Survey of investigations on sudden loss of vacuum to air around equipment cooled with liquid helium

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Abstract. Several large scale superconducting devices such as high field magnets and SRF particle accelerators use large quantities of liquid helium for cryogenic operation. Large helium containers or dewars are routinely used close by these devices to provide liquid helium buffer. These systems as well as the storage containers have an insulation vacuum space to separate the warm surrounding and the cold helium space. In addition to the insulating vacuum, SRF accelerators have their beamlines immersed in baths of liquid helium. Accidental loss of the insulating or the beamline vacuum is considered to be *the worst case* failure scenario of these systems. Following an accidental rupture, warm atmospheric air will rapidly flow into the vacuum space and flash solidify on surfaces cooled by liquid helium. The thermal energy released by solidifying air will ultimately make its way to the liquid helium, cause it to violently boil, and the helium containment to pressurize to potentially dangerous levels. Although imperative to design of adequate pressure relief devices, analyzing the effects of such loss of vacuum in real systems (dewars, magnet cryostats, SRF beamline) is inherently difficult due to the complex interplay of heat and mass transfer from solidification of air and boiling liquid helium. Fortunately, the last two decades have witnessed several pilot projects that performed controlled loss of vacuum into well-instrumental liquid helium experiments and incremented the understanding of the subsequent heat and mass transfer, both in air and liquid helium. This paper provides a comprehensive review of these experiments and their findings in order to guide future investigations of this critical safety issue.

1. Introduction

Sudden loss of vacuum in systems cooled by liquid helium is considered to be an extremely dangerous event that may lead to serious equipment damage as well as loss of personnel life. Several factors contribute to the detrimental nature of this accidental vacuum loss. Firstly, the large pressure differential of 1 atm (atmospheric pressure outside minus vacuum inside the system) results into a rapid inflow of warm air into the vacuum space surrounding the liquid helium container. Secondly, due to the extreme difference between the temperature of air (~300 K) and liquid helium (<4.2 K), the air will flash desublimate (solidify) on the liquid helium container wall and quickly release the air's sensible plus latent heat, close to 500 kJ/kg. Thirdly, the liquid helium container material (routinely stainless steel) has extremely small specific heat near liquid helium temperature, which will cause it to rapidly warm up due to the heat deposited by the desublimating air. The rapidly warming container walls will ultimately transfer large heat fluxes to the liquid helium within the container. Fourthly, as the helium has very small superheat (~0.5 K above normal boiling point of 4.2 K) at normal saturation conditions as well as relatively small enthalpy of vaporization (20 kJ/kg for helium compared to 500 kJ/kg deposited by air), the liquid helium will violently boil and vaporize. Lastly, due to helium's large volume expansion ratio (>700 m^3 of gas at room temperature per m^3 of liquid), the helium container can quickly pressurize to dangerously high levels. With all effects combined, the accidental loss of vacuum can quickly bring the helium container to pressure levels causing it to destruct and damage nearby equipment as well as life.

2. Main configurations

Two helium system configurations have been mainly researched from the point of view of accidental loss vacuum. The first major configuration is a liquid helium storage (aka dewars) that has a stainless steel liquid helium vessel enclosed by vacuum within an outer stainless steel jacket at room temperature. The helium vessel is wrapped with multilayer insulation (aka MLI) to reduce thermal radiation coming from the room temperature vacuum jacket. A slight variation of this configuration is a liquid helium cryostat used to conduct experiments using a bath of liquid helium. Such a vessel may be used to cool superconducting magnets or radiofrequency (SRF) cavities during their performance tests. These experimental vessel may or may not carry MLI on their liquid helium vessel but mostly have a thermal radiation shield actively cooled by liquid nitrogen or cold helium gas that boils off from the inner bath. These vessels also have insulating vacuum around the liquid helium vessel. When such a configuration suddenly loses the insulating vacuum, the inflowing air is expected to fill the vacuum space more or less uniformly, resulting into a spatially uniform rate of air desublimation on outer surface of the liquid helium vessel. If the rate of air desublimation can be estimated, one can calculate the resulting heat flux to helium, determine is boil-off and pressurization rate, and then design a suitable pressure relief device for protecting the liquid helium vessel.

