IOP Conf. Series: Materials Science and Engineering **101** (2015) 012014 doi:10.1088/1757-899X/101/1/012014

Developments in advanced and energy saving thermal isolations for cryogenic applications

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Abstract. The cooling power consumption in large scale superconducting systems is huge and cryogenic devices used in space applications often require an extremely long cryogen holding time. To economically maintain the device at its operating temperature and minimize the refrigeration losses, high performance of thermal isolation is essential. The radiation from warm surrounding surfaces and conducting heat leaks through supports and penetrations are the dominant heat loads to the cold mass under vacuum condition. The advanced developments in various cryogenic applications to successfully reduce the heat loads through radiation and conduction are briefly and systematically discussed and evaluated in this review paper. These include: (1) thermal Insulation for different applications (foams, perlites, glass bubbles, aerogel and MLI), (2) sophisticated low-heat-leak support (cryogenic tension straps, trolley bars and posts with dedicated thermal intercepts), and (3) novel cryogenic heat switches.

1. Introduction

Keeping temperatures of a large scale cold mass within a few kelvin of absolute zero is a great challenge. Many superconductivity projects have cold masses kilometers in length or huge complex machines, such as CERN, RHIC, Fermilab, CEBAF, DESY and ITER [1-3]. The high Tc superconducting applications and other usages with LO_2, LN_2 and LH_2 present different requirements.

For example, requirements for the LHC magnets distributed in a tunnel of 27 km can be summarized in terms of heat load per meter as follows [3]: total leak from 290 K vacuum vessel to 80 K shield is 4.26 W (3.76 W by MLI, 0.68 W by support) and from the 80 K shield to the cold mass is 0.18 W (0.09 W by MLI and 0.09 W by supports). Obviously, the design and implementation of high thermal efficient supports is about equally crucial to the contribution of high performance MLI.

This review paper will cover energy saving cryogenic transfer lines and then discuss the sophisticated support structures in large magnets, SRF cavities, and detectors. The merit of traditional powder type insulation and newly developed aerogels insulation are compared [4]. The performance, materials and design combinations of various super-insulations or multilayer insulation (MLI) are summarized. Special attention is then given to the tests and improvements of MLI with penetrations [5]. Finally, novel cryogenic switches for thermal management are also mentioned.

2. Insulation approaches for cryogen transfer lines

Transfer lines used for transporting liquefied gases and low temperature fluids are an important technology for applications such as high temperature superconducting power cables. Providing long length (several km) capability, energy efficiency, and high reliability for long term installations (30 years or more) are crucial in the design of these lines [6-7].

2.1. Insulations for liquid nitrogen and hydrogen transfer lines

Due to low cost and easy fabrication, foam insulation is still used for LN_2 as shown in figure 1a. There are various foam materials and foaming methods such as foamed in situ and prefabricated foam tiles. Aerogel-based insulation systems are also now being used for heat leaks about half that of foams for the same thickness [8-9]. Vacuum jacketed (VJ) piping as shown in figure 1b is widely utilized to reduce the heat leak to about 40 times less than in foam insulated piping [10]. The stainless steel inner and outer pipes can be rigid piping with expansion joints and/or flexible hose assemblies. Solid conduction is greatly reduced by low thermal conductivity radial supports designed for minimum cross section and small contact areas. Multilayer insulation (MLI) is wrapped on the inner pipe to reduce the radiation. The vacuum is maintained for long life by gettering materials to minimize the gaseous conduction heat transfer. The loss of vacuum in MLI insulated lines produces a rapid sharp increase in the heat load for line section [11-12] making vacuum maintenance crucial for long term installations.

Transfer lines for LH_2 are generally VJ with MLI, but for some for complex assemblies evacuated glass bubbles can be an alternative system [13]. Vent lines for LH_2 systems can be double-walled or mechanically insulated with foam or aerogel blankets, or even sprayed with a syntactic epoxy composite coating to keep the surface temperature above that for liquid air formation [14].

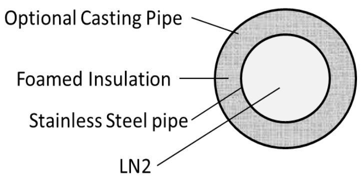


Figure 1a. Foam insulation for piping.

