



Cryostorage tank failures: temperature and volume loss over time after induced failure by removal of insulative vacuum

Kimball O. Pomeroy¹ · Michael L. Reed² · Brian LoManto¹ · Stanley G. Harris³ · W. Brent Hazelrigg⁴ · Dawn A. Kelk⁵

Received: 14 June 2019 / Accepted: 25 September 2019 / Published online: 24 October 2019
© Springer Science+Business Media, LLC, part of Springer Nature 2019

Abstract

Purpose To determine liquid nitrogen evaporation rates of intact liquid nitrogen storage tanks and tanks with their vacuum removed.

Methods Donated storage tank performance (LN₂ evaporation) was evaluated before and after induced vacuum failure. Vacuum of each tank was removed by drilling through the vacuum port. Temperature probes were placed 2 in. below the bottom of the styrofoam cap/plug, and tanks were weighed every 3 h. Evaporation rate and time from failure to the critical temperature was determined.

Result Storage tanks with failed vacuum have a much higher evaporation rate than those with intact vacuum; evaporation rates increased dramatically within 3 to 6 h in the smaller tanks, and time to complete depletion varied according to starting LN₂ volume. Tanks with storage racks/specimens may have altered evaporation profiles compared to tanks without. Locating temperature probes 2 in. below the styrofoam cap/plug suggests that for most applications, alarms would sound approximately 1 h prior to reaching the critical warming temperature, approximately –130 °C. External signs of vacuum loss were dramatic: vapor, frost, and audible movement of air.

Conclusion For the first time, we have data on how liquid nitrogen storage tanks behave when their vacuum is removed. These findings are conservative; each lab must consider starting volume, tank size/capacity, function (storage or shipping), age, and pre-existing evaporation behavior in order to develop an emergency response to critical tank failure. Times to complete failure/evaporation and critical warming temperature after vacuum loss are different; these data should be considered when evaluating tank alarm systems.

Keywords Liquid nitrogen tank · Vacuum failure · Cryopreservation · Cryostorage

Introduction

The liquid nitrogen Dewar was named for its inventor, James Dewar, in 1892. Today, the connotation most often used for

this device is the liquid nitrogen (LN₂) tank, found in virtually every reproductive (human and nonhuman) laboratory in the world in one of several designs. The design of the modern LN₂ tank is descended from the first practical semen storage tank developed as a joint venture between the American Breeders Service and the Linde Division of the American Cyanamid Company, in 1956 [1]. Up until this time, it was more common for livestock breeders to use fresh or cooled extended semen. After semen cryopreservation became reliable [2], the cryopreserved semen was stored with dry ice—the LN₂ storage systems available to researchers were unreliable and required frequent management, e.g., close monitoring and frequent filling.

The design of the modern LN₂ tank has not changed dramatically from the design founded by the Linde Division; the inner tank (which holds the liquid gas and cryopreserved specimens) is suspended inside an outer shell and surrounded by insulation and a vacuum space.

✉ Kimball O. Pomeroy
kim@theworldeggbank.com

¹ The World Egg Bank, 7227 North 16th Street, Suite 160, Phoenix, AZ 85020, USA

² Fertility Center of New Mexico, 201 Cedar Street SE, Suite S1-20, Albuquerque, NM 87106, USA

³ Kaiser Permanente Center for Reproductive Health, 39141 Civic Center Drive, Suite 350, Fremont, CA 94538, USA

⁴ Repro Tech, Ltd., 18 South Ninth Street, Suite 201, Columbia, MO 65201, USA

⁵ Yale Fertility Center, 150 Sargent Drive, New Haven, CT 06511, USA

Aluminum is the most common metal used for construction of small-capacity tanks, steel for construction of large-capacity tanks.

