated flexible heater pad to regulate the shell temperature to ~300 K during cold tests with. In the case of testing without a thermal shield, the temperature sensor was sandwiched between the second and the third layers of the foil near the mid plane of the LHe vessel.

The heat load in the LHe bath was monitored by a 15" AMI superconducting LHe level sensor and a MKS flow meter connected to the vent tube of the LHe vessel. The sampling interval of the level sensor was set to 10 minutes in order to allow sufficient time to remove the background Joule heating generated by the built-in heater in the level sensor. As seen in Fig. 6, between the flowmeter and the vent of the LHe vessel, a heat exchanger was used to stabilize the temperature of the GHe before entering the flowmeter. A Varian V250 turbo pump station with a pumping rate of 250 liter/sec was used to evacuate the vacuum jacket. The vacuum was maintained at below 5×10^{-5} Torr at room temperature, and at ~ 5×10^{-7} Torr in the presence of LHe.
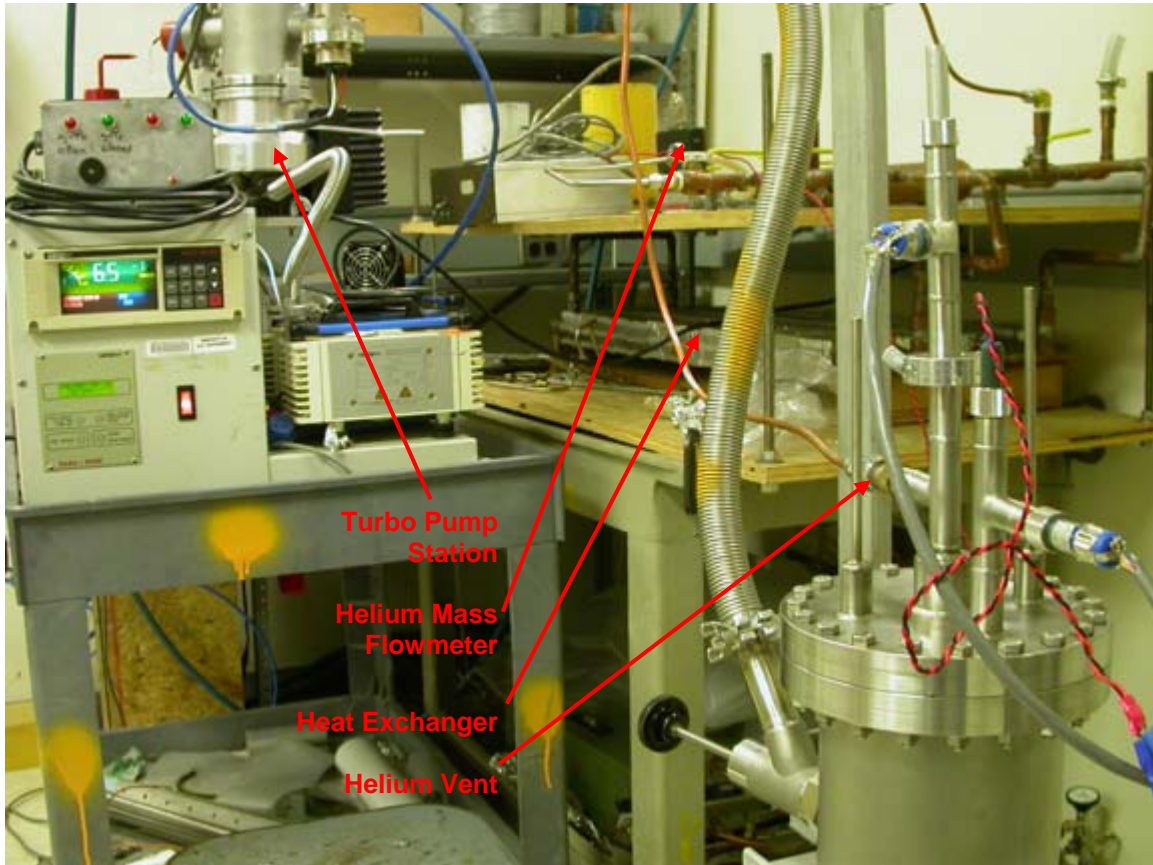
Fig. 6 External instrumentation and equipment.

TEST PROCEDURE

The cryostat was precooled by charging LN vessel overnight after the vacuum jacket was pumped down to better than 5×10^{-5} Torr. The heater was energized during LHe transferring. The data acquisition system was triggered when the temperature of respective heater shell and thermal shield, if used, was stabilized to near 300 K and 80 K.

TEST RESULTS

The raw data of all the test shots are plotted and attached in the APPENDIX.

MLI with Thermal Shield

Fig. 7 shows the heat loads in the LHe bath when MLI was used as thermal radiation insulation. The open circles were the results tested with 5 layers of MLI installed between LHe vessel and the active thermal shield. The close circles were those tested with 2 layers of MLI in the inner vacuum clearance. In both cases, the thermal shield and 10 layers of MLI between the thermal shield and the heater shell were used.

The radiation heat load, which is proportional to the surface area, and therefore the height of the LHe bath, was 0.47 mW / cm in the case of using 5 layers of MLI as inner insulation, which was not much improvement compared with 0.48 mW / cm tested with 2 layers. By extrapolating the heat load to zero height of the LHe level, the background heat load was respectively 44.5 mW and 21 mW for the case of using 5 layers and 2 layers. The height independent background heat load contained the end effect of the LHe vessel, the radial conductive heating via the insulation layers, and the conductive heating by residual gas.

Fig. 8 shows the comparisons of the temperatures in both cases. The temperature sensor readings of the thermal shield were ~ 80 K with 5 layers of MLI and ~ 88 K with 2 layers, while the heater shell was kept at 294.5 K in both tests.

With the same heater shell temperature, the same external insulation, and the same end effect to the LHe bath in both cases, the test results indicated that using 2 layers of MLI lower the heat conduction between thermal shield and the LHe vessel. Consequently, the thermal shield temperature was higher and the heat load in the LHe bath remained low.
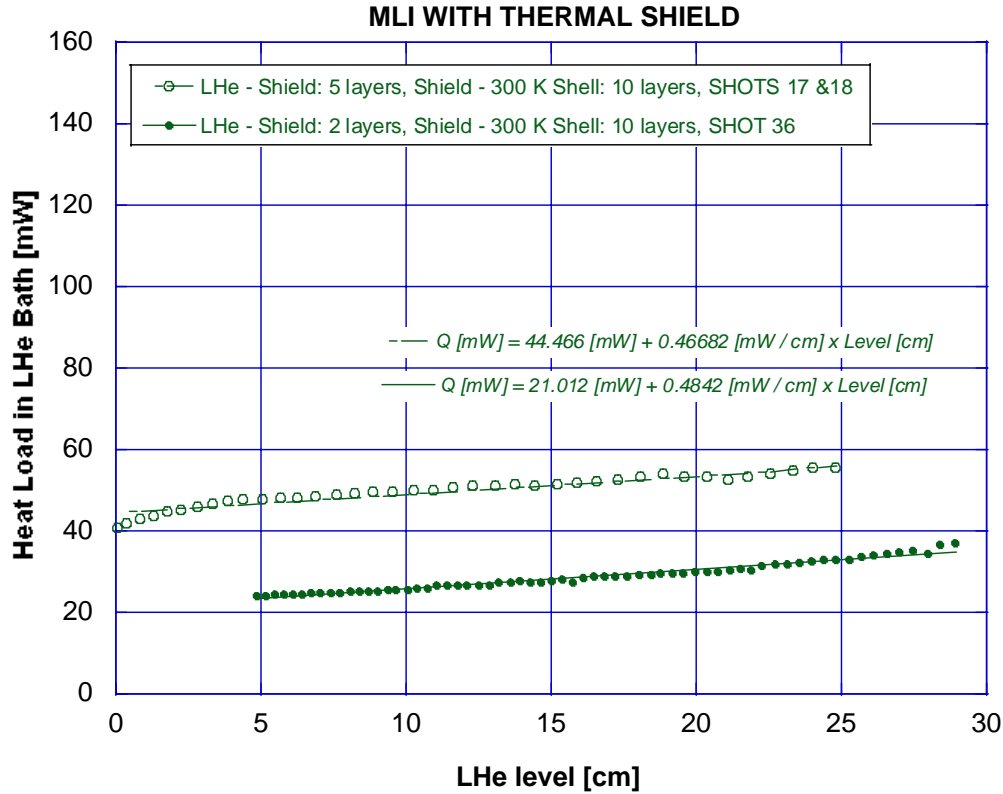
13

MLI WITH THERMAL SHIELD

Fig. 7 Heat loads in LHe bath tested with active thermal shield and MLI as radiation insulation.