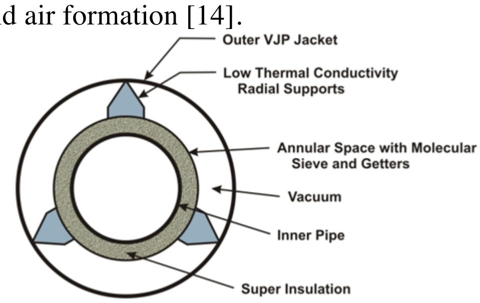


Figure 1b. VJ/MLI insulation system.

2.2. Insulations for liquid helium transfer lines

Liquid helium is expensive and due to its low boiling temperature (4.2 K) and latent heat (20.6 J/g), easily vaporized. Various high efficiency LHe transfer lines have been successfully designed and operated in many institutions. The significant design features can be summarized as the follows: (1) use of an annular screen (at ~77 K) to intercept a large fraction of heat load at higher temperature, (2) uniquely designed low-heat-conduction spacers (fiberglass/epoxy composite) having minimal cross sectional area, extended heat conduction path, and high-impedance thermal contacts, (3) optimized MLI layers wrapped on the pipe and screens to reduce radiation load, and (4) combine multiple transfer lines into one large common vacuum pipe for less cost, space, and energy saving. The KEK design sketch shown in Figure 2 combines four cryogen lines (LN_2 supply, LN_2 return, LHe supply, and LH_2 return) in one common vacuum pipe [15]. The common vacuum pipe of CERN is 650 mm in diameter and includes cryogen lines at temperatures of 4 K, 4.6 K, 30 K, 50 K, and 75 K [16].

3. High thermally efficient support systems for cold mass or storage tank

3.1. Support system for thin solenoid magnets with very large toroid warm bore

The cold mass must be supported inside the cryostat in a stable and rigid fashion. For example, the solenoid coil for the Collider Detector Facility (CDF) at Fermilab consists of a single layer helix winding of aluminum stabilized superconductor located inside a support cylinder and surrounded by radiation shields, superinsulation, and vacuum shell [17]. The solenoid physical characteristics are summarized as follows: outer diameter 3.3 m, inner diameter 2.8 m, overall length 5.1 m, total weight 13 tons, cold mass 5570 kg. The central field is 1.5 T and the axial magnetic force on coil is about 100 tons. The cold to warm support system consists of 6 axial members all on one end to provide axial stiffness. Each support element is 26 mm x 20 mm made with low conductivity Inconel 718. Twelve members of Inconel rods on each end carry the cold mass and provide radial stiffness. The members are thermally intercepted at 77 K and 4.4 K to reduce the heat flux and avoid hot spots. Spherical bearings on both ends of each member eliminate bending stresses due to differential thermal contraction. The coil and support cylinder are thermally screened from 300 K radiation by inner and outer LN_2 cooled shields. Figure 3a shows the CDF axial support and the cryostat [17]. Conduction heat leak is 0.25 W for each axial support and 0.31 W for each radial for a total support heat leak of ~9 W.

The CERN ATLAS detector magnet with a 2 T axial magnetic field is designed extremely lightweight as a single layer coil wound inside a thin AL alloy cylinder. The inner diameter is 2.3 m, the length 5.3 m, and the coil weighs 5.5 tons [18]. Figure 3b shows the structure of the warm to cold support in ATLAS and figure 3c is a photo of the conceptual design of the CERN CMS detector cryostat which is 12.5 m long by of 6 m diameter and providing a 4 T magnetic field [19].

