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The Future of Cryogenic Storage:

A Comparative Analysis Between Liquid Nitrogen and Mechanical Freezers

WHITE PAPER

Advancements in cryogenic storage technology have far-reaching implications across scientific research, medical applications, and industrial processes. In this piece, we conduct a comparative analysis of two prominent approaches: liquid nitrogen freezers and mechanical cryogenic freezers. By understanding the trade-offs inherent in each method, readers can make informed decisions tailored to their specific storage needs.

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INTRODUCTION

Methods of Cryogenic Storage

For both commercial and research purposes, there are two primary methods to achieve and maintain cryogenic storage temperatures below the crystallization point of water. Let's explore these methods in detail:

Vapor Expansion of Liquid Nitrogen:

- In this method, liquid nitrogen undergoes vapor expansion, transitioning from a liquid to a gas. This process generates cryogenic temperatures.
- To minimize evaporation, liquid nitrogen must be stored in highly insulated containers. Conical dewars, constructed with inner and outer steel shells, maintain a deep vacuum gap for optimal insulation.

Mechanical Refrigeration:

- Mechanical cascade refrigeration systems combine multiple refrigeration cycles, often using exotic blends of refrigerants. These systems operate at different temperatures and are effective for achieving cryogenic conditions.
- The storage chamber in mechanical freezers typically consists of high-insulation materials, such as blown-in foam and vacuum insulation panels (VIP). These layers are sandwiched between steel inner and outer shells.
- The design allows for rectangular storage areas that seamlessly integrate with other lab equipment layouts.

MDF-C2156VANC-PA
8.2 cu. ft. | 231 L

Energy Cost of Production

Nitrogen is produced at air separation plants by high pressure liquefaction of atmospheric air and separation of both nitrogen and oxygen. There is four (4) times more liquid nitrogen produced in this process than liquid oxygen. Since the demand for liquid oxygen far exceeds the demand for liquid nitrogen, much of the nitrogen is released back into the atmosphere,[1] thus wasting energy.

From an energy perspective, under ideal conditions the amount of work to liquify nitrogen is 0.21 kWh/kg.[2] However, typical air liquefication plants are only 25% efficient.[3] As a result, in many cases the cost to produce liquid nitrogen can approach 1kw per kg, not counting the losses due to evaporation.

Losses in Cryogenic Storage Systems

Nitrogen is lost in liquid nitrogen freezers due to the size of the freezer and the ability to access the samples. Most of the nitrogen loss in any liquid nitrogen cryogenic freezer is through the top access opening. Dewar style liquid nitrogen freezers have very small openings and top plugs to minimize heat gain. This design, however, severely limits the number of samples that can be stored, as the rack must both hang from the lip and fit through the small opening. Additional heat gain is also created through the conduction of heat energy through the metal used to make the handles on the racks. The largest capacity for dewar-type liquid nitrogen cryogenic freezers is around 6000 x 2 ml samples.

Securing more liquid nitrogen sample storage requires larger storage vessels. Larger storage vessels require a larger opening at the top to access more inventory racks. As a result, the opening gets bigger as the capacity increases and the static liquid nitrogen loss increases. Compounding the issue of nitrogen use, as more people use the freezer, even more nitrogen is lost because the top is opened, and samples are added or removed. This additional nitrogen loss can be difficult to determine since there are so many variables involved including thermal capacity of the product being added (how warm it is), integrity of the vacuum insulation, ambient temperatures, how long the lid is open, etc. Liquid nitrogen is also lost every time the freezer is refilled with liquid nitrogen from a source tank. Transfer hoses and hardware between the interior of the source tank and the interior of the freezer boil away nitrogen until it is cooled down from room temperature to liquid nitrogen temperature. In sum there are four sources of loss of liquid nitrogen in cryogenic storage systems. The larger the system, the larger the nitrogen loss.

Cost of Ownership

All the costs of nitrogen production, delivery, and storage are generally passed onto the end user. When all the costs are totaled, mechanical cryogenic storage can become an obvious choice for long term storage at cryogenic temperatures. In fact, one large global pharmaceutical customer (Fig. 1), saw a payback on their investment in a mechanical cryogenic storage freezer in less than a year.

Fig. 1

Case Study

- Annual LN_2 usage to operate 1-LN_2 cryo-freezer was around 433,000 CF
- Cost of LN_2 (2-year Avg) = $17,563
- $300 of taxes delivery charges x 2022 fillings per year - $6,300
- Tank rental / fees - $1,019 month - $12,228 year
- **Annual cost of LN_2 services - $36,091**
- **Cost of electric for new freezer - $680.00 annually - Our site is 100% renewable**
- **Overall Savings - ~$35,411**
- **Cost of freezer = $28,258 (less than one year payback on investment)**
  - No unsustainable LN_2 supply chain
  - Freezer always on epower

Liquid Nitrogen Usage

The primary consumable cost of running a liquid nitrogen storage system is the consumption of liquid nitrogen due to thermal loss. Liquid nitrogen consumption will increase as more product is added if the product must be pulled down to cryogenic temperatures. Considering that cold is the absence of heat energy, the liquid nitrogen will need to change state from a liquid to a gas to remove the heat energy of the product being added. As shown in Fig. 1, in an average cryogenic freezer, over 400,000 cubic feet of nitrogen will be consumed in a year, which translates to an annual cost of approximately $9000. This number will vary depending on several factors, including usage, the age of the LN_2 system due to insulation degradation over time, and the cost of liquid nitrogen from the supplier which in recent years has increased dramatically, even though liquid nitrogen suppliers charge up to 40 times the cost to produce it.[4] Furthermore, due to the effects of differential pressure, 10% of the liquid nitrogen in a cylinder is typically inaccessible. This means that users could be paying for 10% of supply they can't utilize.[5] Additionally, liquid nitrogen in storage will off-gas, meaning the stored liquid nitrogen will constantly be converting to a gas which needs to be released to prevent dangerous pressurization on the cylinder. Off-gassing can consume up to 20% of the purchased supply.[5]

