

Efficient biostorage below $-150\text{ }^{\circ}\text{C}$, without sacrificial cryogen

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Abstract. Biostorage is a multi-billion dollar business worldwide and growing rapidly; yet the commercially available options force the user to choose either optimal storage temperature (below $-137\text{ }^{\circ}\text{C}$, the “glass transition temperature” of water) or convenience (no cryogen refill). Passive liquid-nitrogen freezers (storage Dewars with liquid nitrogen pooled at the bottom) provide very cold storage ($-190\text{ }^{\circ}\text{C}$) but the LN2 must be replenished as it boils off. The alternative, so-called “ultra-low” vapor-compression freezers, have no cryogens to replenish and are convenient to use, but only reach storage temperatures above $-90\text{ }^{\circ}\text{C}$. In addition, these tend to be inefficient and costly. Chart Industries is introducing a novel combination of a storage Dewar with a cryocooler (the “Fusion” freezer), that can maintain storage temperatures below $-150\text{ }^{\circ}\text{C}$ without the need to replenish any cryogen, while drawing less electricity than any ultra-low on the market. This new product also fits into a relatively narrow “demand window” where on-site cryocooling is not merely more convenient, but also more cost-effective than liquid nitrogen delivery.

1. Introduction

According to a “Global Market Insights” report from 2016, the biopreservation¹ market was already at \$3B in 2015, and projected to equal almost \$10B by 2024 [1]. Biostorage applications include preservation of tumor cells, blood, vaccines, and tissue cultures. Optimally, most biological samples should be stored below the so-called “glass transition temperature” of water T_g , to inhibit ice-crystal growth that can damage cell membranes. There is some controversy about exactly where this temperature should be specified, but it is commonly given as around 136K, or -137°C [2]. However, the biostorage market is dominated by “ultra-low” cascaded vapor-compression freezers, which typically cannot get below -86°C . These freezers also draw a lot of electric power, typically 18 to 20 kWh/day for a full-height cabinet.

The other readily available option is a liquid nitrogen freezer, or a storage Dewar with a pool of liquid nitrogen (LN2) in the bottom of the storage space. This provides very cold storage, down to -190°C , but the LN2 must be replenished as it boils off. Currently, there is no commercially available product which offers cold storage below T_g , with the convenience of a mechanical freezer.

¹ In this context, “biopreservation” means cold biostorage, but this term is also in use to mean using beneficial bacteria to retard food spoilage.

1.1. Economic challenge of competing with LN2

Despite the inconvenience of refilling storage Dewars with LN2, and the existence of cryocoolers capable of reaching LN2 temperatures, the refilling approach persists in part because LN2 is very inexpensive when produced at large air-separation plants and delivered in bulk. The price drops dramatically for large-volume consumption; some approximate values for filling various size tanks are shown in Table 1 [3].

Table 1. Approximate delivery or refill cost for different size LN2 storage vessels (Total cost to user includes miscellaneous charges like ‘demurrage,’ which vary from vendor to vendor).

Type of vessel	Volume	Refill cost
Wheeled cylinder	180 liter	45¢/liter
“Micro-bulk” tank	1000-1500 liter	15¢/liter
Bulk tank	≥3000 liter	7¢/liter

Delivery of volumes below 180L is even more expensive than 45¢/liter; but it does not follow that using a cryocooler for low-volume applications is cost-effective. At low enough LN2 usage, the cost savings will never equal the first cost of purchasing a cryocooler. There exists a fairly narrow “demand window” where a cryocooler with a second-law efficiency of 15% (say), costing several thousand dollars, is cost effective—a high enough demand that it can justify the initial expense, but where bulk pricing of LN2 is not available. This turns out to be roughly between 2 and 10 liters a day. Most applications that use less than 2 liters a day won’t be able to justify the expense of a cryocooler, even with the added convenience. One that uses over 10 liters/day can take advantage of bulk pricing. By this logic, the best opportunities for using cryocoolers for applications in the LN2 temperature range are where the cooling load approximates around 5 liters per day.