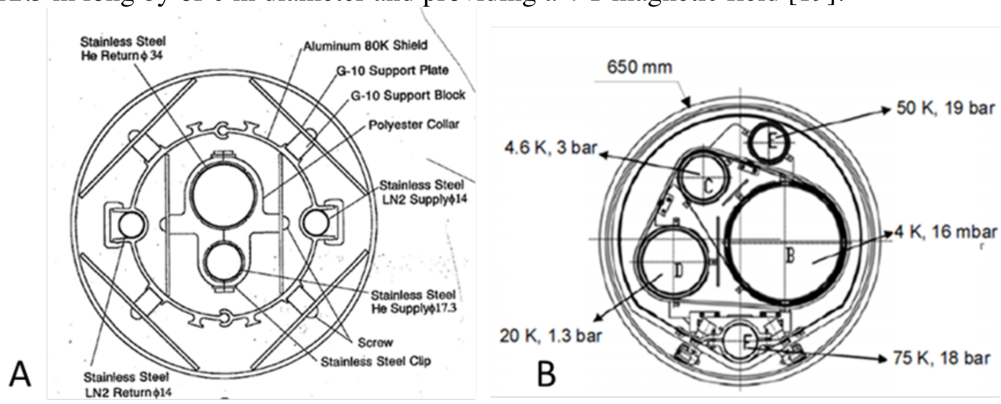


Figure 2. Thermal isolation for liquid helium piping: (a) KEK high performance transfer line [15] and (b) Cross section of the LHC transfer [16].

3.2. *Support system for long cylindrical heavy weight cold mass*

Since the 1980s, based on the continuing international collaboration through projects of HERA, SSC, LHC, and ILC (TESLA, XFEL), post type supports between 300 K and 2 K were successfully developed and utilized in large superconductivity projects [20]. The support post minimizes heat leak and is capable of withstanding the axial and radial loads. For example, LHC is a 27 km long superconducting accelerator based on the large scale use of high-field twin-aperture SC magnets (each >10 m long) operated at 1.9 K. Top and bottom stainless steel flanges of the LHC magnet post are glued to each post column of carbon-fiber/epoxy. Two heat intercept plates of aluminum alloy are shrink-fitted and glued to the post column (at ~80 K and 5 K) to efficiently reduce heat leak to the cold mass. The inner flanges are fiberglass plate glued to the column. The measured heat leaks with a column thickness of 6 mm fiberglass are: 300 K/80 K ~ 7 W, 80 K/5 K ~ 1 W, 5 K/1.8 K ~0.1 W. In fact, the 6 mm thickness was oversized and 4 mm is the final thickness in the LHC specification. Figure 4 shows a schematic of the LHC magnet post and how the post supports the cold mass [20].

The ILC and XFEL also developed a similar post with very efficient thermal performance for SRF cavities (cryostat length >10m) [21]. Reverse from the LHC arrangement, the support posts are fixed on the top of the vacuum shell. The ILC/XFEL superconducting cavities, placed upside down through the large helium pipe, are suspended to the post in the SRF cavity cryostat.

3.3. *Other advanced supports for cryostats and storage tanks*

The XRS CSS configuration shown in Figure 5a includes an instrument cooled far below 1 K by a demagnetization refrigerator, which is in turn cooled by superfluid He in the tank [22]. The inner vessel is supported by fiberglass/epoxy tension straps. Helium vapor cooled shields are used to reduce the heat leak and MLI layers are wrapped on the four shields. Similar support systems have been widely used in space cryostats and other cryogen vessels.

Another thermally efficient support system for experimental cryostats and storage dewars is shown in figure 5b [23]. To minimize the heat leak, multi-conducting shields are fixed to the neck and the shields are cooled by the neck and/or by the cold vapor bypass tube, then MLI layers are separately applied to the shields. The boiloff vapor rate of LHe can be minimized to less than 1% without instruments. Figure 5c shows a test cryostat and its inner vessel is supported mainly by the neck [24]. Suspension systems using HTS magnets have also been demonstrated on a laboratory scale for transfer piping and tanks. These advanced systems have potential for future superconducting power transmission lines and cryogenic tanks for cryofuels in transportation vehicles [25-26].