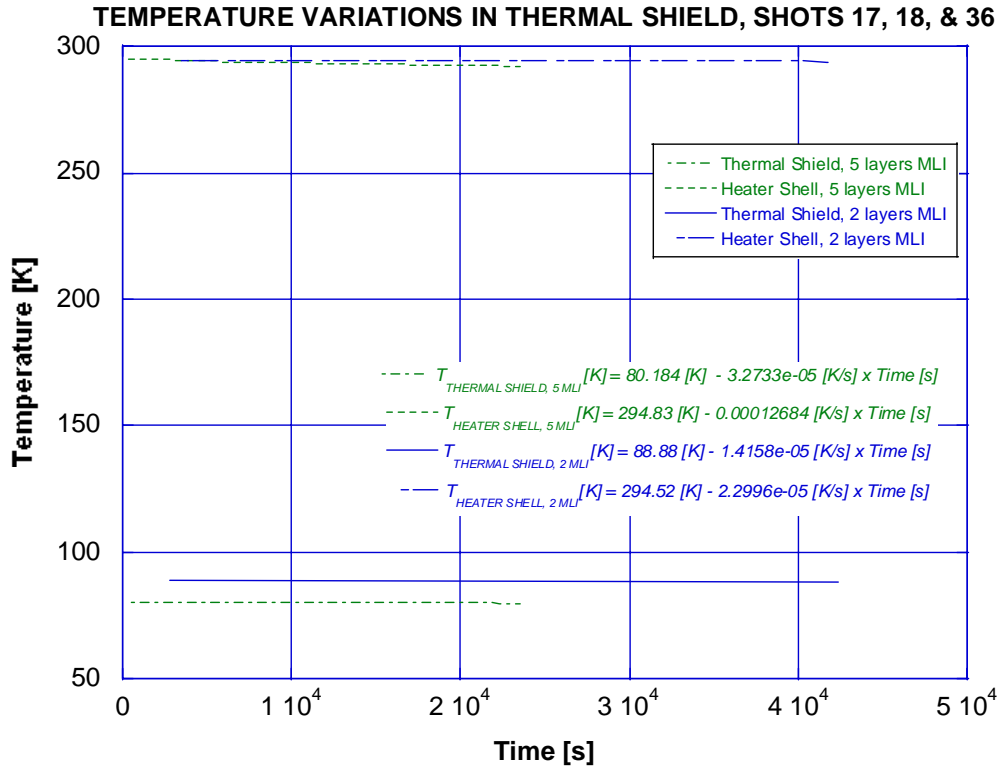**TEMPERATURE VARIATIONS IN THERMAL SHIELD, SHOTS 17, 18, & 36**

Fig. 8 Temperature variation in the thermal shield and the heater shell. The heater shell temperature and the outer insulation were kept the same.

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Foil with Thermal Shield

In this test setup, the MLI was replaced with foil. The cryostat was insulated with 2 layers of foil between the LHe vessel and the thermal shield, and another 2 layers of foil between the thermal shield and the heater shell. The dimensions and the installation of the thermal shield and the heater shell were maintained the same as those tested with MLI. As seen in Fig. 9, only the heat load at LHe level between 7 cm and 19 cm was used to characterize the radiation heating. Within this range of LHe level, the radiation heat load was estimated as 2.94 mW / cm.

At LHe level below 7 cm, the temperature of the thermal shield increased due to low level of LN. This was improved in the later tests.

FOIL WITH THERMAL SHIELD, SHOTS 26 & 27

LHe Vessel - Shield: 2 layers; Shield - Heater Shell: 2 layers

$Q\ [mW] = 13.356\ [mW] + 2.944\ [mW\ /\ cm]\ x\ Level\ [cm]$
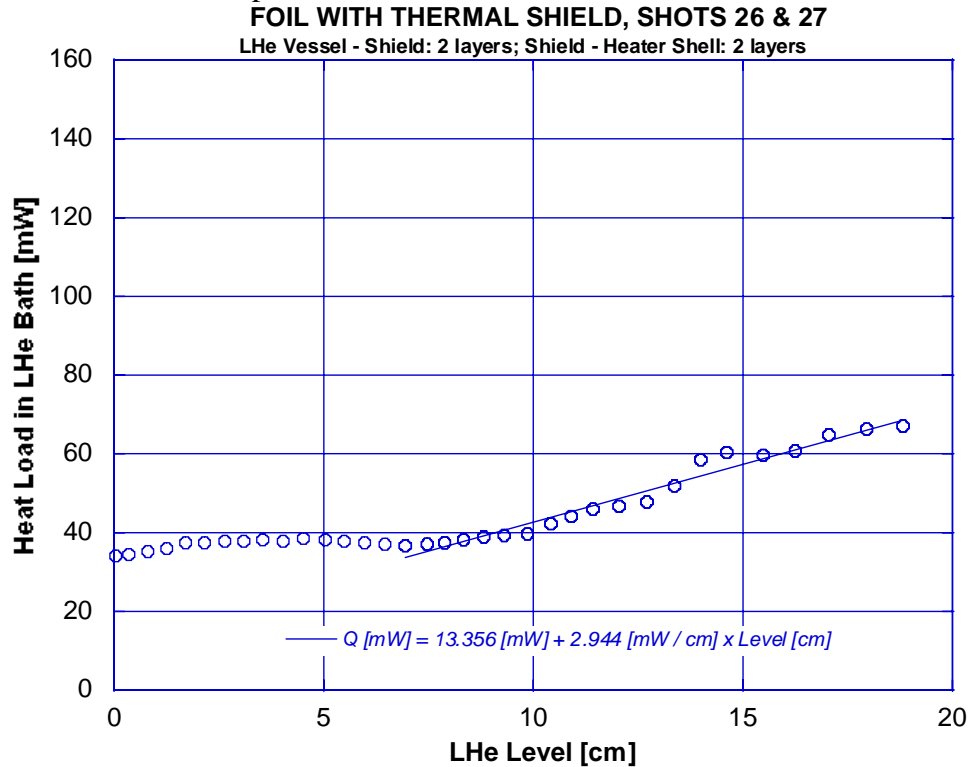
Fig. 9 Heat load in LHe bath tested with foil and thermal shield.

Foil without Thermal Shield

The test was performed with the LHe vessel insulated with four layers of foil without an active thermal shield. In the test setup, the 0.012" thick cylindrical aluminum thermal shield was removed. The diameter of the heater shell, and therefore, the 4K to 300 K vacuum clearance was preserved. Also, the number of foils and the vacuum clearance were similar to that of the warm bore region in the previously tested HCX cryostat. In the earlier shots, #39 and #44, the outer-most foil next the heater shell was spot-welded with spacers made of the same foil material on both sides of the foil. In a later shot, #46, the inner spacers were removed, only the outer spacers in contact with the heater shell were preserved.

Fig. 10 shows that the heat load variation of shots 39 and 44 were both 15.9 mW/cm, which was reduced to 10.7 mW/cm in shot 46 due to the removal of the inner spacers. Since there were only a few layers of foil in this application, the heat load was highly sensitive to the interlayer contacts, which was again dictated by the packing density and the construction of the spacers.

Fig. 11 shows the comparison of the thermal shield temperature variations in shots 44 and 46. With the heater shell temperature kept at ~ 287 K, the intermediate temperatures between layers 2 and 3 were higher than 230 K in both cases, which was not an effective temperature to use this type of foil. The intermediate temperature decreased at a rate of - 0.24 K/min in shot 44, and - 0.05 K/min in shot 46. Since LHe vessel was the only heat sink for heat removal, the price to pay for the intermediate temperature to reduce to below 80 K will be boiling off LHe for 5 – 50 hours.