2. The Fusion approach

The “Fusion” freezer developed by Chart Industries is based on an existing 1500-liter LN2 freezer, but instead of a pool of LN2 in the bottom of the storage space, there is a cryogen reservoir in the center of the freezer, with a neck extending up to a flange attached to the coldhead of a cryocooler, so that as the cryogen boils off, it is recondensed and drips back down into the reservoir. An external view of the system, and a (coarse) cutaway are shown in Figure 1.

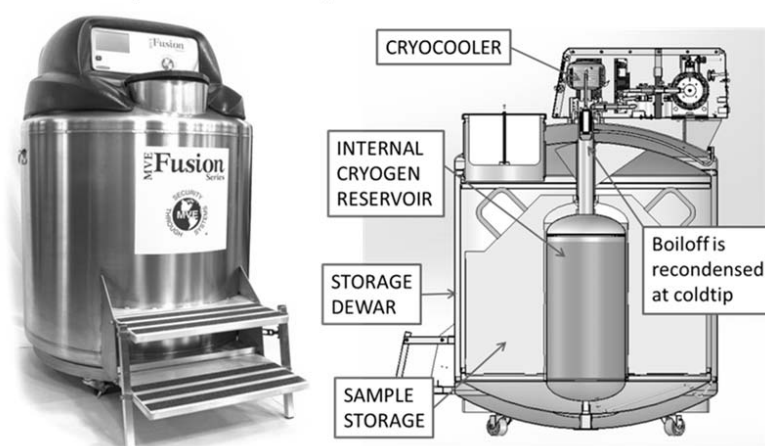


Figure 1. A Fusion freezer (left) and a cutaway view from the solid model (right).

Zero-boiloff cryostats are not in themselves novel, of course. The Fusion freezer configuration is somewhat different from a simple cryostat, in that the cryogen reservoir is separate from the actual Dewar storage space, and is not insulated. Rather, the outside of the reservoir serves as an isothermal

heat-exchange surface, cooling the air around the stored samples. The reservoir thus behaves a bit like the thermosiphons used in Stirling-powered freezers [4], except at a much colder temperature. The large volume of liquid in the reservoir also provides ‘thermal ballast’, or hold time (over a week), in the event of a power failure.

One might ask, why *not* essentially fashion the freezer as a zero-boiloff cryostat, with liquid in the bottom of the freezer (as is now done with regular LN2 freezers) and let the coldtip live in the storage space, recondensing the boiloff directly in that space? There are two main arguments against this approach. One is that the saturation temperature is a very sensitive function of pressure. Unless the cryocooler temperature is controlled with exquisite precision, the pressure inside the storage space will tend to be slightly higher than the outside world, in which case vapor will leak out (depleting the store of cryogen) or slightly lower, in which case air (and water vapor) will tend to leak into the storage space, speeding the growth of frost and ice. Another reason is that since the cold tip of the cryocooler will always be the coldest location, it will soon accumulate a coating of ice from whatever water vapor does find its way into the storage space. This will create a temperature defect between the cold tip and the condensing vapor, forcing the cryocooler to operate at a colder temperature. This increases the system power draw, and eventually may prevent it from working at all.

Using a separate vessel for the cryogen allows the pressure inside that vessel to vary within some limits, absorbing changes in the load (for instance, when the lid is open or closed, or when new, warm samples are added) without losing any cryogen.

3. Cryocooler

The enabling technology in this new product is the cryocooler (QDrive 2S132K) used to recondense the cryogen inside the reservoir neck. For a cryocooler to suit this application, it has to meet several criteria:

- *Capacity*: Cryocooler must be able to overcome two or three times the Dewar heat leak (which is 12–13 watts at 77K) to accommodate the insertion of fresh samples and achieve reasonable cooldown recovery times for short-term power outages.
- *Efficiency*: To keep operating cost low, the cryocooler must have a fairly high efficiency (15–20% of Carnot).
- *Size and placement*: To keep from increasing the footprint of the freezer over its passive counterpart, the cryocooler has to mount to the top of the freezer, including all controls and cooling fans.
- *Maintenance*: To appeal to the same markets that currently support passive nitrogen freezers, the cryocooler should ideally require no maintenance and no scheduled downtime.
- *Cost*: While the improved convenience of a self-sustaining freezer will command some premium, the cost has to fall within the norm for laboratory equipment.