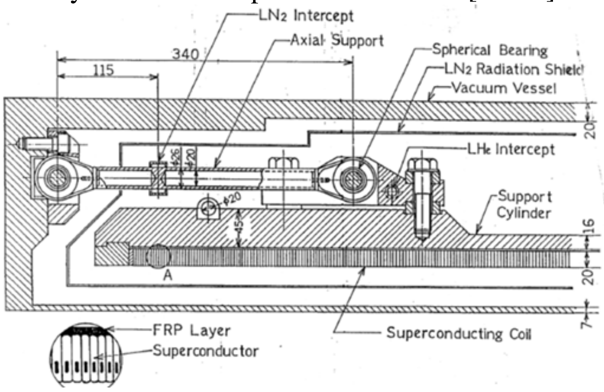
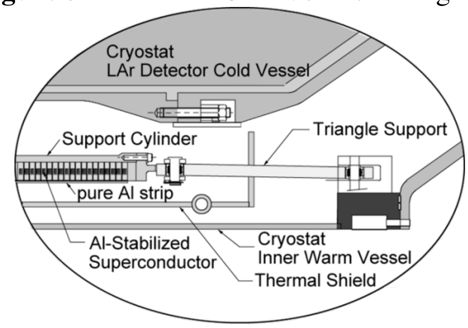


Figure 3a. Fermilab CDF Solenoid Magnet Low Thermal Conduction Support System [17].



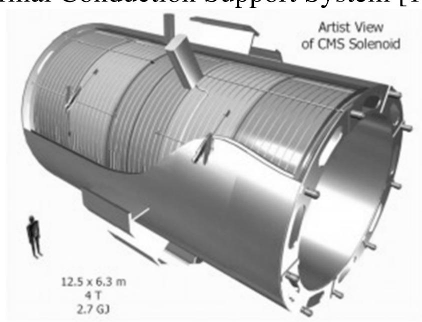


Figure 3b. ATLAS Detector Support [18]. **Figure 3**c. CMS Solenoid Cryostat [19].

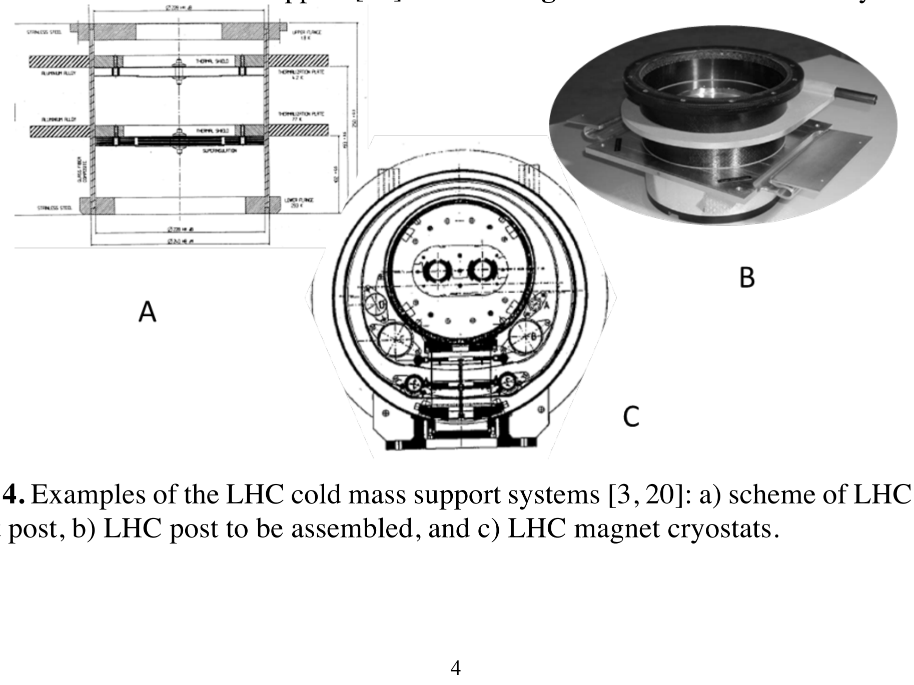


Figure 4. Examples of the LHC cold mass support systems [3, 20]: a) scheme of LHC magnet support post, b) LHC post to be assembled, and c) LHC magnet cryostats.