The second major configuration is a particle accelerator that uses SRF cavities for producing energetic particle beams. An SRF particle has a long beamline made of niobium cavities containing vacuum on the inside while immersed in baths of liquid helium. The string of such liquid helium cooled cavities are enclosed in a vacuum space provided a vacuum vessel. The liquid helium baths are wrapped with MLI and also surrounded by a thermal radiation shield in the vacuum space. There are thus two vacuum spaces in a SRF particle accelerator – (a) the insulating vacuum very much like in the helium dewar or cryostat configuration and (b) the beamline. A sudden loss of insulating vacuum may have same heat and mass transfer dynamics as in the case of helium dewar/cryostat loss of insulating vacuum, i.e., more, or less uniform spatial desublimation of air. However, the beamline loss of vacuum is much more complicated. This is because the beamline is a very long structure (of the entire length of the accelerator) and will likely lose vacuum very locally, most likely at one of the many room temperature interconnect. This local rupture lets the atmospheric air in the cold beamline vacuum space, which then propagates down the beamline vacuum space and simultaneously desublimate on the beamline wall. The resulting heat and mass transfer from air desublimation in the presence of longitudinal propagation is quite difficult to estimate, which means the helium heat flux is also unknown making it difficult to estimate the bath pressurization rate and then to design a pressure relief device.

3. Overview of experimental and theoretical investigations

A number of experimental investigations have been carried out, especially in the last two decades, that aim to understand the complex heat and mass transfer processes that happen following sudden loss of vacuum in the above liquid helium systems. They can be broadly categorized into:

1) Crash test of liquid helium cryostat/dewar – in this category, the helium bath of a cryostat is filled with a known quantity of the liquid and then the atmospheric air is rapidly vented into the insulation vacuum space. The resulting helium boil-off if directed out via a pressure relief line instrumented a mass flow metering and pressure and temperature sensors. The mass flow rate of inflowing air is determined using either an inlet flow meter or simply from the size of the vent hole and using choked flow equations. The helium boil-off rate is measured using the flow meter on the pressure relief line.
2) Measurement of air desublimation rate on liquid helium cooled surfaces – in controlled, well instrumented setup, a small metallic plate with a vacuum column on one face is immersed in a bath of liquid helium. Warm air at a known/measured flow rate is then let into the vacuum space. As the air desublimates on the surface, its temperature increases and heat transfer to liquid helium on the other side begins. Helium heat flux as well the energy that goes into the heat capacity of the plate are determined by from the temperature profile of the plate. The rate of air desublimation is then calculated using energy conservation.
3) Cryomodule crash test – a real SRF beamline is evacuated and then the enclosing liquid helium baths are filled with liquid helium. A fast acting valve located at the room temperature interconnect on the SRF beamline is quickly opened to simulate sudden loss of vacuum. The incoming air is allowed to propagate and simultaneously desublimate on the inner surface of the beamline. The air flow rate is measured using a flowmeter located at the interconnect. The relieving flow of helium is taken out via a pressure relief line, which carries pressure, temperature, and mass flow instrumentation. The helium relieving rate is measured using this instrumentation.
4) Controlled scaled-down experiments to understand air propagation and its effect on helium heat flux – a long channel carrying pressure and temperature sensors along its length is evacuated and then immersed in a bath of liquid helium. Warm air is vented into the longitudinal vacuum space, its propagation is tracked by the pressure sensors and the helium heat flux is estimated from the rise in temperature of the channel wall.

