CONFORMABLE TILE METHOD OF APPLYING CRYOCOAT™ UL79 INSULATION TO CRYOGENIC TANKS

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ABSTRACT

A procedure for fabricating, forming, and bonding thin tiles of CryoCoat™ UL79 cryogenic insulation to a large curved surface was developed and its performance was verified. This effort was undertaken as a result of safety concerns for the Alpha Magnetic Spectrometer (AMS), which is a particle physics experiment for use on the International Space Station (ISS). At the heart of the detector will be a large superconducting magnet cooled to 1.8 K by superfluid helium. From ground safety and flight safety considerations, the system must be safe in the event of a sudden catastrophic loss of insulating vacuum. Previous testing showed that a 3 mm layer of CryoCoat™ UL79 reduces the heat flux in the event of vacuum loss by nearly a factor of 8, which satisfied the safety concern. Now a practical method of applying a thin uniform layer of the CryoCoat™ UL79 insulation to a helium vessel containing a superconducting magnet was required. The conformable tile method was designed to meet this need to apply a nominally 3mm layer of CryoCoat™ UL79 to a cryogenic tank with a diameter of at least 25cm. The fabrication and application procedure was developed and validated through application of the CryoCoat™ UL79 onto a prototype helium tank, which was subsequently tested at cryogenic temperatures. As a result of these successful tests, NASA has accepted the conformable tile method for applying CryoCoat™ UL79 and has agreed that AMS is safe to fly.

THE NEED FOR INSULATING A CRYOGENIC SYSTEM [1]

In many cryogenic systems, the sudden loss of insulating vacuum is a safety concern. A sudden loss of vacuum occurs when the outer shell of a cryogenic vessel is punctured. The possibility of this happening, for example, from a fork lift blade during transport cannot be excluded. A puncture allows air from the surrounding environment to fill the vacuum chamber. There is no material designed to prevent convective heat loss within the vacuum chamber on a typical cryogenic vessel. This allows a large heat leak directly from the air to the metal inner-tank holding the cryogen. This causes the cryogen to rapidly boil resulting in a pressure build-up within the vessel. Burst discs or pressure release valves are commonly used to relieve this pressure. However, the cryogen rapidly escaping through the burst disc system is a remaining safety concern. Additionally, the installation of a burst disc system increases the heat leak into the cryogen during normal operation. This merits the exploration of a secondary insulation layer within the vacuum chamber to provide thermal insulation from the atmosphere in the event of a sudden loss of insulating vacuum.

The addition of a thin (3mm) insulating layer of material to the inner tank of the cryogenic vessel within the vacuum chamber does not significantly change the thermal properties of the vessel during normal operation as the vacuum provides far greater insulating properties. This thin insulation layer does, however, substantially decrease the heat leak into the cryogen after a loss of the insulating vacuum has occurred. This smaller heat leak causes a much less violent effect. The cryogen will slowly begin to build pressure requiring the venting of the tank. This venting, however, takes place at a much slower rate than previously which substantially reduces the safety hazard. A burst disc is still required to allow the venting to take place. The area of the burst disc is directly proportional to the heat load into the vessel. Therefore, because the heat load is many times smaller with an insulated system, the area of the required burst disc is also many times smaller. This reduces the heat leak into the cryogen through the burst disc system during normal operation.

THE INSULATION MATERIALS

Due to its robustness, compatibility with vacuum, and very low density the thermal insulation system chosen was CTD's CryoCoat™ UL79. This is a layered insulation system and for this application consists of the high strain adhesive CryoBond™ 920 and the modified syntactic foam insulation, CryoCoat™ UL79. The CryoCoat series of materials are designed specifically for cryogenic applications to replace the less reliable, traditional insulation systems such as foamglass or urethane foam. They have also been thoroughly tested at cryogenic temperatures and have demonstrated exceptionally good mechanical properties over a wide range of temperatures, particularly for materials of such a low density and ease of fabrication. CryoCoat™ UL-79 is a 2-part epoxy system utilizing hollow microspheres as the insulating component. It provides densities similar to chemically expanded foams (<0.01 specific gravity or a density of ~ 0.10 g/cm^3), yet has superior mechanical robustness. The adhesive layer, CryoBond 920 is of a similar 2-part epoxy formulation, but with fewer microspheres. It, therefore, has a much lower viscosity allowing excellent wetting and adhesion to the metal surface. [2]

