Title

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Abstract: In this paper I will outline the science relevant to the construction of a cryostat. I will then outline the techniques that others have used to augment cryostats to allow for ultra-low vibration experimentation. I will begin by describing the fundamental characteristics required of a cryostat then proceed into discussion of the specific mechanisms employed in our specific solution and the constraints this places on material composition.

Introduction: Cryostats have been around as long as dewars and thermoses have and follow many of the same principles. They are all designed to inhibit the transfer of head between the outside world and their contents. Heat has three main mechanisms by which it may be transferred; conduction, convection, and radiation. All three of these must be minimized to provide the highest possible thermal isolation.

Conduction is one of the simpler forms of heat transfer. When particles possess heat-energy they vibrate. This vibration is one of the understandings of what it means for a material to be hot. There are many ways in which the particles may vibrate but regardless of how they vibrate they will vibrate against one another. This transfer of random, undirected kinetic energy is the process known as conduction. To inhibit conduction one may use a material that functions as a thermal resistor as the atoms within said material are unable to transfer heat energy to each other with any efficiency. The best way to inhibit conduction is, however, to remove all material as without a medium for conduction there cannot be any conduction. Examples of good thermal insulators in this sense include air, rubber, Styrofoam, and a vacuum.

Convection is the process by which particles with grater heat energy vibrate with greater amplitude and thus have a lower density than surrounding particles. By virtue of their lower density these particles rise relative to other particles. These cooler particles are now in thermal contact with the source of heat and themselves gain enough thermal energy to rise above their neighbours. This gives rise to circular currents known as convection currents. As the reader may have already deduced, this a method of heat-transfer only possible in fluids e.g. gases and liquids. This is the process by which we boil water in our everyday lives. The main method for inhibiting convection is to remove all fluids from the system.

Radiation is a method of heat transfer completely different from the other two. Radiation is emitted from bodies containing thermal energy as self-propagating electromagnetic fields i.e. light. The spectrum of this light is given by the blackbody curve and the energy emitted is given by:

$$\frac{P}{A} = \sigma T^4$$

Here P is power in units of Joules per second, A is area, σ is the Stefan-Boltzmann constant equal to $5.67*10^{-8}$ W m^{-1} K^{-4}, and T is the temperature of the object. For this equation to be true the object must be a blackbody.

The emission of heat as radiation is only half of the story when it comes to heat transfer. The other half is that this radiation may then be absorbed as heat by another material. The absorption of a given wavelength is heavily dependent on the material. To reduce heat-transfer via radiation we must use highly reflective i.e. shiny materials.

As may be evident to the reader, no one material can be a perfect insulator. Further, the order in which these heat-transfer impediments are employed has a great impact on the effectiveness of the solution. One could make a glass shell around an air pocket with a metal inner liner. Certainly there would be no conduction or convection from the outside world, but the metal could easily conduct heat to and from the contents and convert said heat into radiation while incoming radiation would could heat the metal and thus the container. Rearranging this system such that the metal is on the outside would work far better. In fact, the weakest part of a thermos, from a thermal isolation perspective, is the lid. Were we not required to maintain an opening through which to place or remove material or samples from the cavity we would be able to impede heat transfer almost completely.

To reiterate: thermoses, cryostats, and dewars must be constructed with many of the same principles in mind. They all aim to reduce the rate of heat transfer to the largest degree possible. The differences come in the subtleties, sizes, and quality requirements of the application. A thermos may be stored readily within a bag and is designed to keep edible goods similar temperatures over a period of several hours, be that temperature “hot” or “cold” relative to room temperature. Dewars and cryostats, by comparison, are specifically design to keep materials cold. Dewars allow for larger volumes to be kept cold and are constructed more carefully with regards to heat transfer than thermoses are, but are often required to have lids that are incapable of creating a strong seal lest the dewar become a pressure vessel thus a danger to those interacting with it.

The similarity that thermoses and dewars share that cryostats do not is that they are passive. Cryostats are an inherently active device. Cryostats are also the most extreme cooling mechanism and may require customisation for specific purposes. There are two aspects of cryostats that make them active devices. The first is that a vacuum pump must be used to keep the sample in an environment free of any gasses that may conduct or convect heat. The second is the implementation of a cold head to actively reduce the temperature within the cavity.

Current State of Technology: The goal of a cryostat is to cool samples down to cryogenic temperatures. In our case this means below 4 Kelvin. The current solution achieves this by having a three-layered cooling system. The layers are vacuum can, liquid nitrogen can, and a liquid helium can into which the cold-head is placed. The vacuum can layer is precisely as it sounds; there is an outermost container constructed in the form of cylinder within which a vacuum is pulled such that all inner components are out of thermal contact with the outside world as there is no method of conduction or convection available. The liquid nitrogen can acts as a thermal buffer for the liquid helium can as nitrogen condenses at approximately 77 Kelvin. Thus, until all of the nitrogen has evaporated, the highest temperature that the outside of the liquid helium can may experience is 77K.

This reduces the thermal load on the cryostat cold head as this part has a maximum power at which it can cool. The cold head has two stages. The one closest to the base is capable of reaching temperatures as low as 45K, usually, although this varies by model. The second head is the one that delivers the truly cryogenic temperatures. It is often rated as being capable of getting down to 4K, although in reality it is often relied upon to produce lower temperatures. The maximum cooling power is different between these two heads and the 45K head too acts as a sort of thermal buffer for the 4K head. It is worth noting that neither of these heads are actually in contact with the outside of the can. This reduces the thermal load on both heads. It is also worth noting that, when the apparatus is in its correct position, the 4K head is closer to earth than the 45K head.

This is important because the liquid helium can is filled with helium. In both its liquid and gaseous forms helium is a fluid. It is capable of both conduction and, to a greater degree, convection. However, in this situation, the convection is being used to our advantage. As the helium is cooled it becomes more dense and descends instead of ascending. The helium that has gotten to the bottom of the can stays around 4K and at the bottom of the can. This results in a reduced thermal load for the system.

Once the helium has been cooled to 4K it starts to condense on the 4K head into liquid helium and dripping to the bottom of the can in a pool. The sample is mounted to the underside of this can. Because the bottom of the can is made from copper the sample is in good thermal contact with the helium can.

Also mounted to the bottom of the can, and around the sample, are electro-magnets. The specifics of these magnets vary by the use and needs of the users, but super conducting magnets are not uncommon. Because these magnets can be quite powerful another design constraint comes up: what materials can be used without affecting, or being affected by, the magnetic fields that these electromagnetic coils produce. Because of this 316 stainless steel is often used, although it is imperfect, as it is exceptional for how readily available the alloy is. Imperfect in that at extreme cryogenic temperatures, depending on manufacturing, it can become magnetically active.

Future Plans: The largest downside of the cryostat arrangement is that the cryostat cold head produces vibrations. This is the goal of my research; to design an improved cryostat with as many commercially available parts as plausible such that vibrations from the cryostat cold head are minimized. As of yet this appears to require active damping and there is debate between rubber and metal bellows.