4. Summary of experimental investigations

a) Dewar/cryostat loss of insulating vacuum

The most well-known and highly referenced paper describing loss of insulation vacuum around liquid helium dewars and cryostat is by Lehmann and Zahn [1]. In controlled experiments, liquid helium containers of several capacities, with and without multilayer insulation (MLI) were open to atmospheric air. The mass flow rates of in-flowing air and relieving helium were measured to determine the transient heat load to the container wall wetter with liquid helium at 4.2 K. The heat flux on the container without MLI was seen to peak at 3.8 W/cm^2 while that with MLI remained below 0.6 W/cm^2. The tests concluded that wrapping MLI on helium wetted surfaces is an effective way to reduce the heat load resulting from sudden loss of insulating vacuum. Harrison [2] reported measurements of transient heat load to superfluid helium at 1.8 K after venting air into the insulation vacuum space around a 12 liter superfluid helium vessel, with and without a lightweight composite insulation. The peak heat flux was seen to be 3.1 W/cm^2 and 0.44 W/cm^2 for uninsulated and insulated vessels respectively. Harrison's results agreed reasonably with Lehmann and Zahn's albeit the vastly different properties of liquid helium at 4.2 K and 1.8 K.

Heidt *et al.* have modeled the rise in helium pressure in a cryostat whose insulation vacuum space was suddenly vented to atmospheric air [3]. They built a test setup at KIT for quantifying the heat load prevailing in such a loss of vacuum scenario [4], with liquid helium volume of 100 liters, nominal pressure of 16 barg, and a capacity of measuring helium mass flow rates through safety relief devices up to 4 kg/s [5,6]. Figure 1 is a schematic of their test setup. First commissioning test on this facility involved venting room temperature nitrogen gas and air through a 12.5 mm orifice into the insulating vacuum space and understanding the dynamic response of the helium

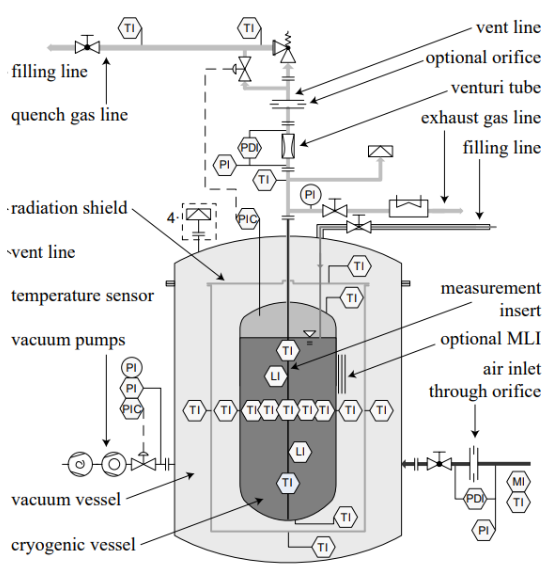


Figure 1: Experiment schematic of Heidt et al. [4]

relief valve on the insulating space. The valve chattered in the initial duration of relief, but held near its set pressure of 3 barg as steady state prevailed. Experiments on Heidt *et al.*'s setup were continued by Weber *et al.* [7,8]. Weber noted from analysis of initial experimental data that the heat load to liquid helium from a non-insulated vessel following a loss of insulation vacuum appears to be smaller than the commonly assumed 4 W/cm^2.

Quantifying the heat load to liquid helium resulting loss of vacuum induced air condensation is difficult unless directly estimated from the helium venting flow rate measurement. This is because the rate of incident heat load from the flash solidification of air is difficult to quantify based on the theory of cryo-desublimation, primarily because the process starts in high vacuum and takes place at extremely low temperature (2-4.2 K). Bosque *et al.* [9] and Dhuley *et al.* [10] conducted experiments to quantify the rate of air condensation on a metallic plate with vacuum on one side and wetted with liquid helium on the other. By carefully controlling the mass flow rate of air venting into the vacuum space above the metallic plate, the teams studied the dynamic air condensation rate. It was seen that the air condensation rate goes through a peak as the vacuum space is pressurized, then follows to a steady rate. The rate of heat transfer to the helium bath below the metallic plate, however, is limited by film boiling heat transfer coefficient. Dhuley and Van Sciver [11] estimated the steady heat transfer rate to 4.2 K liquid helium to be close to 2.3 W/cm^2. This was estimated from experiments conducted by venting air into a metallic vacuum tube immersed in 4.2 K liquid helium and measuring the tube wall temperature. The rate of heat flux was determined using the tube wall temperature and pool boiling heat transfer curve for 4.2 K liquid helium [12].