CryoCoat™ UL79 was initially developed to insulate the cryogenic tanks for a reusable launch vehicle. Insulation thicknesses were typically several centimeters thick and could be dimensionally controlled through the use of molds or vacuum bagging procedures. The adhesive layer was first sprayed onto the bonding surface. Second, the insulation was hand packed onto the surface and vacuum bagged into the appropriate geometry and thickness. However, it was found that for the thin layer of insulation required for the AMS 2 magnet vessel, the current method of applying the insulation did not result in a consistent material with uniform thickness. For the preliminary testing of the insulation for the AMS 2 application, a thick layer of insulation was applied to a test tank and the final insulation thickness was achieved by a machining process. This approach worked very well, the entire tank was placed in a lathe and the insulation was reduced to the appropriate thickness. However, this machining process would not be feasible for AMS owing to the large (2.5 m) diameter of the helium vessel. A conceptually simple solution to this problem would be to cast the insulation in pieces that match the shape of the helium vessel and then bond them to the surface of the vessel. This however is cost prohibitive due to the many large molds that would be required to cast the desired geometry. An alternative approach, called the conformable tile process was developed, which allows the material to be formed into blocks, cut to the desired thickness, and then formed to the curvature of the tank in a partially cured state. The insulation is then final cured after it had been formed to the desired shape.

THE CONFORMABLE TILE PROCESS

The fundamental concept behind the conformable tile process is to cast and partially cure the insulating foam into conformable tiles of the desired thickness that can be placed on the curved tank surface and plastically deformed to the required shape. The conformable, partially cured tiles then fully cure at room temperature on the surface. A detailed description of the process follows:

1. The CryoCoat™ UL-79 is shipped in two containers, parts A and B. These parts must be mechanically mixed together.
2. The mixed CryoCoat™ is then poured into the mold for making the partially cured blocks of CryoCoat™ UL790 as seen in FIG1, and distributed evenly, and compressed to a predetermined thickness.

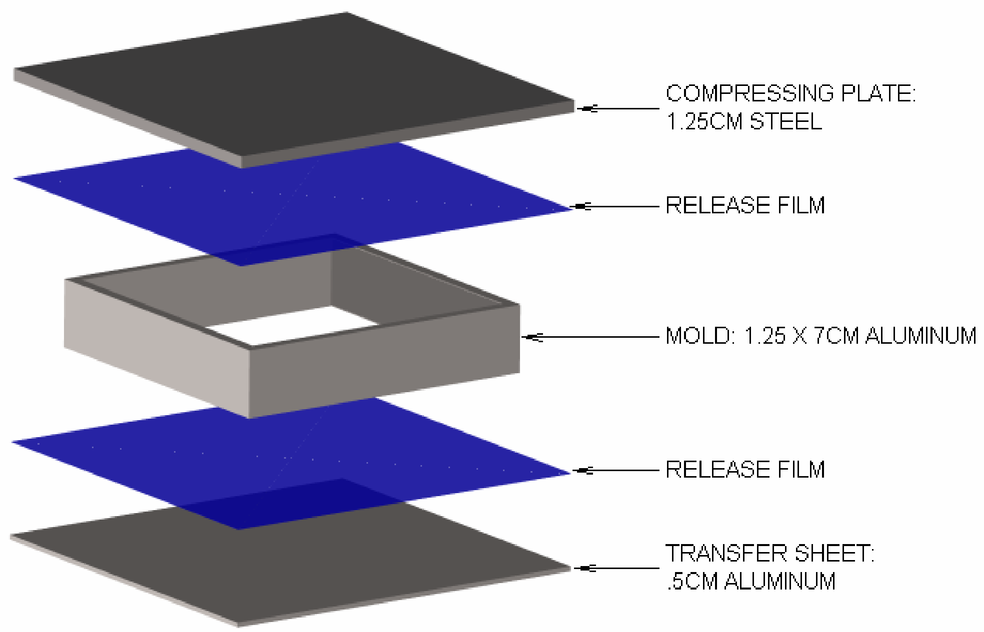

FIGURE 1. An example CryoCoat™ block mold

3. The molded block of insulation is then partially cured at room temperature. This takes approximately 16 hours. The curing process can then be arrested by placing the block in a freezer.
4. The block is then cut into tiles of the desired final thickness. This requires a common band-saw fitted with a scalloped knife blade and a large fence to gauge the correct tile thickness (see FIG 2). The material can be, once again, frozen to arrest the cure process

and enable a large number of tiles to be pre-fabricated, so they can all be applied to the tank at the same time.

