Loss of Vacuum Experiments on a Superfluid Helium Vessel

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[1]***Abstract*—The Alpha Magnetic Spectrometer (AMS) 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 a temperature of 1.8 K by superfluid helium. The helium is contained in a toroidal vessel with a volume of approximately 2500 litres. From ground safety and flight safety considerations, the system must be safe in the event of a sudden catastrophic loss of insulating vacuum. A test facility has been designed and built by the magnet designer and fabricator, Space Cryomagnetics Ltd of Culham, England. This facility allows a sudden, total loss of vacuum event in a small (12 litre) superfluid helium vessel to be triggered and monitored, so that venting rates and heat fluxes can be calculated. This paper describes the design of the test facility and the results of experiments to determine the heat flux to the superfluid helium. Test results are given for a completely uninsulated vessel, and for a vessel insulated with a thin coating of a special, lightweight insulating material.**

***Index Terms*—Cryogenic safety, Superfluid helium, Vacuum.**

I. INTRODUCTION

FOR many cryogenic systems, the worst conceivable failure is a sudden, catastrophic loss of insulating vacuum. A breach in the vacuum case of a liquid helium system results in air entering the vacuum space, where the combination of gas conduction and condensation leads to a dramatic increase in the heat load to the helium. This in turn generates high pressure which must be relieved through some appropriate device. It is common practice to specify burst discs and pressure relief valves to meet the combined requirements of pressure and flow rate expected following a loss of vacuum event.

Cold helium venting from a pressure vessel is always a safety concern, but even more so if the vessel is inside a spacecraft. AMS will fly to the ISS on board a US Space Shuttle, so the safety requirements before, during and after launch are particularly demanding.

Although a number of papers [1]-[3] have been published on this subject in the past, it is often impossible to establish how much the details of the geometry or insulation system affected the results. There is also very little information available on superfluid helium. This makes it difficult to extrapolate the results to systems of different sizes and shapes, or with alternative insulation arrangements. It was therefore decided by the AMS collaboration to carry out a series of cryogenic safety experiments on a superfluid helium vessel.

II. OBJECTIVES

The main objectives of the experiments were to measure the heat load to the superfluid helium, and the venting rate from the vessel, following a total loss of vacuum. Two sets of measurements were required: the first for a vessel with no insulation whatsoever, and the second for a vessel insulated with a 3 mm thickness of lightweight insulating material. This insulation was “Cryocoat Ultralight”, supplied by Composite Technology Development, Inc. of Lafayette, Colorado. The tests were intended to be as generally applicable as possible, so variables such as multi-layer superinsulation and confined spaces were avoided.

III. EQUIPMENT

The test facility was designed in the form of an insert to fit inside a standard bucket test dewar. The layout of the insert is shown schematically in Fig. 1.

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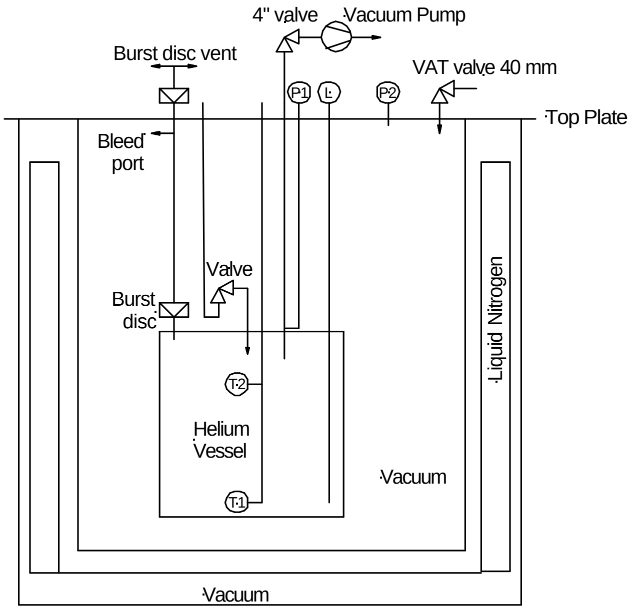

Fig. 1. Schematic diagram of the test set up.

For the experiments, these components are inside a vacuum space. The helium vessel is a cylinder with dished ends. It is suspended from the vessel top plate by a neck. Liquid helium can be transferred into the vessel via a valve, and leaves through the neck. A Roots pump combination is attached to the neck so that the helium pressure can be reduced to lower the temperature. A 40 mm diameter fast acting vacuum valve is mounted in the top plate. This can be opened in about 120 ms to simulate a large hole appearing in the vacuum case.