Filling the LHe vessel with LN as a measure to precool the foil insulation, was attempted and aborted, since the precooling time was slowed down even more due to a lower temperature gradient. It seems to be more cost effective to use an active thermal shield to cool down the intermediate insulation layers, and to remove the heat load in the region between 300 K and the thermal shield.
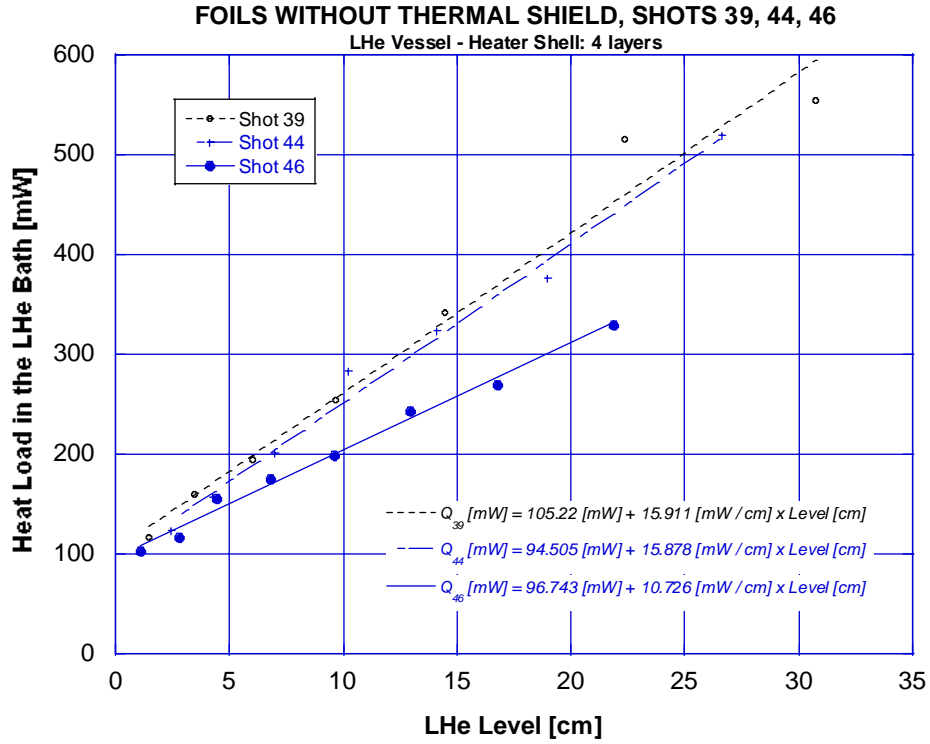
FOILS WITHOUT THERMAL SHIELD, SHOTS 39, 44, 46

LHe Vessel - Heater Shell: 4 layers

Q_{39} [mW] = 105.22 [mW] + 15.911 [mW / cm] x Level [cm]

Q_{44} [mW] = 94.505 [mW] + 15.878 [mW / cm] x Level [cm]

Q_{46} [mW] = 96.743 [mW] + 10.726 [mW / cm] x Level [cm]

Fig. 10 Heat load in LHe bath tested with four layers of foil without thermal shield.

FOILS WITHOUT THERMAL SHIELD, SHOTS 44 & 46

$T_{BETWEEN\ LAYERS\ 2\&3,\ 44}$ [K] = 259.24 [T] - 0.0040544 [T/s] x Time [s]

$T_{HEATER\ SHELL,\ 44}$ [K] = 287.63 [K] - 0.00088992 [K/s] x Time [s]

$T_{BETWEEN\ LAYERS\ 2\&3,\ 46}$ = 238.9 [K] - 0.00083538 [K/s] x Time [s]

$T_{HEATER\ SHELL,\ 46}$ [K] = 286.01 [K] - 0.00011175 [K/s] x Time [s]

Between layers 2&3, SHOT 44
Heater Shell, SHOT 44
Between layers 2&3, SHOT 46
Heater Shell, SHOT 46
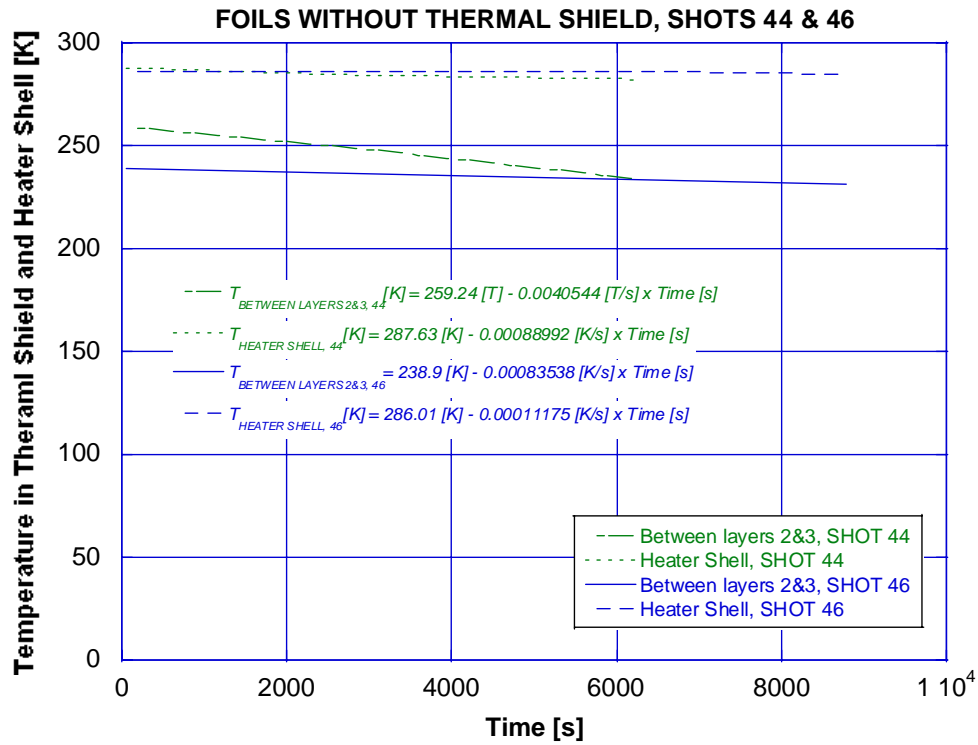
Fig. 11 Temperature variation between foil layers 2 and 3. The foils were used without thermal shield.

Foil and MLI with Thermal Shield

As shown in Fig. 12, by replacing the external layers of foil with a bladder containing MLI, the heat load variation is 7.4 mW/cm, which was better than that using foil without a thermal shield, but worse than that of using all foil with a thermal shield.

As mentioned before, the stainless steel bladder containing 10 layers of MLI was too stiff to bend to a small diameter to conform to the outer diameter of the thermal shield used in the previous tests. An oversized thermal shield was built to cool down the inboard wall of the bladder. This test result did not reflect the issue of tight vacuum clearance. More efforts will be required to improve the fabrication of a compact and leak tight bladder.

MIXED FOIL & MLI WITH THERMAL SHIELD, SHOT 33

LHe vessel - Shield: 2 layers foil; Shield - Heater Shell: 10 layers MLI in SS bladder