Storage tanks are designed to allow liquid gases to be held in the inner tank with minimal exposure to heat; hence, the gases can be maintained in liquid form at temperatures, depending on the gas, nearing $-200\text{ }^{\circ}\text{C}$ and colder. Liquid nitrogen has a working temperature of approximately $-196\text{ }^{\circ}\text{C}$, compared to the temperature of dry ice at approximately $-79\text{ }^{\circ}\text{C}$. LN2 tanks also maintain a relative static head space (not liquid) composed of gas vapor with a temperature close to that of the liquid state, even as the volume of liquid gas decreases. This design helps to maintain a relative stable internal dynamic between the volume of gas and gas vapor. Tanks are not pressurized, and there is loss of vapor through the styrofoam cap/plug of the tank. This results in slow but constant evaporation of liquid nitrogen. Routine maintenance of LN2 storage tanks and filling schedules vary from laboratory to laboratory and may involve daily or weekly inspections, monitoring of tank weight, liquid gas levels/volumes, and/or head space vapor temperatures. Maintenance, e.g., monitoring and filling, may be manual or automated. Tanks have not, in the past, been required to have an emergency call-out alarm system. Recently, guidelines for the proper validation of new tanks and alarms and quality control guidelines have been proposed [3, 4].

The designs of LN2 tanks—size, shape, construction materials, welds, and sealants—do not absolutely prevent loss of structural integrity. Metal fatigue and structural stresses can result in a gradual loss of vacuum and a gradual increased use of liquid nitrogen. Gradual changes in liquid nitrogen levels are normal and expected, and manufacturers of LN2 tanks declare that eventually, all tanks will fail. One of the weakest areas of small-capacity tanks are the welds that join the neck of the tank to the inner chamber and to the top of the outer chamber (Fig. 1). The entire weight of the tank, often around 75 to 100 pounds, is suspended by this neck [4]. These neck welds are not found in large-capacity tanks.

Catastrophic tank failure, due to sudden unpredictable loss of vacuum between the inner and outer containers, can result in the rapid loss of liquid nitrogen and rapid warming of the stored contents as the liquid nitrogen evaporates. Specimens that have been held below a critical glass transition temperature, about $-130\text{ }^{\circ}\text{C}$, could be exposed to warmer temperatures with irreversible damage to cellular integrity unless steps are taken to safeguard the specimens.

Anecdotal accounts of catastrophic LN2 tank vacuum loss have been discussed among human and animal reproductive scientists. Descriptions include the sudden development of cold spots, frost, and sweating of the tanks as external

humidity builds on the outside of the tank. Visible vapor plumes coming from the tank, and on some occasions, sounds coming from the tank, and of course, discovering that a tank has little or no liquid nitrogen the next day, or after several days have passed have also been reported. Even the implosion of the inner-tank around the specimens, such that they are impossible to remove, has been reported.

Until recently [5], there have been no detailed reports in the literature or any studies on catastrophic vacuum loss and the resultant changes in evaporation rates of the liquid nitrogen or temperatures inside the inner chamber of the tank. How long tanks can maintain a suitable temperature after vacuum failure, how much time we have from detection failure until the tank reaches a critical temperature, or even what affect vacuum failure will have on the characteristics of a tank are not known.

This study was developed in response to a call for development of actionable data [6] that can (1) demonstrate routine liquid nitrogen loss in storage tanks of different design (small clinical to large commercial storage) by monitoring weight and internal vapor temperature and (2) document the changes in weight and internal vapor temperature as a result of an induced breach in the outer tank housing to create a sudden loss of vacuum in each of these same tanks.

This study will help to characterize LN2 tank behavior after catastrophic vacuum loss, according to tank size—evaporation rates and changes in temperature—as monitored by tank weight and calibrated probes suspended below the neck of the tank—and to document observations on external events, e.g., frost, sweating, vapor plumes, and so on. Additionally, the goal is to provide actionable data—rate of gas volume loss, rate of head space temperature change—to allow each individual laboratory to refine an emergency response protocol for just such an event.