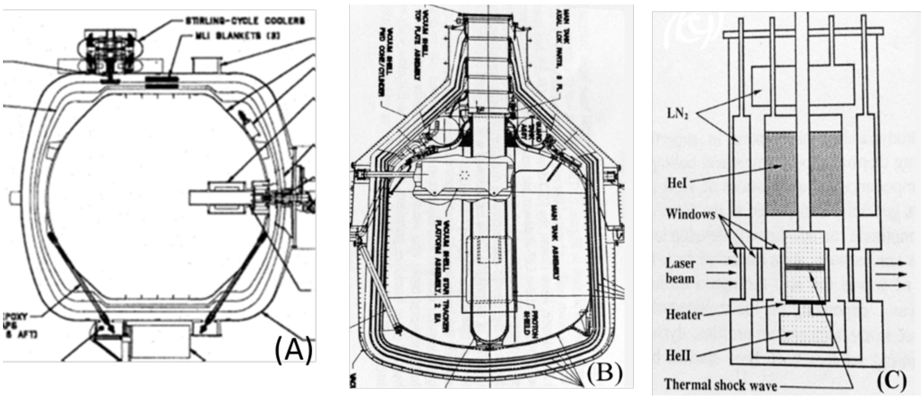
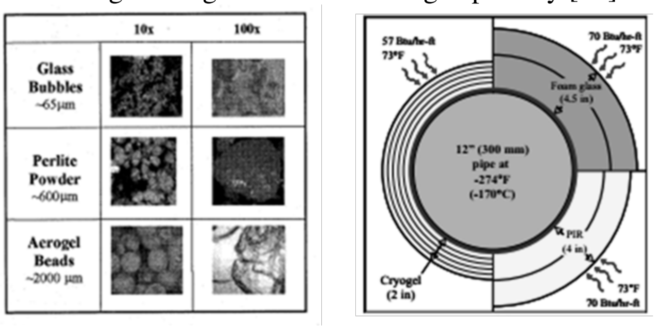


Figure 5. Examples of the different cold mass support systems: a) XRS CSS configuration for AXAF-S [22], b) and c) show different schemes for neck-supported cryostats [23-24].

4. Foams, glass bubbles, and aerogel insulations
Foams and sprayed foams are still employed in storage tanks of LN_2, LO_2, and LNG. Test studies on both VJ and non-VJ storage tanks for LH_2 [27] has led to the use of glass bubbles insulation as a cost efficient and high performance alternative for cryogenic storage tanks of any size. The KSC Cryogenics Test Lab (CTL) began the testing in 2001 as publically reported. The results clearly indicate the thermal performance and operational advantages of glass bubbles over traditional perlite. Glass bubbles insulation has been demonstrated in a 218,000 L LH_2 tank at NASA Stennis Space Center with the boiloff reduced by about 50%. Numerical modeling of boiloff for the 3,200,000 L spherical tank was completed to validate the lab testing results. Extensive data indicate glass bubbles are an excellent insulation for future large storage tanks or replacing the perlite powder insulation in existing tanks [27].

The most comprehensive development of thermal insulation systems utilizing aerogel insulations has been performed by the CTL with industry [4, 8-9, 12, 28-29]. The microscope comparison of traditional perlite powder, glass bubbles, and aerogel beads is shown in figure 6a. Aerogel has advantages in reducing the thickness with thermal performance about twice better than foams or perlite, as shown in figure 6b. Aerogel blanket materials for thermal insulation are now commercially available in several different product versions from Aspen Aerogels, Inc. and Cabot Corp [8-9]. Studies at ORNL indicated that flexible aerogel is a good candidate insulation for HTC SC cables. Aerogel is a top performer at soft vacuum as well and also has a good degree of load bearing capability [12].



(A) (B)

Figure 6. Cryogenic insulation materials: a) Microscope comparison of powder insulations [4] and b) aerogel performance in comparison with foams [8].

5. Multi-layer insulation (MLI or superinsulation)
Since the 1960s multilayer insulation remains the highest efficiency thermal insulation in high vacuum that has been successfully utilized, widely investigated, and tested. An MLI system with high vacuum can provide more than 100X lower heat leak compared to non-vacuum insulation systems like foams. However, the performance of MLI is very sensitive to the application sub-systems configurations,

workmanship, and various penetrations. The R&D of MLI systems continues to address new challenges as projects continue to demand even higher levels of thermal performance. The earlier a cryogenic system design is integrated with heat load requirements, the better likelihood of success in the end.