$Q [mW] = 39.296 [mW] + 7.4072 [mW / cm]$ x Level [cm]
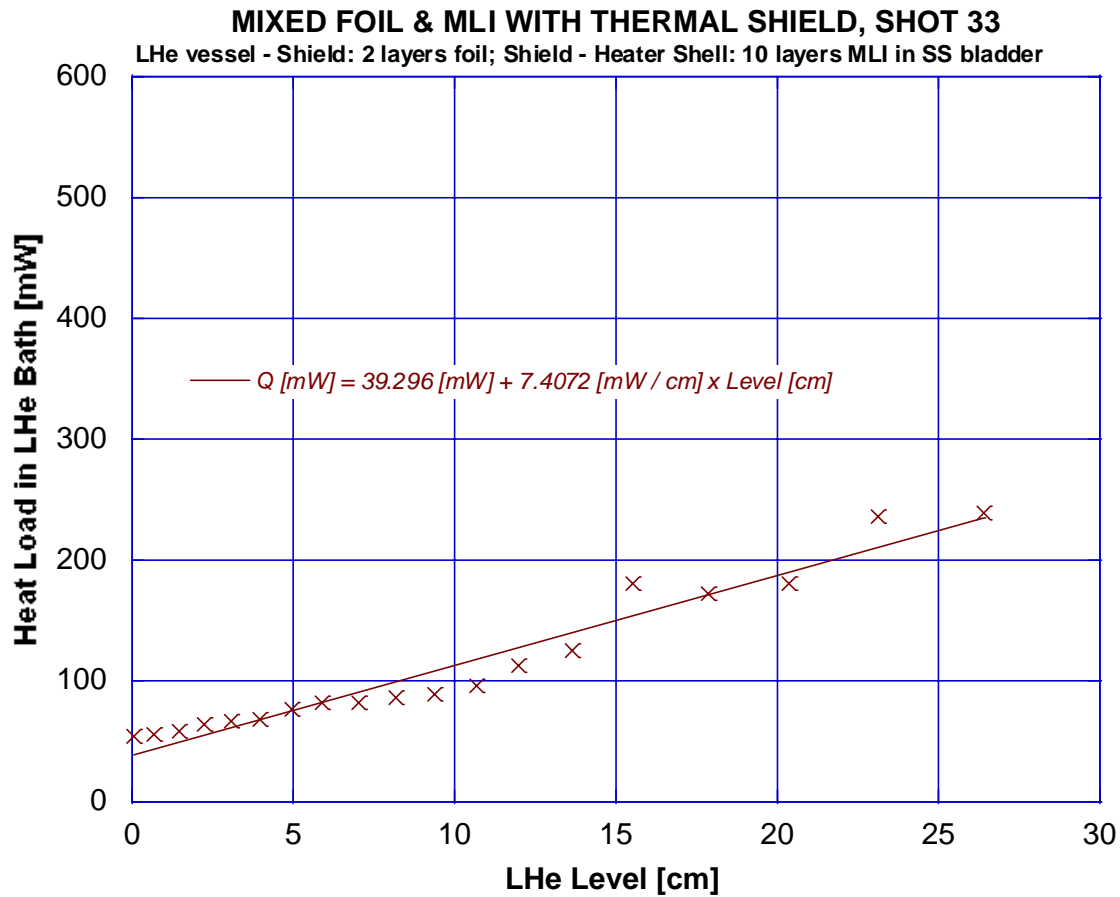
Fig. 12 Heat load in LHe bath tested with mixed foil and MLI.

DISCUSSIONS AND CONCLUSIONS

Fig. 13 summarizes the heat loads in the LHe bath with the LHe vessel installed with different combinations of radiation insulations and thermal shield.

HEAT LOADS WITH VARIOUS INSULATIONS / THERMAL SHIELDS

$Q_{MLI\ w\ SHIELD}$ [mW] = 21.012 [mW] + 0.4842 [mW / cm] x Level [cm]

$Q_{FOIL\ w\ SHIELD}$ [mW] = 13.356 [mW] + 2.944 [mW / cm] x Level [cm]

$Q_{FOIL\ w/o\ SHIELD}$ [mW] = 96.743 [mW] + 10.726 [mW / cm] x Level [cm]

$Q_{FOIL\&MLI\ w\ SHIELD}$ [mW] = 39.296 [mW] + 7.4072 [mW / cm] x Level [cm]
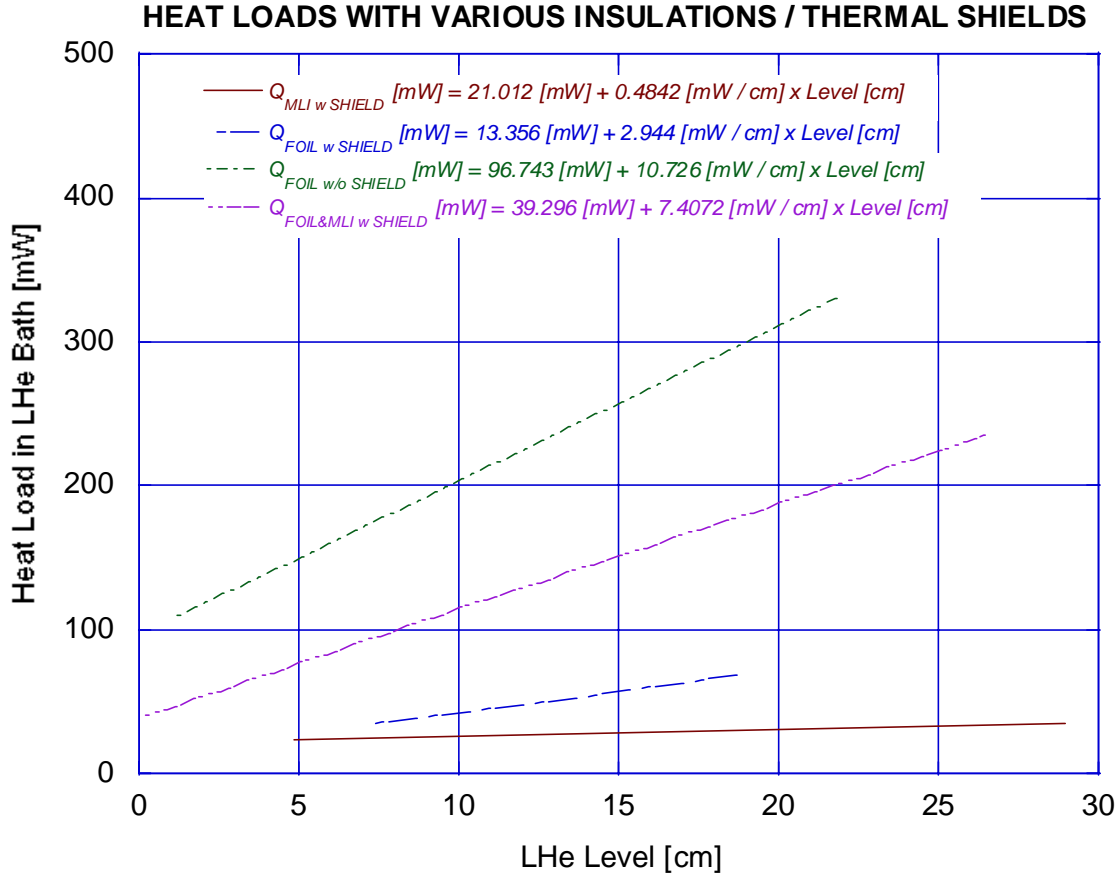
Fig. 13 Cross comparison of heat loads in the LHe bath with the cryostat installed with various combinations of radiation insulations and thermal shield.

Table 1 shows the radiation heat flux entering the LHe bath, which is calculated by dividing the measured heat load per unit height of the LHe bath by the circumference of 16.76 cm of the LHe vessel.

Comparing the test results of using foil with and without an active thermal shield, the conduction-cooled thermal shield is effective in reducing the radiation heat load in the LHe bath by a factor of 3.

The heat flux of using 4 layers of foil with a thermal shield, measured in the present project was 1.76 W/m^2, which was higher than 0.55 W/m^2 estimated in the HCX cryostat experiment. The heat flux obtained in the previous HCX cryostat experiment was estimated in a region with a vacuum clearance of 0.5" – 1", which allowed much lower packing density to reduce conductive heating.

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Table 1 Heat flux in each test setup

Insulation and thermal shield		Heat Flux [W/m^2]
Active shield:	LN conduction cooled	0.29
Insulation:	LHe vessel – Shield: 2 layers MLI	
	Shield – near R.T. Heater Shell: 10 layers MLI	
Active shield:	LN conduction cooled	1.76
Insulation:	LHe vessel – Shield: 2 layers Foil	
	Shield – near R.T. Heater Shell: 2 layers Foil	
Active shield:	LN conduction cooled	4.42
Insulation:	LHe vessel – Shield: 2 layers Foil	
	Shield – near R.T. Heater Shell: 10 layers MLI in Bladder	
Active shield:	None	6.40
Insulation:	LHe vessel – Shield: 2 layers Foil	
	Shield – near R.T. Heater Shell: 2 layers Foil	

The heat flux of using 4 layers of foil without a thermal shield was 6.40 W/m^2 obtained in the present small cryostat test. This was more than a factor of 2 of 2.8 W/m^2 estimated in the warm bore region in the HCX cryostat experiment. The major difference in these two tests was that all layers of foil used in the HCX cryostat warm bore region were uniformly dimpled as built-in spacer. In the present tests, only the foil on the LHe vessel was dimpled. The outer-most layer, next to the heater shell, was spot-welded with a few spacers made of the same foil material. Dimpling was a more effective way in reducing heat conduction among foils.