Pressure relief is provided by two burst discs in series. In zero gravity helium systems it is generally necessary to provide a burst disc at the cold surface as well as outside the vacuum space: although this test rig will not be launched it was decided to incorporate features from the flight system where possible. The pipe between the burst discs is evacuated. In the first experiment (no insulation) it was simply vented to the vacuum space through a small hole. With the helium vessel insulated, the time taken from breaking vacuum to venting helium was expected to be much greater. This introduced the possibility of an air blockage forming in the pipe, so the bleed hole was replaced by a pump out port allowing the pipe to be evacuated externally.

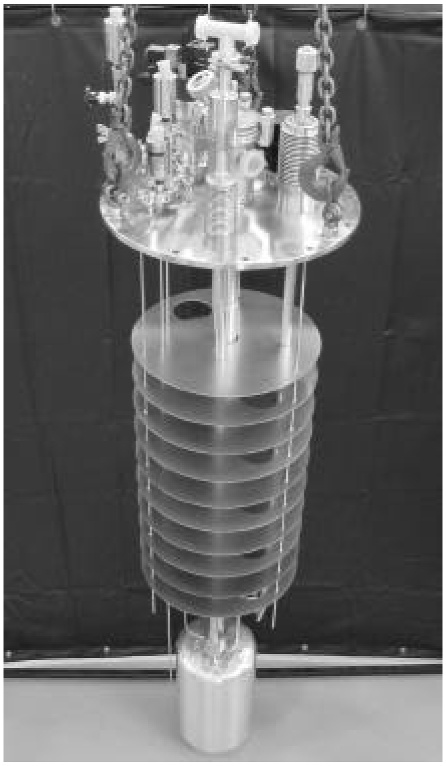

Fig. 2. The test insert ready for assembly into the bucket dewar. The helium vessel at the bottom is approximately 400 mm in length.

The temperature in the helium vessel is monitored by two Cernox temperature sensors suspended inside the vessel itself: T1 is near the bottom and T2 is about 150 mm from the top. Pressures are measured both in the helium space (P1) and in the vacuum (P2). P1 actually consists of two gauges, one for measuring pressures below atmospheric and the other for high pressures.

Measuring the flow rate of helium from the vessel is potentially difficult both because of the wide dynamic range required and because of the wide variation in temperature and density of the venting helium. The entire experiment assembly was therefore suspended from a load cell. By differentiating the mass reading (taking account for liquid nitrogen boiling off from the shield on the test dewar) the flow rate can be calculated. During commissioning, the flow rate from the vessel was calculated using this method and by monitoring the drop in level in the helium vessel, and there was good agreement between the results.

IV. RESULTS – NO INSULATION

For the first experiment there was no insulation on the helium vessel. By repeated filling and pumping cycles, the vessel was filled to 90% with two-phase helium at 1.9 K. The 40 mm valve on the top plate was opened to break the vacuum: it took 1.6 seconds for the vacuum space to reach 90% of atmospheric pressure, and a further 3.4 seconds before helium began to vent through the burst discs. Fig. 3 shows how the pressure and temperature inside the vessel increased before rupture of the burst discs and venting of the helium began when the absolute pressure was about 11.5 bar.

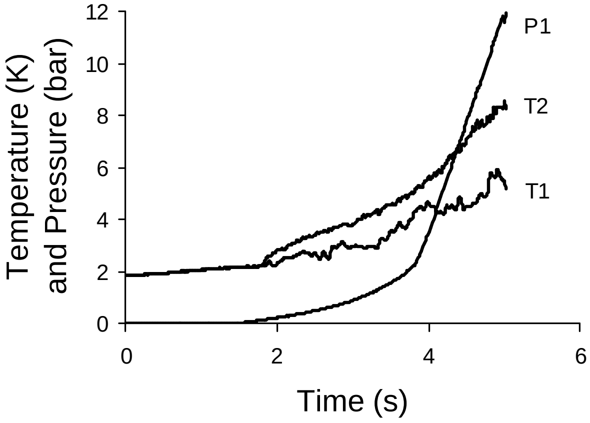

Fig. 3. Temperature and pressure rise in the uninsulated vessel after loss of vacuum.

Once helium started to vent through the burst discs, the pressure P1 inside the helium vessel fell very quickly to atmospheric. Within 17 seconds of first losing vacuum, all temperatures were above 10 K.

V. RESULTS – INSULATED VESSEL

The experiment was repeated with 3 mm thickness of the composite insulation applied to the entire outer surface of the helium vessel. Fig. 4 again shows the rising pressure and temperature in the vessel. The plots are quite similar to Fig. 3, except that the timescale is extended by a factor between 4 and 5: this is the effect of the insulation.

Venting of the helium took much longer as well: there were more than 40 seconds from the time the burst discs ruptured until the pressure in the vessel decayed to atmospheric.