FIGURE 2. Band saw set up to cut conformable tiles

5. The CryoBond adhesive must now be mixed and sprayed onto the bonding surface (also shipped as parts A & B in separate containers).
6. The tiles can then be conformed to the curved surface and cured. To insure adequate insulation at the joint between the adjacent tiles, a 0.5 – 1 cm gap is left between the tiles, which is then filled by hand packing with CryoCoat UL79.
7. After a cure period of 24 hours, the hand packed joints are sanded flush with the tiles. The finished product is shown in FIGURE 3.

FIFURE 3. CryoCoat™ insulated vessel

DEVELOPMENT OF THE PROCESS

The conformable tile process has been developed to allow the application of a thin and uniform layer of a very lightweight, 2-part epoxy insulating syntactic foam based insulation, CryoCoat™ UL79, to a large curved surface. The surface of interest was the exterior of a helium vessel contained within a vacuum vessel. The annular space between the vessels, which was to be evacuated to minimize the heat leak to the cryogenically cooled magnet, required that the layer of CryoCoat™ UL79 be of a precise and very uniform thickness. This process was designed to meet many requirements associated with this type of application. The insulation thickness and density must be sufficiently precise to reliably provide the desired thermal insulation qualities. The process must allow installation of the insulation without cracking or developing large built in stresses within the cured insulation. It is also important that the process be simple to execute and not require a large amount of tooling costs. It must, additionally, have the ability to be installed in a wide range of temperature and humidity conditions without adverse effects.

Two challenges had to be overcome to develop the process and meet the above requirements. The first was creating thin (on the order of 3 mm) tiles with uniform density. The uncured material as mixed has a very low density and is somewhat tacky. This material needs to be compressed by approximately a factor of two to obtain the desired properties. Because of its low density and high tack, it agglomerates. This leads to a non-uniform density with very thin molds because the material cannot be spread throughout the mold evenly before compression. However, it has been found that by applying the insulation in relatively thick sections (>1 inch), a uniform density can be achieved throughout the material. With a sufficiently thick mold the effect of these small agglomerates is absorbed, creating a uniform density material. The process of forming large blocks of the insulation, partially curing the blocks, and then slicing them into tiles of the desired thickness was, therefore, used. This was simply done using a mold as shown in FIGURE 1 to form the block and a typical band saw set up as shown in FIGURE 2 to slice the block into conformable tiles.

The second development challenge was to understand the curing process as a function of time and the effect of various atmospheric conditions, such as temperature and relative humidity, on this process. This was needed to partially cure the material to the appropriate level consistently. The cure process was found to not only be dependant on temperature and humidity, but also the volume and geometry of the insulation. Therefore the partial cure cycle was developed for the pre-cut molded block of insulation. Detailed procedures were developed to be able to obtain suitable partial cure of the insulation material, in the geometry of the molded block, for a variety of environmental conditions. An environmental chamber was used to simulate the range of environments, temperatures and humidity levels, to validate the partial curing procedures. It was found that the procedures developed for partially curing the molded block were sufficient for temperatures ranging from 13-24°C and a humidity range of 20-90%.

TESTING [1]

To verify the benefits of the insulation, its performance had to be calculated or tested. Although past work has been done on the subject ([3] and [4]), it is difficult or, in many cases, impossible to discern the effects of geometry and insulation type on the thermal performance of the insulation. Also, very little past work has been done with superfluid Helium, the cryogen of interest for the AMS project. It was, therefore, not feasible to extrapolate the results of past work to the AMS cryogenic system and it was necessary to conduct laboratory tests to verify the insulation performance.

The objective of the insulation was to reduce the heat flux into the cryogen thereby making the effects of a catastrophic loss of insulating vacuum less dramatic and reducing the safety hazard of the system. The objective of the lab test was, therefore, to measure the heat flux into the cryogen in the event of a loss of vacuum in a non insulated system and in an insulated system.