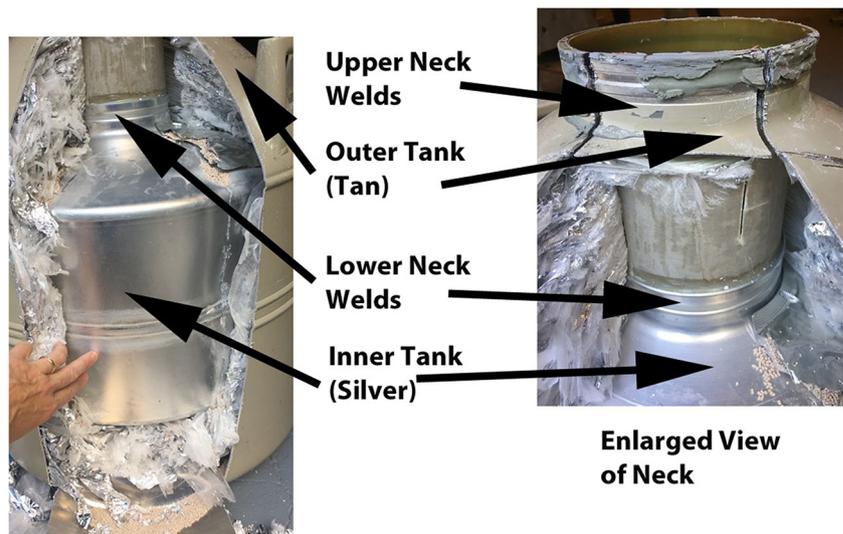
Materials and methods

This study was developed as a multicenter investigation into cryogenic storage tank performance under routine and vacuum loss conditions. The tanks used for this study were donated, as use of new and multiple tanks was prohibitive; no inclusion or exclusion criteria applied to use of any tank donated for this study. Characteristics of these tanks are described in Table 1.

No human subjects participated, and no patient PHI data were used or mined. Materials, monitoring devices, and cryostorage tanks did not directly impact patient care; therefore, Internal Review Board approval was not solicited.

A recognized limitation to this study was inclusion of tanks that may have been previously suspected of or had demonstrated increased LN2 evaporation. Repeated

Fig. 1 View of a cut open MVE 47/11 liquid nitrogen tank. Note that the weight of the entire tank is supported by the neck which is glued to the outer and inner tank



evaluations of each tank were not performed, and no comparative statistics were performed between cryostorage tank performance; data are descriptive, with the intent to provide foundation data for understanding performance characteristics of cryostorage tank vacuum failure.

The same study protocol was used by all participants to facilitate consistency, recognizing also that different tanks might have different performance characteristics before and after induced vacuum loss; variables that could not be controlled included age of the tanks and prior performance history of each tank.

The study consisted of three parts, aimed to determine the static evaporation rate of (1) full tanks, (2) nearly empty tanks, and (3) nearly empty tanks whose vacuum has been compromised by drilling through the vacuum port. These rates were compared to manufacturer’s published rates where available. Tanks were monitored daily or hourly for overall weight and temperature. To convert between imperial and metric, and weight and volume, the standard conversions for pounds to grams were used (453.6 g/lb.), followed by conversion to volume using the density of LN₂ (0.807 g/mL). Additional experiments were

performed to ascertain the time needed to respond to a large-capacity tank and a dry-nitrogen shipper following vacuum loss.

Determining static evaporation rate of liquid nitrogen (LN₂) in intact tanks

Each cryogenic tank (except for the large-capacity Chart model 1840 tank, see below) was fitted with a temperature probe that was connected to an Onset Hobo UX100-014M high-capacity data logger. Placement of the probe tip was extended to precisely 2 in. below the internal surface of the plug for the small-capacity tanks, and at the level of the top specimen (about 12 cm below the bottom of the lid) for the large-capacity tank.

The empty weight of the tanks was measured prior to filling to the top of the rim, such that excess liquid nitrogen would spill out as the styrofoam plug was inserted. The filled tanks were weighed, and this data point became *t*₀. To establish the static daily evaporation rate in a full tank, tank weight was recorded for a total of 7 days. Only one tank was fitted with an

Table 1 Summary of some of the key results in the study of the 6 tanks

	Tank 1	Tank 2	Tank 3	Tank 4	Large	Shipper
Tank	Union Carbide	MVE	MVE	MVE	MVE	MVE
Model	LR-31	XC-47/11	XC-47/11	XC-47/11	XLC 1840	SC4/3V
Volume (L)	30	47	47	47	669	3.4
Static hold (days)	90	76	76	76	53.5	22.5
Manufacturer’s static evaporation rate (L/day)	0.34	0.39	0.39	0.39	12.5	0.15
Measured evaporation rate (L/day)	0.845	0.49	ND	18.2	22.8	0.15
After puncture evaporation rate (L/day)	38.9	19.1	80	ND	31.4	11.3
Other	Old	Full rack	Failed tank	Failing tank		

inventory rack (tank 3). The others consisted of tanks without racks.