PHC Corporation of North America, a subsidiary of PHC Holdings Corporation, Tokyo, Japan

Tax and Delivery Charges

Often, the cost of liquid nitrogen delivery is related to how far away the customer is located from a liquid air processing plant. Typically, transportation to the site is performed via specially designed cryogenic liquid tank trailers. Liquid air production facilities are generally located in largely industrialized areas where heavy industry customers are concentrated, so often LN_2 must be transported hundreds of miles to reach the site where it is needed for biological storage. Liquid nitrogen is often transported to local suppliers where it is loaded into smaller storage containers. This additional handling can increase delivery charges. If a facility doesn't have bulk storage capabilities, delivery charges and taxes can add up quickly.

Tank Rental

Although a facility's primary liquid nitrogen storage tank may be automated, dewars are still needed to transport liquid nitrogen from the loading area to the storage tank to supply the equipment. Many facilities rent storage dewars and their condition which is difficult to assess, will affect their capacity and storage of liquid nitrogen. Furthermore, these tanks need to be maintained regularly which adds to the cost.[4]

Hidden Costs

Supply issues can create many challenges with liquid nitrogen delivery. Deliveries can be delayed for many reasons including drivers not available due to illness, truck breakdowns, or missed deliveries if the customer is at the end of a long delivery run. Customers can also be subject to long-term delivery contracts, preventing them from switching if a more cost-effective alternative is discovered.[5] Considering all the accumulated charges and costs, the cost of LN_2 storage can really add up. This doesn't even consider the initial cost of the liquid nitrogen storage system itself.

Liquid Nitrogen Dangers

Beyond the cost of maintaining liquid nitrogen storage, there are a host of dangers to be considered.

Asphyxiation is a primary concern. Although nitrogen is not poisonous, air is about 78% nitrogen, if sufficient liquid nitrogen is vaporized to reduce the oxygen percentage to below 19.5%, users are at risk of oxygen deprivation. The liquid-to-gas expansion ratio of nitrogen is 1:694,[6] which means liquid nitrogen boils to fill a volume with nitrogen gas very quickly. Rapid venting can cause near-total displacement of normal air, leading to a local concentration of about 100% nitrogen. This is one of the reasons that it is not advisable to carry liquid nitrogen in an elevator or store it in a cold room. Confined spaces increase the potential danger.[7] For this reason, it is advisable to have oxygen detectors wherever liquid nitrogen is stored,[8] further adding to the cost as sensors typically cost several thousand dollars.[9]

Liquid nitrogen can cause terrible burns or death of living tissue caused by the extreme cold. Hand protection and goggles (not safety glasses) are to be worn when dispensing and handling liquid nitrogen. When handling large quantities, a full-length apron will minimize the chance of a spill going into someone's shoes, where it might destroy flesh before someone can remove their shoes and socks.[7]

Cryogenic containers are equipped with pressure relief devices to control internal pressure. Under normal conditions, these containers will periodically vent the product. These containers must be properly maintained to prevent the container from exploding.[10]

Liquid nitrogen containers may accumulate oxygen that is condensed from the air. As the nitrogen evaporates, there is a risk of violent oxidation of organic matter,[11] even materials which are ordinarily nonflammable.

LIQUID NITROGEN ALTERNATIVE

Mechanical Cryogenic Storage

An alternative method to liquid nitrogen storage is mechanical cryogenic storage. These systems can reach temperatures as low as -150˚C, well below the glass transition temperature required for cryogenic storage.

-150˚C mechanical cryogenic freezers eliminate the hazardous operating conditions and frequent maintenance and cost requirements associated with LN_2 storage.[7] They also minimize the possibility of cross contamination between multiple samples since air phase cooling is the method utilized in mechanical cryogenic freezers.[12] The dangers associated with liquid phase cooling are removed. these freezers deliver a uniform temperature of +/-5˚C without the worry of handling liquid nitrogen. Using a mechanical cryogenic freezer is simple: plug the unit into an electrical outlet, and let it do the rest. The only cost is electricity, far less than that of liquid nitrogen at about $700 per year (Fig. 1). These units are almost maintenance free and only need periodic cleaning of the filter to keep them operating in top condition.

For added protection of irreplaceable inventory, mechanical cryogenic freezers offer an LN_2 back-up system to maintain cryogenic temperatures in the unlikely event of a warm-up or power loss.

CONCLUSION

When it comes to cryogenic storage choices for biological specimens, the options come down to deciding between mechanical storage or liquid nitrogen. Although each has their advantages, it is important to weigh the consumable cost of the resources used whether it be liquid nitrogen or electricity to make an accurate assessment of which method is more economical. Mechanical freezers are simply plugged into a standard 220V electrical outlet to provide uniform -150˚C storage. Liquid nitrogen users must consider the cost to purchase a continuous supply of liquid nitrogen, delivery, storage rental and transfer of liquid nitrogen waiting to be used. This cost also includes the constant movement and upkeep costs of storage containers around the facility to ensure an adequate supply. Further considerations of safety related to handling of liquid nitrogen are minimized. In many cases, mechanical refrigeration can be the most economical, time efficient, and safe.

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