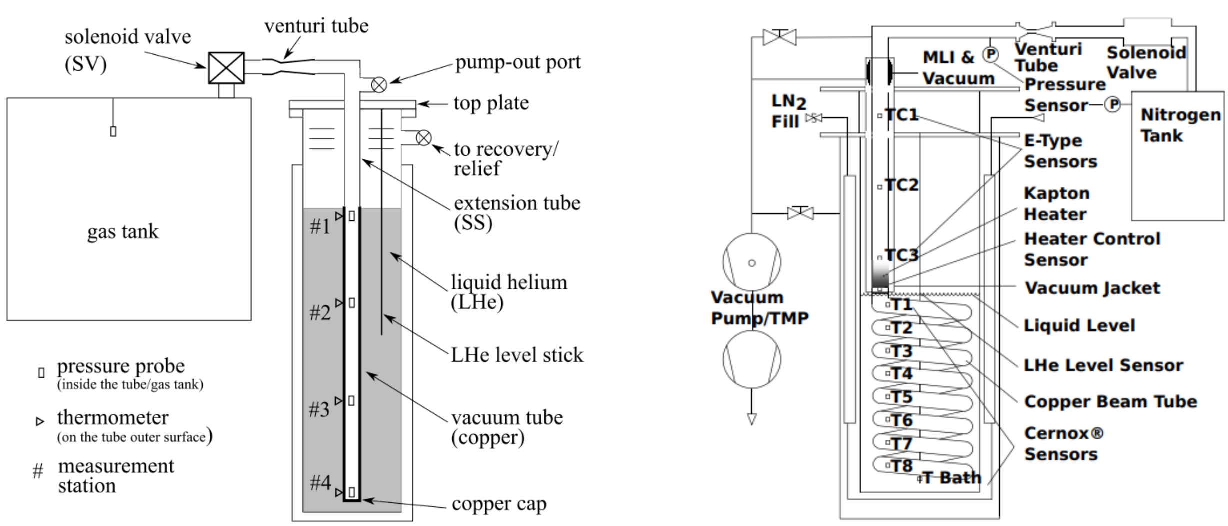
Loss of insulating vacuum on an SRF cryomodule was conducted at CEBAF [13] by controlled venting of atmospheric air into the cryomodule insulation vacuum space. The vacuum failure was simulated by opening a 3.2 mm diameter orifice to the vacuum space. This resulted into an air mass flow rate of 3.3 gm/s and peak heat flux of 749 W/m^2 to liquid helium before the rupture disc on the vacuum space actuated. Interestingly, this value exceeded the calculated sum of sensible and desublimation enthalpy of the inflowing air, which was 427 W/m^2. This important observation signifies that the total thermal energy brought in by the air per unit time is <u>not</u> the upper limit of heat load to helium resulting from a loss of insulating vacuum. The researchers at CEBAF credited the difference to the convective heat transfer through air from the warm vacuum surface to the cold helium surface.