Using an active thermal shield with foil seems to be less effective than that with MLI in reducing the radiation heat load in the LHe bath. However, this was the second experience in using foil in a tight vacuum clearance. The cryogenic performance of the cryostat using novel foil with low emissivity can be improved by optimizing the foil thickness and the spacer configuration, as well as gaining more experiences in installation and handling.
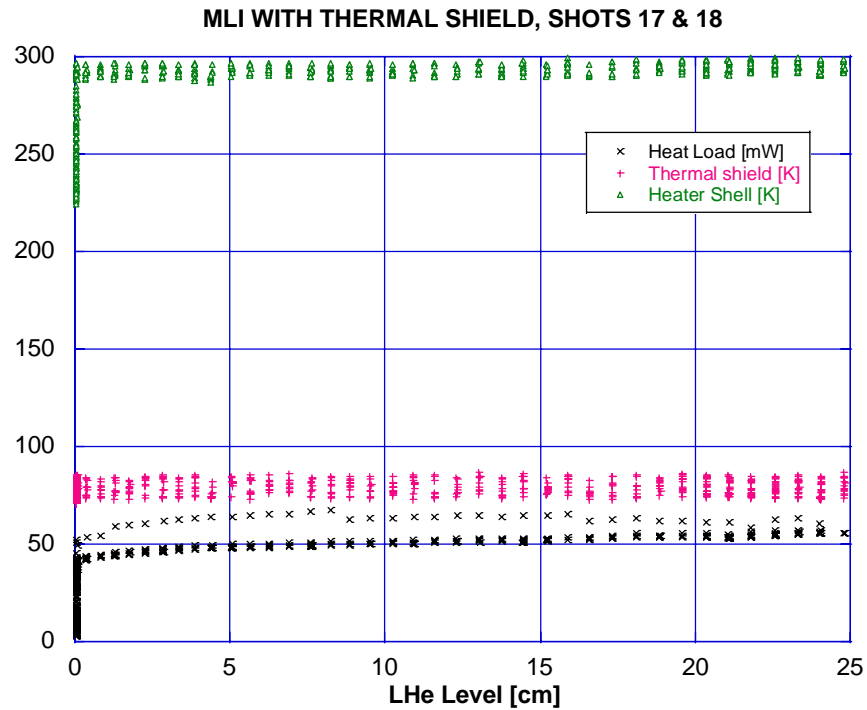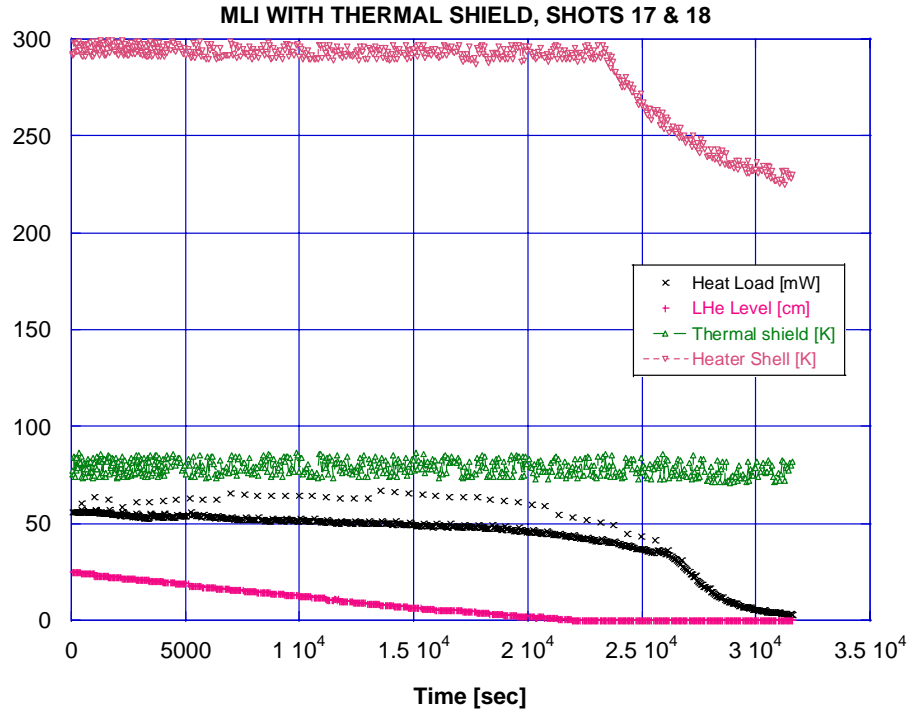
The performance of mixed foil and MLI contained in a stainless steel bladder, falls between those of using foil with and without an active thermal shield. The present attempt in reducing radiation heat load by replacing foils between thermal shield and the heater shell with MLI contained in the bladder, is not effective due to the difficulties in making an optimal thin wall stainless steel bladder. It is possible that the heat from the heater shell was conducted through the outboard bladder wall, which increased the operation temperature of the MLI packed in the bladder. The emissivity of the MLI is degraded by the temperature rise. The concept of the MLI-in-bladder could be improved by reducing the wall thickness of the bladder and increasing the clearance inside the bladder. However, welding the bladder becomes more difficult and costly when the wall thickness is further reduced and the configuration becomes more complicated. The cost / benefit of using bladder should be re-evaluated before spending more efforts on this concept.
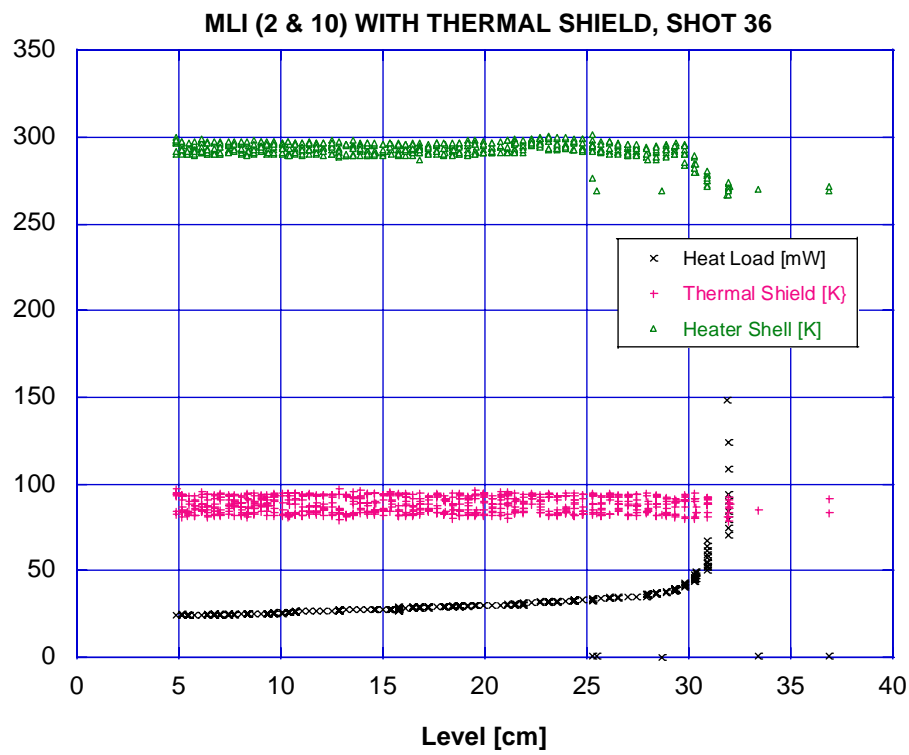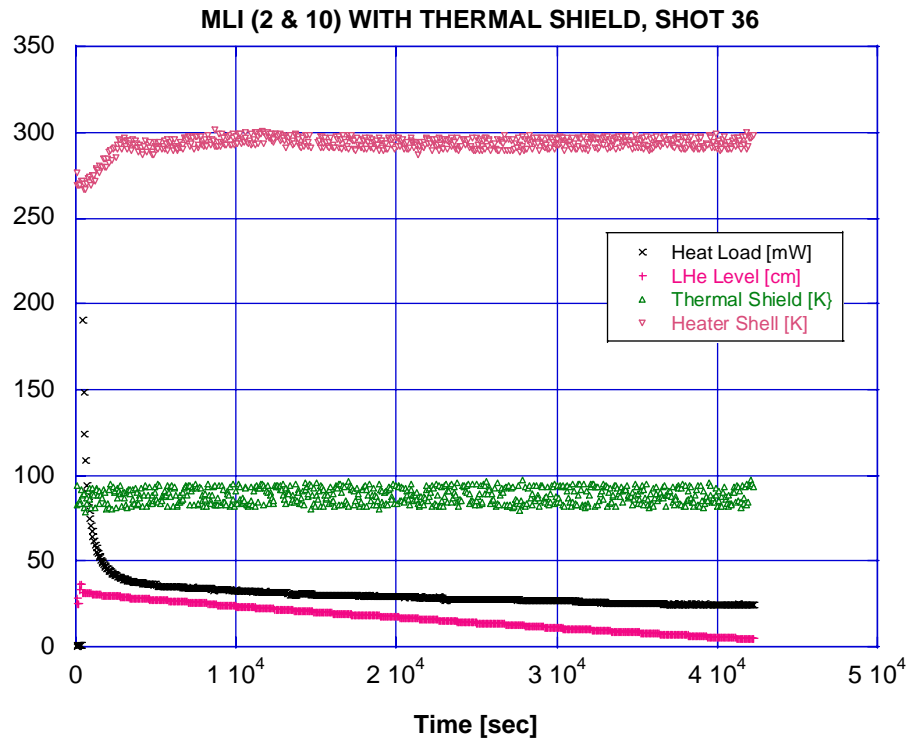
The lowest achievable heat flux of 0.29 W/m^2 was obtained by using MLI with an active thermal shield, which had each end connected to a copper block cooled with LN trace. The heat flux is of the same order of magnitude as the preset goal of 0.1 W/m^2 in the phase I proposal. The results can be further improved in the future activities by optimizing the number of layers of MLI used between room temperature shell and the thermal shield, as well as the spacer / insulation near the LHe vessel surface.