5.1. General optimization of MLI performance

The optimization of MLI performance, based on experience, is generally summarized as follows. Common reflector materials include aluminium foil or aluminium deposition on both sides of a thin layer of Mylar or Kapton film. Gold coatings are utilized in space applications due to high emissivity and superior stability against chemistry, cosmic rays, and solar radiation. Perforated or crinkled Mylar forms are used to achieve the best vacuum levels between layers. A thin spacer layer of polyester or fiberglass between each reflector layer minimizes the thermal contact thermal link. The spacer layer may cause some outgassing. Some self-pumping layers with absorbent carbon powder were tested, but have not been widely used. Lightweight materials are important to reduce self-compression. The number of layers used is a trade-off amongst minimum heat leak, material cost, and space availability. The typical number of layers for tanks is: 40-50 layers for LN_2 level, and 60-80 layers for LHe level. The number of layers for piping: 10-30 layers for LN_2, 30-40 layers for LHe. Optimizing the layer density to a particular structure has been considered to avoid the drawbacks of using too many MLI layers.

Intermediate temperature screens inserted between several layer groups has been the commonly used approach to greatly reduce the heat load to the cold mass. How many shields and what temperature of each shield are highly dependent on the cooling power budget, cold mass temperature, and the cryogen temperatures available in the operating condition. Figures 3-5 and their reference papers provide a wide range of recommendations on designing the shields and their temperatures. Based on LHC experience, Lebrun suggests that the 5 K shield for the 1.8 K cold mass (SC magnet) is unnecessary [3].

The superior thermal performance of MLI is rapidly degraded with degradation of the high vacuum level [29]. It was proposed and tested by CTL that a combination of aerogel blanket with MLI and certain layered composite systems can sustain a degree of vacuum deterioration or vacuum loss [30].

5.2. Thermal degradation and remedy of MLI with penetrations

Penetrations in real MLI systems (such as cold mass supports, power leads of SC magnets, RF power couplers for SC cavities, and scientific instruments in space explorations) are inevitable. Around the penetrations there are always gaps, cracks, or overlaps. In large cryogenic devices, there are often joints and gaps between pre-made MLI blankets. Research indicates that thermal performance degradation of MLI systems by cracks and slots is more serious than previously thought. For example, the heat load increment, due to a unit crack area through a 6 mm crack in a 90 layer MLI blanket, was more than 200 times the heat load through a unit area of the MLI blanket without cracks [5].

Comprehensive investigations to systematically reduce the effects of cracks-gaps-holes in MLI were performed by a Fermilab cryogenic team [5]. The heat loads vary (compared with original MLI blanket) uniquely due to narrow slots or square cracks. Different sizes in 20, 50, and 90 layer MLI blankets were measured with two temperatures boundaries, 300 K/77 K and 77 K/4.2 K. The temperatures distributions from the crack/slot into MLI blanket were recorded in different layers to monitor the blanket thermal performance. Based on these investigations, the Enhanced Black Hole Model was created to explain and understand the MLI degradation, and a series of patch approaches to efficiently improve the thermal performance with crack/slot were successfully developed. The heat loads of blankets are shown in figure 7 which indicates: cutting MLI by a sharp knife has minimal impact on performance (so gentle cutting in MLI blankets to improve vacuum is allowed); several slots of 3 mm width by 100 mm length about double the heat load; and 4-5 patches inserted would almost recover the original MLI performance.

To understand the complex heat transfer mechanism of MLI systems with penetrations, a series of calorimeter testing coupled with thermal modeling of the calorimeter was conducted by the CTL [31]. Testing of various styles of integration of structures and fluid components into MLI blankets was completed for a test matrix spanning 22 different tests as indicated in figure 8. Both temperature and heat load data were obtained through calorimeter testing. These data were used to verify a detailed thermal model. An analytical equation was generated to allow for calculation of the integrated (total system) heat load from various penetrations into cryogenic tanks. These developments should decrease the uncertainty of thermal performance of insulation systems applied to cryogenic tanks and vessels. Testing also indicates a buffer of fiberglass material is a robust method of closing out MLI penetrations.