DESY recently conducted a loss of insulating vacuum in a XFEL-line cryomodule with it s cavity string cooled to 2 K in superfluid helium [14], with results expected soon to be published.

b) SRF beamline loss of vacuum

Two notable SRF beamline loss of vacuum tests (also known as cryomodule crash tests) are those done at CEBAF, Jefferson Lab in 1994 [15] and at XFEL, DESY in 2008 [16]. Both tests used real SRF cryomodule, venting atmospheric air through a solenoid actuated orifice into an SRF beamline immersed in a bath of liquid helium. Measurements of air mass inflow rate and relieving helium mass flow rate were performed to estimate the dynamic heat load to liquid helium. The DESY test noted an interesting ‘slow air propagation’ effect down the beamline due to the complex interplay between the air trying to propagate down the beamline vacuum and solidifying on the cold walls of the helium cooled beamline. This propagation effect made it cumbersome to accurately quantify the dynamic heat load. An upper limit to the heat load is the total amount of thermal energy brought in by the air, which is equal to the air mass flow rate times the change in enthalpy from ambient pressure and temperature to its final solidified form.

Dalesandro *et al.* performed loss of beamline vacuum experiments on a scaled-down LCLS-II SRF cryomodule [17], specifically to further study the slow air propagation effect. Flakey instrumentation provided data of limited use; however, the propagation effect was again noticed. The authors found that the air front has ~10 m/s average velocity along the cold vacuum tube, about two order of magnitude slower than if the beamline was at room temperature. Dhuley and Van Sciver reported the foundational and most systematic experimental measurements of air propagation down a liquid helium cooled vacuum channel. The authors developed a well instrumented cold vacuum tube as depicted in Figure 2, with longitudinally placed miniature pressure probes and thermometers to accurately record the arrival of the air front along the channel [11,18]. Using data obtained from parametric experiments with different mass in-flow rates, the authors developed a phenomenological model describing the slow air propagation. This model explained not only why the air flow slow along a cold beamline (this is due to solidification of the air on the cold walls of the tube) but also that the speed of air falls exponentially along the channel [19,20]. Their model predicted that for small enough mass flow rates (resulting from smaller air leaks in the SRF beamline), the propagating front will freeze out over a finite length of the beamline. The authors further studied dynamic heat load from the solidifying air along the vacuum tube [21-24] and observed that although the peak heat deposition to the tube can be >100 kW/m^2, the maximum heat load to liquid helium is limited by film boiling to 20-25 kW/m^2.



(a) (b)

Figure 2: Experiment schematic of (a) Dhuley and Van Sciver [22] with a straight vacuum channel and (b) Garceau et al. with a helical vacuum channel [25].

Dhuley and Van Sciver's experimental setup had two shortcomings – (1) the vacuum tube was short in length and (2) experiments were conducted with 4.2 K liquid helium only (SRF beamlines are commonly cooled with 2 K superfluid helium, with vastly different thermofluid properties than the 4.2 K liquid). Garceau, Bao, and Guo modified Dhuley and Van Sciver's setup in the following ways: (1) the straight tube was replaced with a spiral tube, allowing the slow air propagation effect to be studied over a much longer length, (2) the upper part of the tube was thermally insulated to accurately define the liquid helium wetted length, and (3) superfluid helium at 2 K was used to cool the vacuum tube. The instrumentation for tracking the propagating air front remained same as Dhuley and Van Sciver's. Garceau et al. also developed a numerical framework to model the air propagation speed and other characteristics along the vacuum spiral tube. Their numerical model closely reproduced the experimental findings, highlighting its scaling potential to real sized SRF beamlines. The work is published in a series of paper, see [25-29]. Figure 2(b) shows a schematic of Garceau et al.'s experiment [29].

5. Codes and standards for pressure relief design

A few design codes and standards provide methodology for sizing relief devices for handling the helium pressure build-up in cryostats/dewars following accidental loss of insulating vacuum. Notable amongst these are Compressed Gas Association's S1-3 [30] and International Standards Organization's ISO-EN-21013 [31]. The ISO code provides guidance for determining the heat load to liquid helium for multilayer insulated as well as uninsulated containers. The CGA code requires calculated of this heat load based on the surface area of the helium containing vessel, the thickness of thermal insulation, and thermal conductivity of the insulation material. For dynamic thermos-fluid properties of helium, reference is made to NBS's Technology of Liquid Helium paper [32].

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