With the fabrication experiences and test results obtained in this project, we have proved that it is feasible to install an active thermal shield in a vacuum clearance as tight as 3 mm between 4.5 K and 300 K to reduce the heat load in the cold mass at LHe temperature. The light weight aluminum conductive shield is more appropriate than that of copper for horizontal application in the magnet bore in the HCX cryostat.
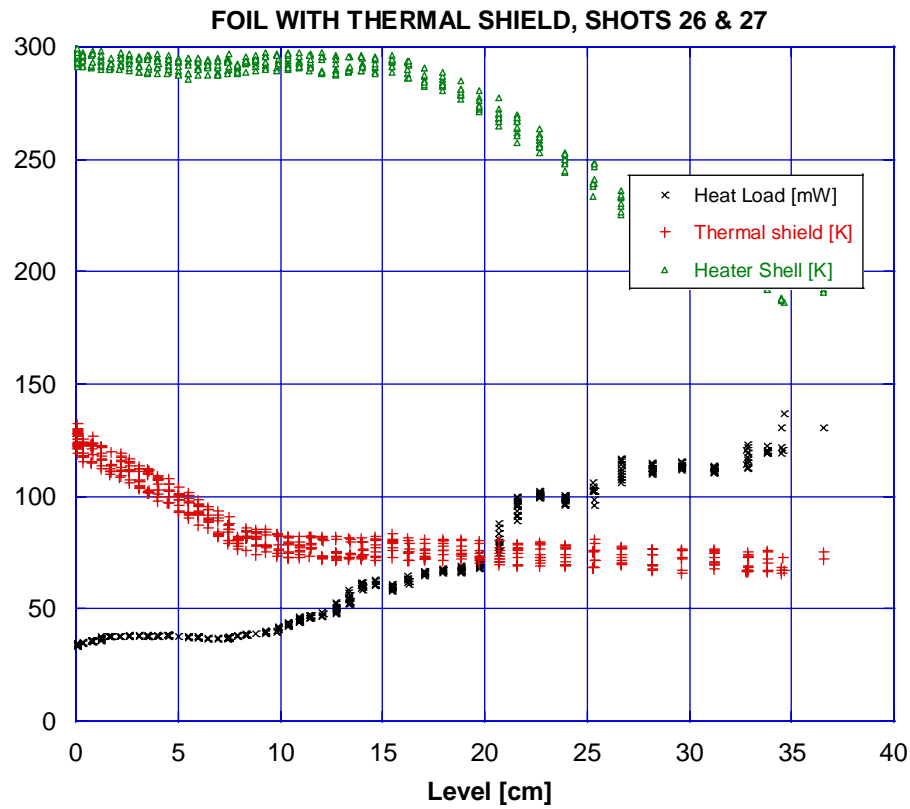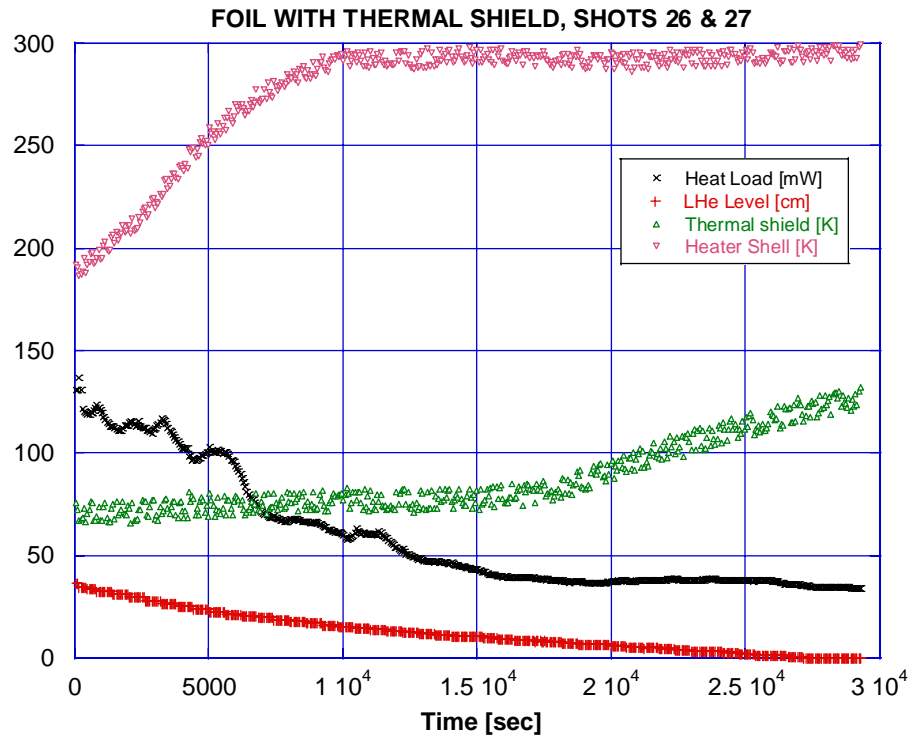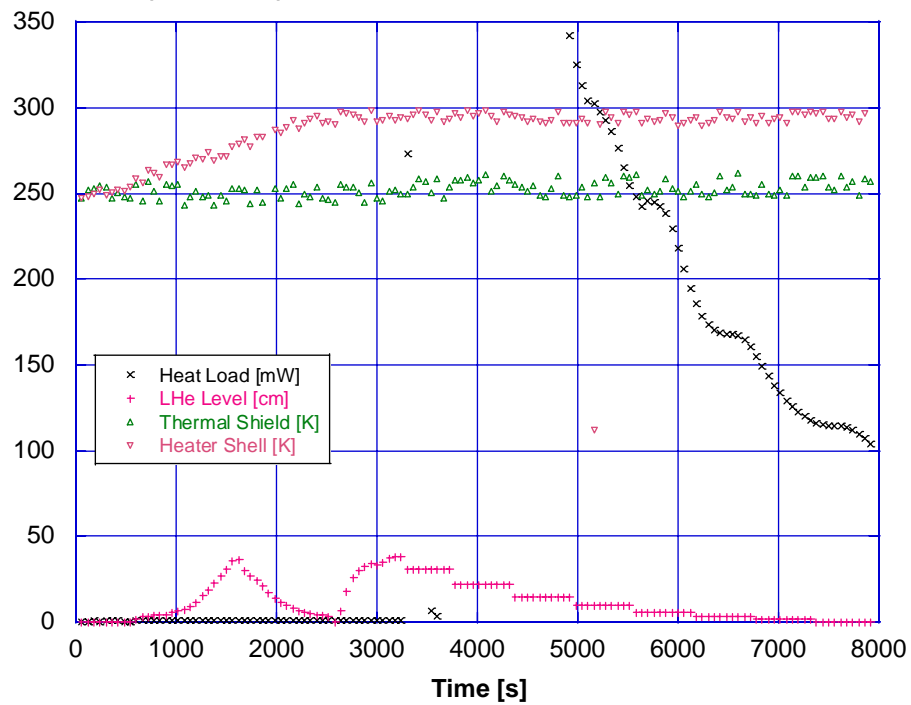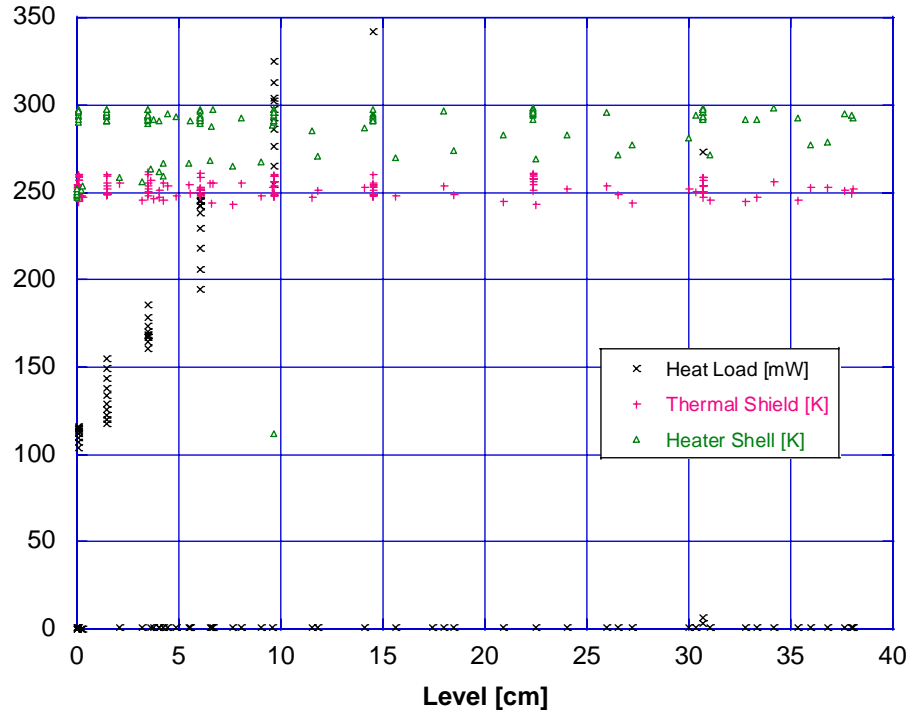
APPENDIX