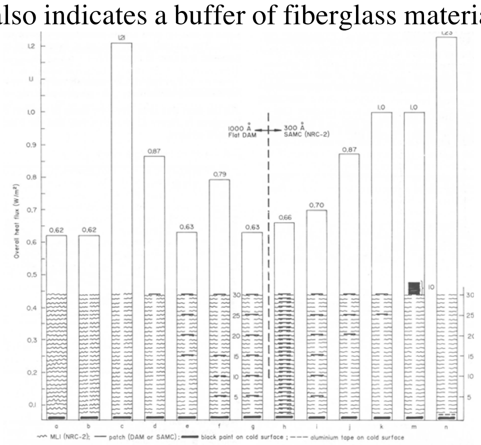


Figure 7a. Heat flux results of patch study. No cracks; b, 1-dimensional slits; c-m, runs 2 to 11; n, 0.09mm aluminium tape on cold surface, no patches [5].

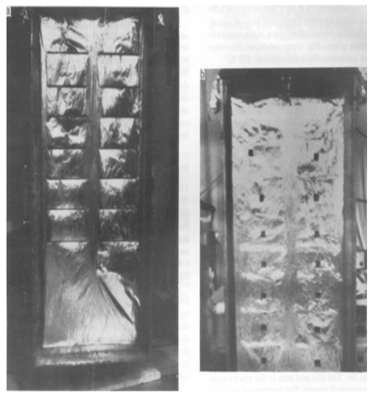


Figure 7b. The flat board with MLI in a box of 176x76 x15 (cm). T paired as 4.2-77 K and 77-300 K in cryostat [5].

Test Description	Reason	Figure
No Penetration	Baseline	
No Integration a) Without gap b) With gap (a no buffer case)	Worst Case	
Isolated Penetration a) 1/2" Aerogel Blanket b) ½" Bead Pack c) 1" Aerogel Blanket d) ½" CryoLite e) 1" CryoLite	Isolate bulk insulation from penetration insulation	
Temperature Matched a) Lockheed b) Test #1	Best Case (assumes single warm temperature)	

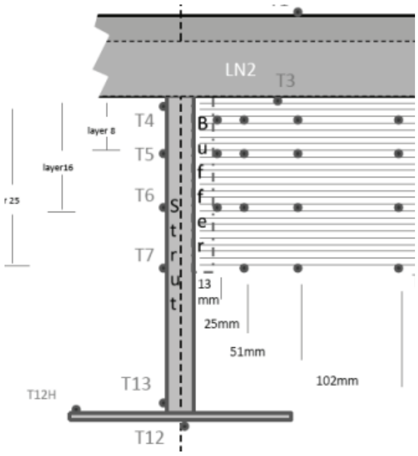


Figure 8. Temp sensor locations with struts (right) and key test results (left) of MLI study [30].

6. Novel heat switches for managing heat load to a cold mass

There are many developments of novel heat switches, which can alternatively provide high thermal connection or provide ideal thermal isolation to the cold mass. These technical areas are briefly listed as follows: 1) magnetic levitation suspension post and bearing, 2) shape memory alloys switches, 3) quad-Redundant thermal switches, 4) differential thermal expansion thermal switches, 5) helium or hydrogen gap-gap heat switches, 6) superconducting-normal switches, 7) piezoelectric heat switches, 8) cryogenic diode heat switches, and 9) mechanical demountable connections.

7. Conclusion

All the unique and significant developments of various insulation materials, sophisticated cold mass supports, and high thermal efficiency cryostats have enabled success in large scale superconducting projects, extremely long lifetime space devices, and future superconducting power applications. Since the performance of thermal isolation technologies are still sensitive to the configurations and operational conditions of applications, the up-front integration of materials, thermal, and structural engineering aspects are of crucial importance. Therefore, continued R&D is required as new applications and challenging projects emerge on the horizon. The achievements based on the previous design achievements and research investigations provide a thorough source of guidance to future efforts.

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