The test facility consists of a helium vessel suspended in a standard bucket-type dewar (FIG 4). These components are within a large vacuum chamber fitted with a fast acting vacuum valve which is opened to simulate a breach of vacuum pressure. Temperatures, pressures, and the flow rate are monitored. A direct mass flow rate measurement of the cryogen is difficult to obtain. The helium vessel is, therefore, suspended from a load cell which monitors the mass of the cryogen over time.

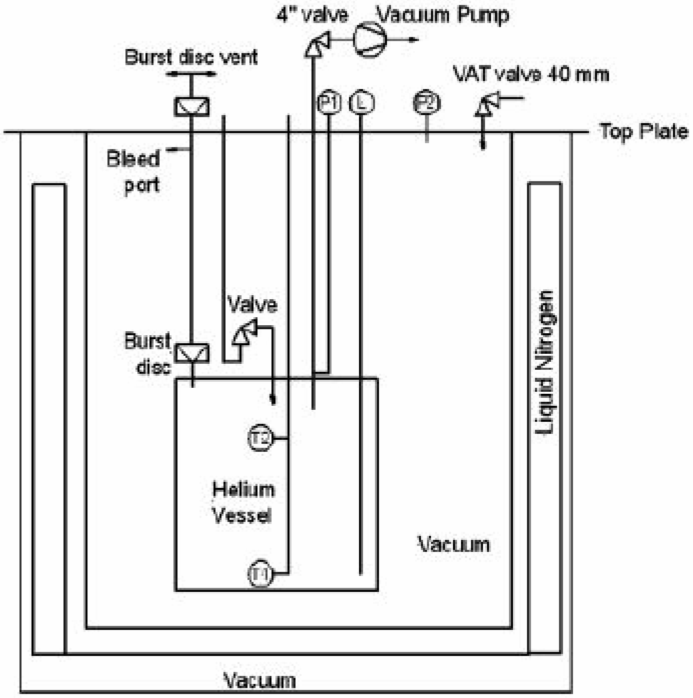

FIGURE 4. Test facility

Two sets of tests were required, one for an un-insulated helium vessel and one for an insulated vessel. The breach of vacuum with the un-insulated vessel, as expected, was rapid and violent. The bust disk system began venting the cryogen 5.3 seconds after the breach and all temperatures were above 10 K within 17 seconds. The heat flux in the non-insulated system was non-linear and difficult to calculate. The internal energy at every data point had to be calculated and differentiated with respect to time to generate the heat flux trend shown in FIGURE 5. The heat flux peaked at the saturation point near 31000 W/m^2 and slowly decreased thereafter.

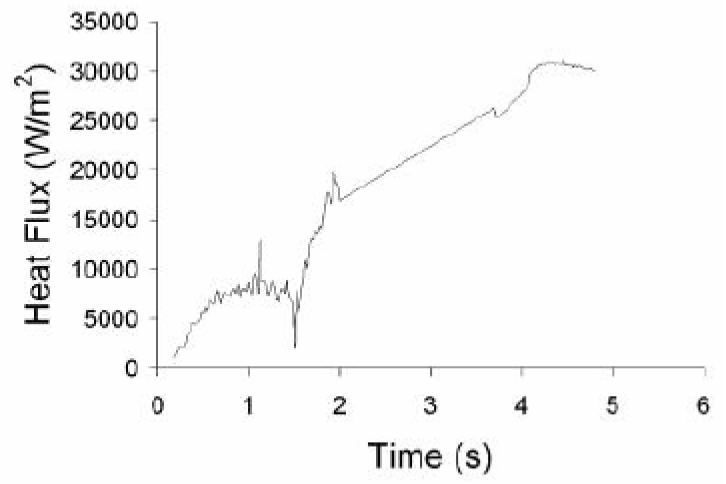

FIGURE 5. Heat flux trend for non-insulated vessel

The breach of vacuum test with the insulated vessel generated similar pressure/temperature trends (see FIG 6), but over a time scale extended by a factor of 4. The cryogen began to vent through the burst disk system 21.5 seconds after the breach and all temperatures were above 10 K after nearly 60 seconds. Due to the extension of the time scale, the heat flux into the insulated system was constant. The average heat flux required to raise the pressure to 11.3 bar (the vent pressure) in the 21.5 seconds that it took to reach this pressure is 4400 W/m^2. If a constant heat flux of 4400 W/m^2 is assumed, the temperature and pressure trends can be calculated using energy conservation. The temperature and pressure trends generated by this procedure follow the data very closely (see FIG 7). The heat flux is, therefore, very close to linear and standard compressible flow techniques can be used to predict the velocity and flow rate of the venting cryogen.