The capacity, efficiency, and zero-maintenance requirements indicate a free-piston Stirling cooler or a Stirling-type pulse-tube cooler; the cost requirement indicates a true commercial product (as opposed to the many Stirlings or pulse-tube coolers developed for spaceflight.) While we do not present here a thorough review of all existing commercial offerings, to our knowledge there few, if any, commercially available cryocoolers that meet the above criteria. This may explain, in part, why a self-sustaining cryogenic biostorage freezer has not previously been developed.

3.1. 2S132K cryocooler performance

The 2S132K is a Stirling-type ‘pulse-tube’ (or ‘acoustic-Stirling’) cryocooler in a split configuration, shown in Figure 2. The inertance tube is coiled up inside the compliance tank. For scale, note that the coldtip is approximately 2 inches in diameter. The acoustic power is provided by a balanced twin-motor pressure-wave generator. The air-side cooling is provided by the same standard heat-pipe heatsinks as are used by computer gaming enthusiasts to cool their CPUs.

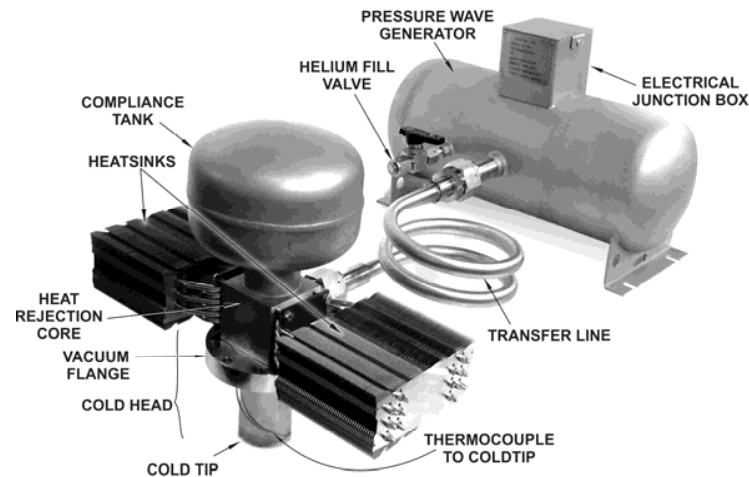


Figure 2. Basic 2S132K cryocooler, with major parts labeled.

Typical performance of the 2S132K is shown in Figure 3. At 77K, when water-cooled, its efficiency is 16.4%; when air-cooled (as in the Fusion application) it is 15.6%. The cooling power in both cases is above 30W. At temperatures more often associated with ‘ultra-low’ freezers, i.e. -80 to -90°C (193 to 183 K) the 2S132K has over 100W of cooling power, suggesting it could be used in that application, too. If it were used in a higher temperature range, however, it could be optimized for better performance in that range.

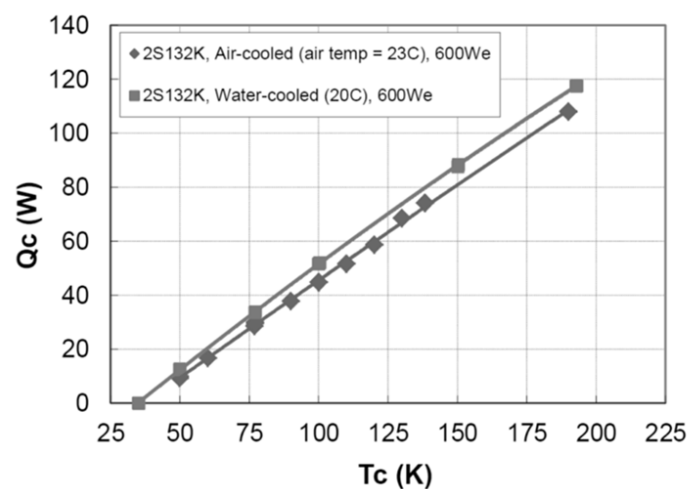


Figure 3. Typical performance of a Fusion 2S132K cryocooler.