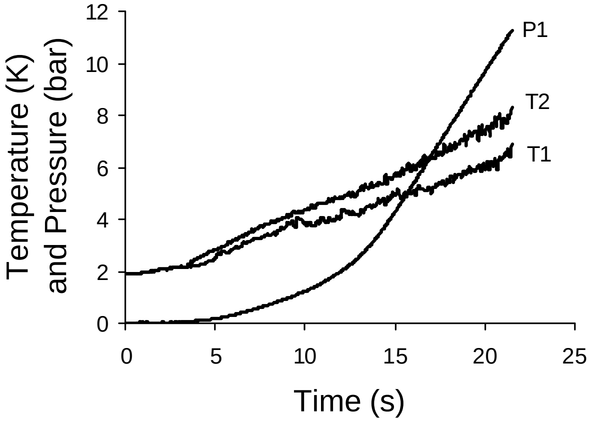

Fig. 4. Temperature and pressure rise in the vessel insulated with 3 mm of lightweight composite after loss of vacuum.

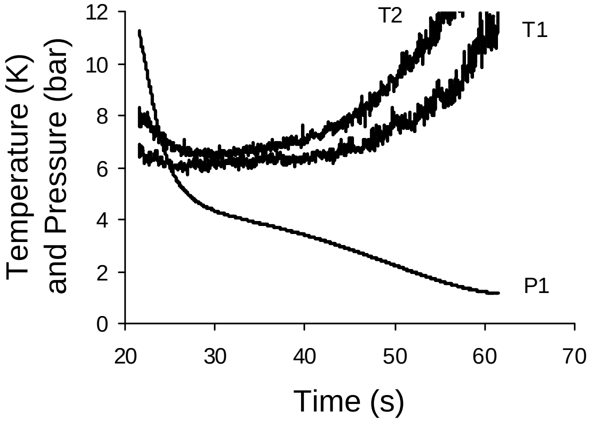

Fig. 5. Temperature and pressure in the vessel insulated with 3mm of lightweight composite during venting of the helium.

VI. ANALYSIS

In principle, it should be possible to calculate the heat flux on the vessel from the rate of rise of pressure or temperature. Since the outlet from the neck into the pumping line is sealed, the helium is heated isochorically until the burst discs relieve the pressure.

While the helium is superfluid, it can be seen from Fig. 3 and Fig. 4 that the two temperature sensors coincide exactly, indicating that the helium in the tank is isothermal. But as soon as the helium passes through the lambda point the temperatures begin to diverge: there must therefore be considerable thermal stratification of the helium within the vessel. This makes it less straightforward to estimate the heat transfer. Moreover, the pressure – which could be expected to be the saturation pressure – appears to bear no relation to either of the measured temperatures.

A. *No Insulation*

In the first experiment (no insulation), the vessel must contain liquid and gas which are not in thermal equilibrium: the gas is warmer than the liquid. It seems likely that the gas lies around the walls of the vessel, giving some degree of insulation to the liquid inside. For calculation of the heat load, the gas and liquid are treated separately. The liquid is assumed to be at the average temperature of T1 and T2, and the gas is assumed to be at the saturation temperature.

If the internal energy of the helium is calculated from the temperature and pressure using these assumptions, the curve is fairly smooth when the helium is either superfluid or supercritical, but rather noisy when the helium is two-phase. By differentiating the internal energy with respect to time, the heat load can be calculated and thus the heat flux through the wall of the vessel into the helium. Fig. 6 shows the result of this calculation.

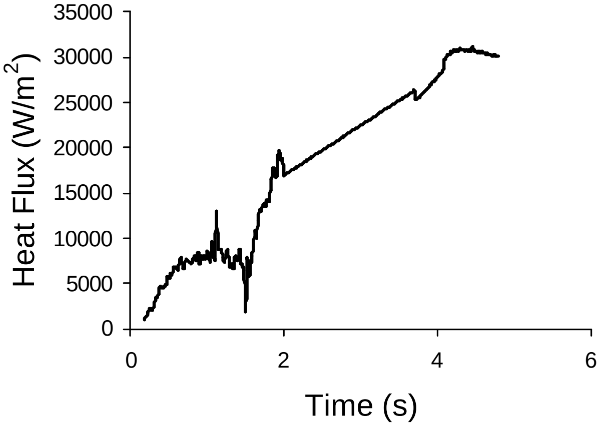

Fig. 6. Loss of vacuum heat flux to helium in a vessel without insulation.

The heat flux rises – very unsteadily around the lambda point – from zero to a value of about 31000 W/m^2. It then decreases slowly until venting begins.

B. Insulated Helium Vessel

Because the heat loads are much lower in the insulated vessel, conditions are generally more steady. Before breaking vacuum the helium is saturated at 1.907 K. The average heat flux required to raise the pressure to 11.3 bar (when venting begins) in 21.5 seconds is 4400 W/m^2.