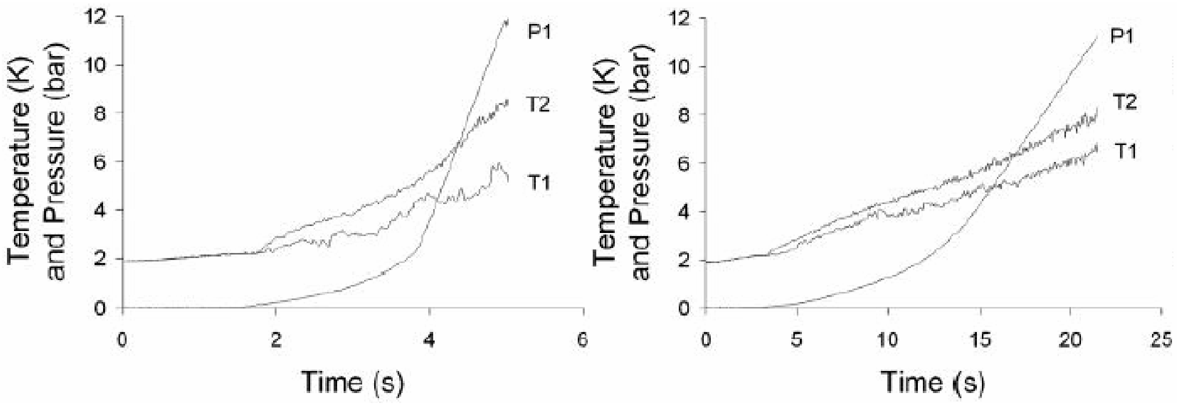

FIGURE 6. Pressure and temperature trends (Non-Insulated and Insulated Respectively).

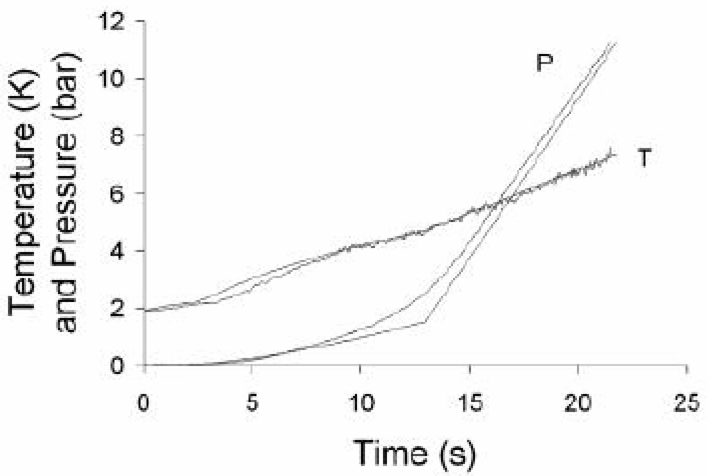

FIGURE 7. Temperature and pressure after loss of vacuum in the insulated vessel. Experimental and calculated values are plotted together and the correspondence is very close.

SUMMARY

A secondary insulation system is needed for the Alpha Magnetic Spectrometer experiment that is planned for installation on the International Space Station. This secondary insulation system will mitigate the violent effects of a sudden loss of insulating vacuum surrounding the superfluid helium required for the experiment. This reduces safety concerns before during and after flight. CryoCoat™ UL-79 was chosen as the insulation due to its low density, mechanical robustness and vacuum compatibility. A novel application method was developed for this insulation to allow it to be easily applied with a consistent thickness and density. This method involves forming the material into tiles and partially curing the polymer based material to a consistency that holds together, but is very conformable. These tiles are formed to the curved surface of the cryogenic vessel after an adhesive is applied to the surface, resulting in a form fitting bonded insulation. They then cure at room temperature on the vessel. This insulation system was tested on a representative cryogenic vessel. The result was a substantial reduction of heat flux into the cryogen and, therefore, a reduction in the violence, rapidity, and safety hazard of the venting cryogen. Additionally, the insulation layer caused the heat flux into the cryogen to be constant rather than the non-linear heat flux measured with the non-insulated vessel. This allows a simple analytical method of determining the system behavior in the event of a breach of insulating vacuum.

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