4. Fusion system performance

Linear-motor drives are easily modulated with voltage, as opposed to the frequency modulation required with rotary drives [5]. The Fusion control system takes advantage of this and continuously modulates the voltage to the cryocooler, following the load. Thus, rather than operate in a duty-cycle fashion, the Fusion draws a steady, low power when idle. Coupled with the low heat leak enabled by the use of a Dewar (as opposed to a standard freezer cabinet) and the efficient pulse-tube cryocooler,

the resulting power draw of a Fusion system at standard (e.g. EnergyStar) conditions is only 270W, or 6.48 kWh/day. By contrast, the “ultra-low” freezer that is advertised as the most efficient on the market, the Stirling Ultracold SU780XLE, has a published power draw of 6.86 kWh/day—at merely -75°C [4]. This is not to disparage the Stirling Ultracold product, but to highlight the advantage of using the Fusion-style combination of a cryocooler and a storage Dewar. There are still advantages to the standard ultra-low configuration; for applications that don’t benefit from a lower storage temperature, the SU780XLE offers almost twice the sample storage capacity in the same or slightly smaller footprint as the Fusion. This is true in general for round Dewars versus square or rectangular cabinets.

The Fusion product is still in beta testing as of this writing, and detailed data were not available on the air temperature within the Dewar, sample temperatures at various locations, or their history during power outages. However, in its current configuration, the storage temperature is typically -165°C . This temperature can be controlled in part by what cryogen is used in the reservoir and at what pressure. However, the use of a reservoir tank instead of a pool of liquid nitrogen at the bottom of the Dewar does introduce a temperature defect between the cryogenic liquid and the storage space, and so the Fusion product will not maintain samples as cold as the passive nitrogen freezers will. While it may be doubtful that any samples will be adversely affected by the storage temperature in Fusion, one can always argue that a lower temperature will grant a little more hold time in the case of a power outage, or if the lid is accidentally left off for a prolonged period. Thus there may be some users who will continue to prefer the familiar nitrogen freezers, despite the inconvenience.

5. Summary

The Chart MVE Fusion freezer is the first product of its type, offering refrigerated storage at true cryogenic temperatures, without any sacrificial cryogen. It provides an alternative to the existing biostorage products in the marketplace, which are either self-sustaining or cryogenically cold, but not both. It is enabled by the development of a pulse-tube cooler (the 2S132K) with $>15\%$ of Carnot’s efficiency, and over 30W of cooling at 77K, and also designed for industrial mass-production. A summary of the Fusion performance specifications include:

- Sample storage temperature of -165°C
- Steady-state power draw of 6.48 kWh/day
- Storage capacity for 26,000 2-ml sample vials
- 7-day hold time below -140°C in the event of a power outage

5.1. Future development

The success of the first Fusion product in the marketplace may spur the development of similar products with even greater storage capacity. In parallel with this development, there are some interesting challenges presented by self-sustaining cryostorage products that bear investigation and further work. One of these is the issue of ice and frost buildup inside the storage space. In passive nitrogen freezers, there is always a slight positive pressure from the boiling nitrogen to keep moisture-laden air from entering. Many such freezers are configured so that they are refilled with fresh liquid whenever the lid is removed, or a heater is momentarily activated, so that a burst of nitrogen vapor pushes air away. A self-sustaining freezer does not have these advantages, and it will be interesting to see how ice and frost accumulate over long periods without the dry nitrogen vapor to displace the air.

Another issue of interest is the temperature defect between the cryogen and the storage space, and the uniformity of the temperature in the storage space. There are some differences in convection patterns in the Fusion versus the passive nitrogen freezers, and understanding these better could lead to colder, more uniform storage temperature.

It is also worth noting that while this paper makes a case for the cost-effectiveness of the Fusion system for a certain rate of LN2 usage, the market may extend well beyond this narrow demand window. Interest in this product so far appears to suggest that the convenience of eliminating sacrificial cryogens may be worth a premium to many customers.

Acknowledgments

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