Tests with MLI

MLI WITH THERMAL SHIELD, SHOTS 17 & 18

MLI WITH THERMAL SHIELD, SHOTS 17 & 18

MLI (2 & 10) WITH THERMAL SHIELD, SHOT 36

Legend:
- × Heat Load [mW]
- + LHe Level [cm]
- △ Thermal Shield [K}
- ▽ Heater Shell [K]

X axis: Time [sec]

MLI (2 & 10) WITH THERMAL SHIELD, SHOT 36

Legend:
- × Heat Load [mW]
- + Thermal Shield [K}
- △ Heater Shell [K]

X axis: Level [cm]

Tests with Foils

FOIL WITH THERMAL SHIELD, SHOTS 26 & 27

FOIL WITH THERMAL SHIELD, SHOTS 26 & 27

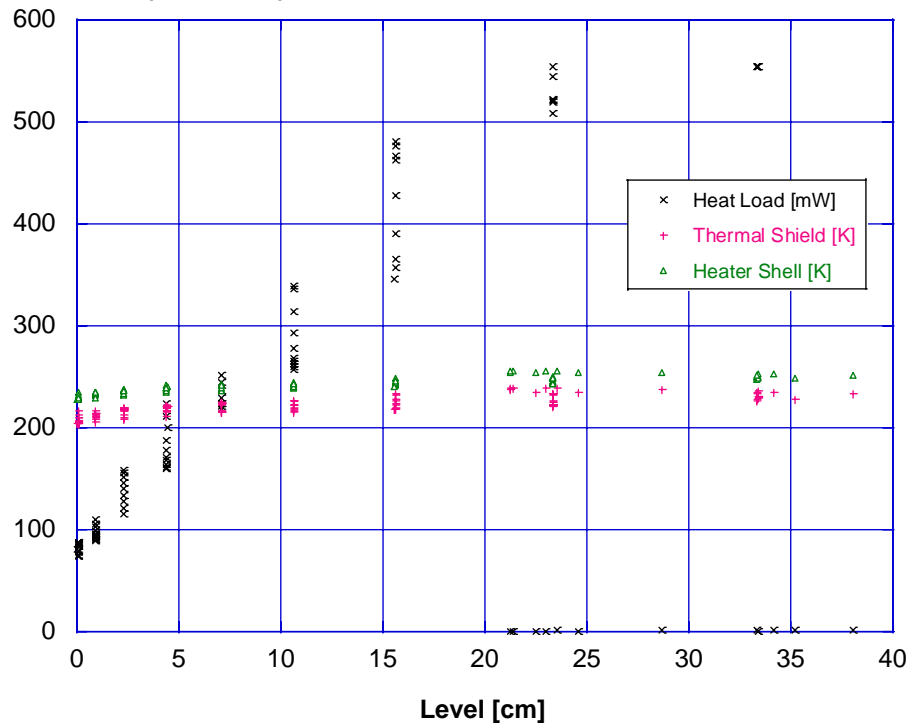**FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 39**

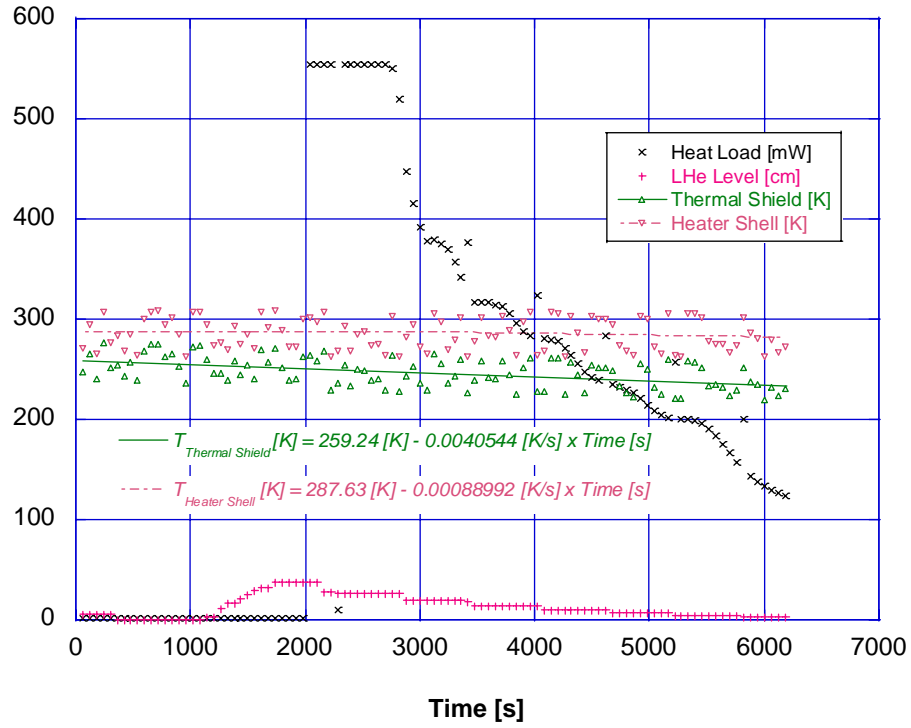**FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 39**