When a constant heat flux of 4400 W/m^2 is used to calculate the pressure and temperature rise in the vessel, the agreement between experiment and theory is extremely good (Fig. 7).

The venting process can be analysed using the energy equation

$$Q = c_v \frac{d}{dt}\left(M\,T\right) + m\left(h + \frac{V^2}{2}\right) \tag{1}$$

where Q is the heat input, M is the helium mass in the vessel, T, c_v and h are the helium temperature, specific heat capacity and enthalpy, and m and V are the mass flow rate and velocity of the venting helium. The velocity and flow rate can be calculated, using standard compressible flow techniques, by assuming the helium expands isentropically from the vessel into the atmosphere.

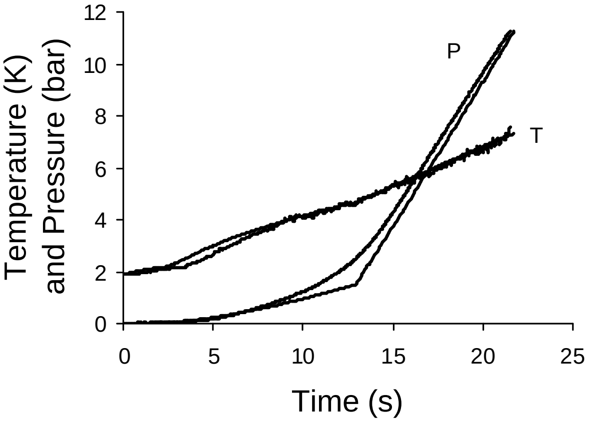

Fig. 7. Temperature and pressure after loss of vacuum in the insulated vessel. Experimental and calculated values are plotted together with the calculation using a constant heat flux of 4400 W/m^2: the correspondence is very close.

When the first attempt was made to apply this equation using the same heat flux of 4400 W/m^2 and the known geometry of the relief outlet, the calculations did not match the experimental results at all. The discharge of helium from the vessel, and the rate of depressurisation, were both much smaller than predicted. However, when the burst discs were removed and dismantled it was found that both were still occluding up to 80% of the vent passage. This is a known problem with reverse-buckling bladed burst discs when used with liquids or fluids with low compressibility, although for various reasons this type is still often preferred for cryogenic space missions.

The open area of the burst discs was measured and applied to the expression for the isentropic expansion of the helium and (1) was recalculated. Again, with a constant heat flux of 4400 W/m^2 applied there is a good correlation between the experimental and calculated values (Fig. 8). The main discrepancy is that the temperature measured in the experiment rises more slowly than predicted by the calculation. This is because the calculation assumes that all the helium in the vessel – and the vessel itself – are at the same temperature. In reality, the helium at the center of the vessel (where the thermometers are mounted) will warm up more slowly.

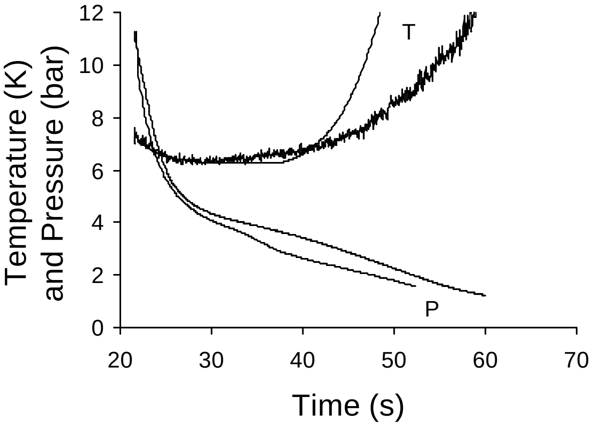

Fig. 8. Temperature and pressure during venting of the insulated vessel. The temperature appears to warm up more slowly than anticipated because the vessel is not isothermal.

VII. CONCLUSIONS

Following catastrophic loss of vacuum of a superfluid helium cryostat the helium will pressurize and vent. The main difference between superfluid and normal helium in these circumstances is the relatively long time taken to pressurize the superfluid owing to its very high specific heat capacity. While the helium is still superfluid it is isothermal, but as soon as it warms above the lambda point there can be considerable thermal stratification.

If the helium vessel is completely uninsulated and thin-walled, the heat flux through the walls can be as high as 31000 W/m^2. The heat flux does not appear to be affected by the change from two-phase to supercritical helium, possibly because in the two-phase case the liquid is insulated by a layer of gas at the vessel wall.

Application of a 3 mm layer of lightweight composite insulation reduces the heat flux to 4400 W/m^2.

Standard compressible flow calculations, together with the energy equation, can be used to predict with very good accuracy the pressurization and venting of a helium dewar following loss of vacuum.

Caution should be used when specifying reverse-buckling bladed burst discs for cryogenic helium systems.

VIII. REFERENCES

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