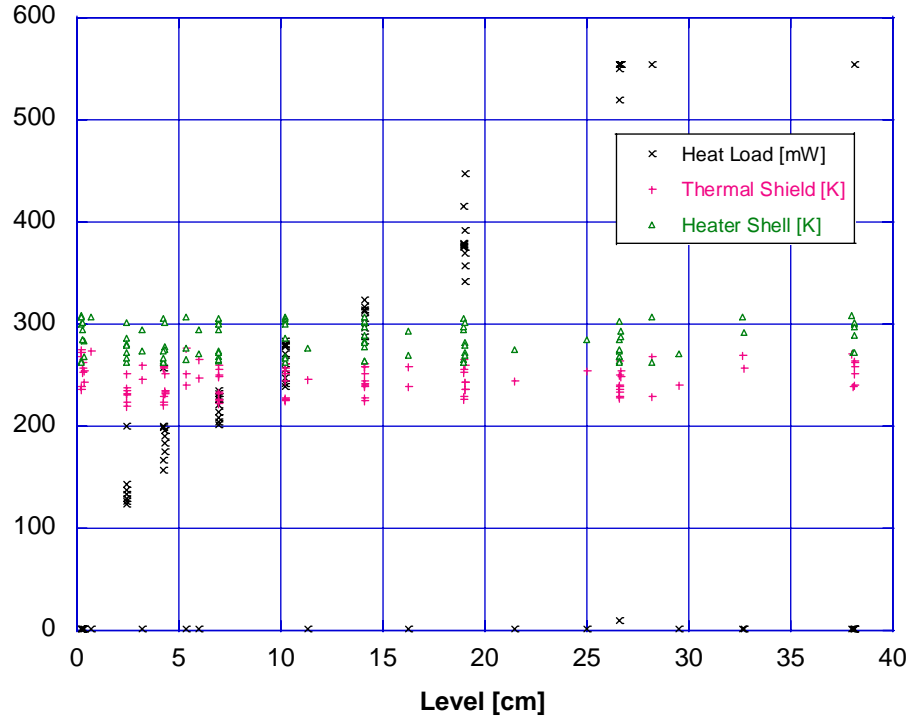**FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER OFF, SHOT 40**
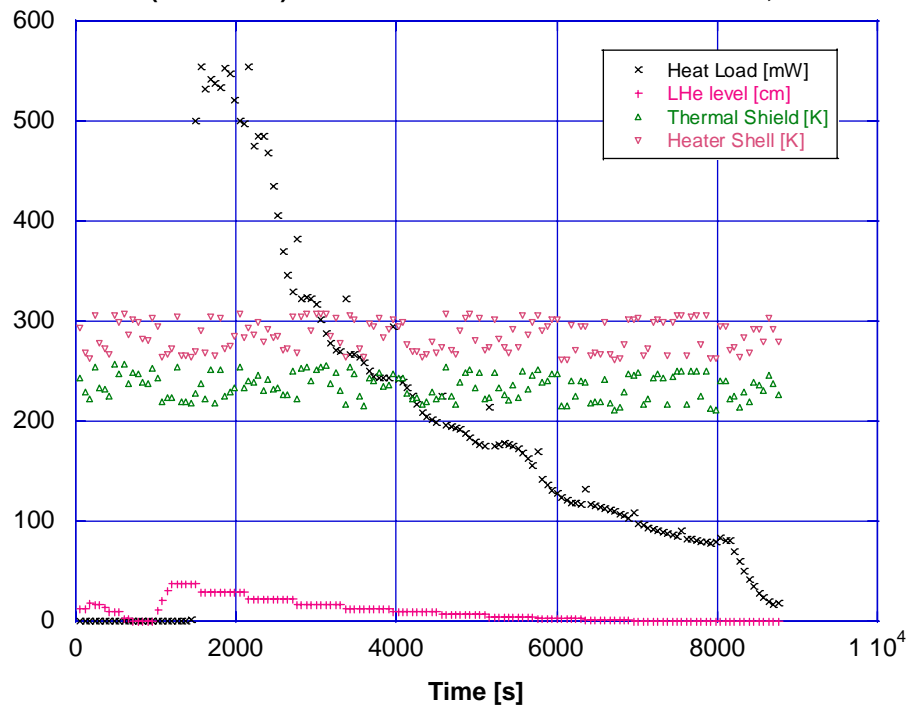

FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER OFF, SHOT 40

FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 44

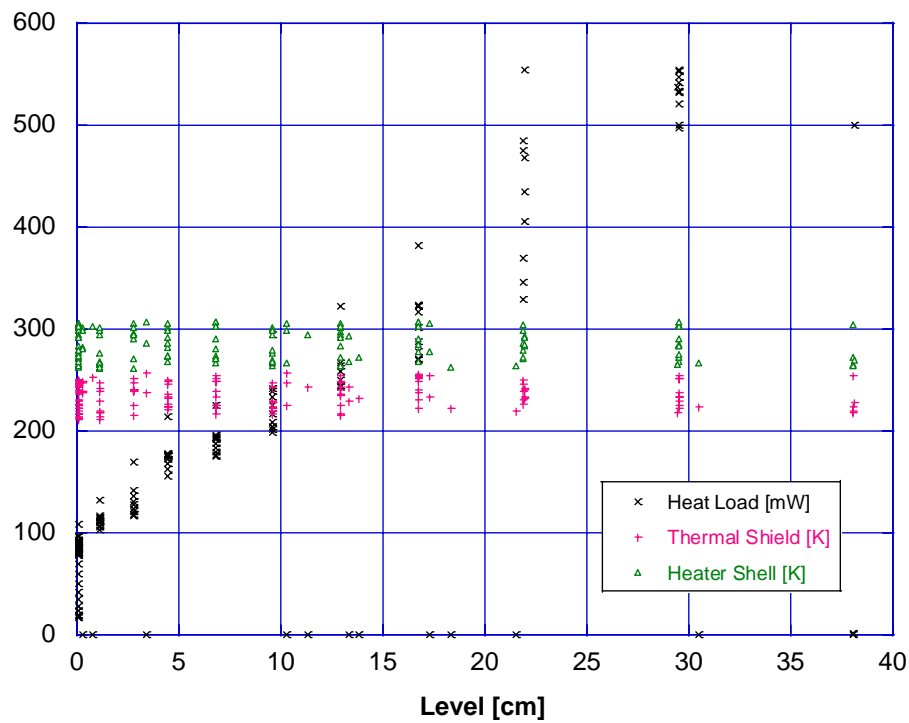
$T_{Thermal\ Shield}[K] = 259.24\ [K] - 0.0040544\ [K/s] \times Time\ [s]$

$T_{Heater\ Shell}\ [K] = 287.63\ [K] - 0.00088992\ [K/s] \times Time\ [s]$

Time [s]

FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 44

Level [cm]
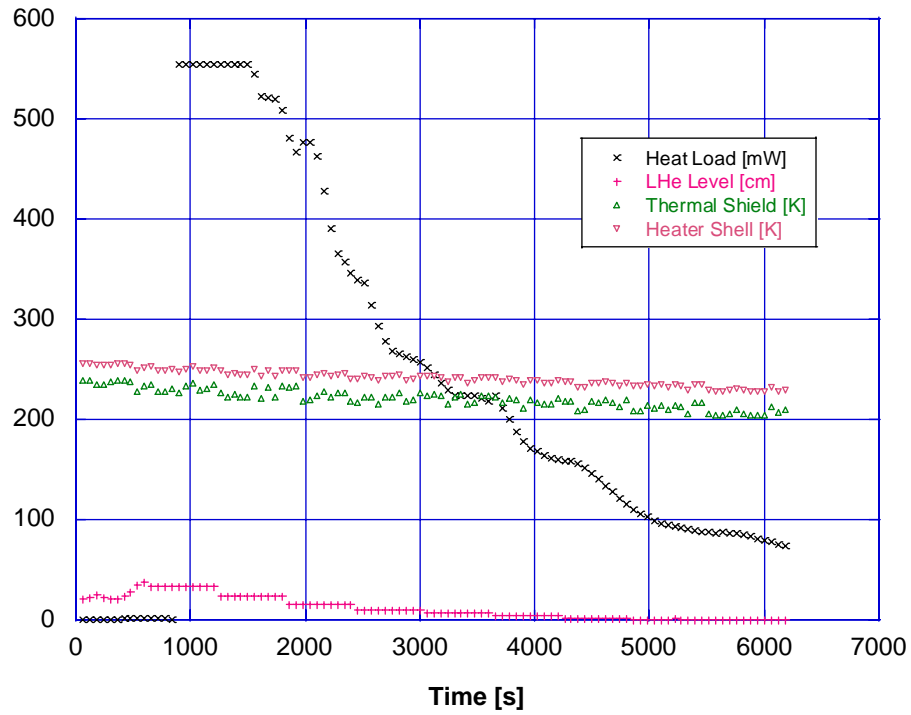
FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 46

FOILS (4 LAYERS) W/O THERMAL SHIELD W/ HEATER ON, SHOT 46

Tests with Foils and MLI-in-Bladder

TEST WITH MLI AND FOIL WITH THERMAL SHIELD, SHOT 33

Legend:
- × Heat Load [mW]
- + LHe Level [cm]
- △ — Thermal Shield [K]
- ▽ - - Heater Shell [K]

Time [sec]

MLI & FOIL WITH THERMAL SHIELD, SHOT 33 (2nd COOLDOWN)

Legend:
- × Heat Load [mW]
- + Thermal Shield [K]
- △ Heater Shell [K]

LHe Level [cm]

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