In order to determine if there were any differences between the evaporation rate of a full tank and a nearly empty tank, a comparison was made by removing LN₂ to a depth of 6 in. and repeating the weight loss measurements. It is important to note that these tanks were donated due to either suspected failure or potential imminent failure due to age of the tank.

Determining static evaporation rate of liquid nitrogen in a vacuum-compromised, small-capacity system

In order to decrease the amount of time for a tank to go from full to empty, the measurements of vacuum depletion were performed on two tanks that were nearly empty—an MVE 47/11 and an old, discontinued Union Carbide LR-31. Liquid nitrogen was removed so as to leave 6 in. in each tank. As in the previous experiments, storage vessels were measured in the same way with the exception that the insulative vacuum barrier was compromised by either drilling a 1/8" hole into the vacuum sealing joint (VSJ) or hammering a similar sized nail through the VSJ until air could be heard entering the void. Because evaporation rates increased dramatically with the loss of vacuum, the weight of the tank and LN₂ contents were recorded hourly until empty.

A third tank, tank 3, was an MVE 47/11 storage tank fitted with an inventory rack system. It was the only tank where the evaporation rate after the release of the vacuum was followed from full to empty.

Determining evaporation rate of liquid nitrogen in a vacuum-compromised, large-capacity system

A large-capacity system (Chart Industries MVE model 1840) with LN₂ capacity of greater than 600 L was tested for evaporation rates following vacuum loss in a similar process as the smaller, routine storage tanks. Weighing a large capacity system presents several logistical hurdles including the availability of a scale with enough capacity to measure the total weight of a 600-L system and the ability to move it to and from a scale. The experimental design was similar to that used with the smaller tanks except that LN₂ level monitoring was manually performed using a graduated dip stick. A Vaisala HMT140 high-capacity data logger was used to record temperatures. Temperature measures were obtained by placing a temperature probe at the normal monitoring position just above the minimum liquid level previously validated to produce a temperature of -185°C , the system alarm threshold. The nitrogen level in the tank was set near the level that would cause an alarm. The measurements began once the temperature alarm sounded.

Determining evaporation rate of liquid nitrogen in a vacuum compromised dry shipper

A small dry shipper (MVE SC4/3E) was filled with liquid nitrogen as per the manufacturer's suggested method. Two hours prior to testing, the shipper was topped with LN₂ every 15 min to ensure fully charged status. It was then fit with two temperature probes, one 2 in. from the plug and the other 6 in. from the bottom. The weight of the tank was taken every hour until it was the same weight as the empty tank. Next, the tank was refilled as above, and the vacuum was released by drilling the VSJ with a 1/8" drill bit. The temperature was recorded every minute and the weight was recorded every hour until the tank reached room temperature.

Results

Determining static evaporation rate of liquid nitrogen in a vacuum-compromised, small-capacity system

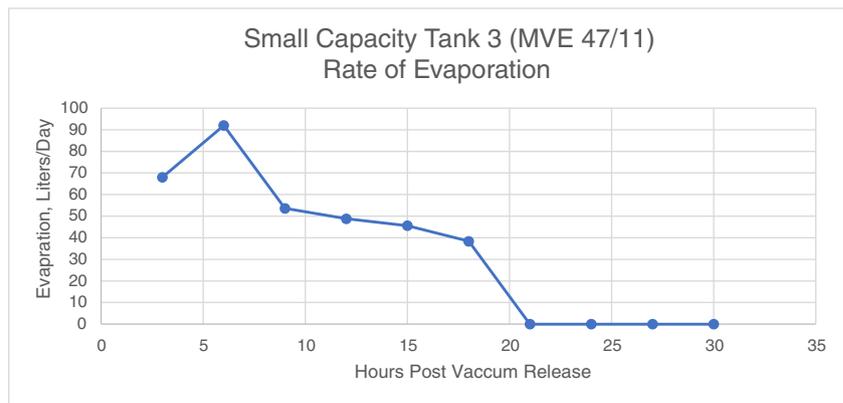
The most dramatic result from the small tanks was that the evaporation rate went from less than a liter per day to at least 40 L per day within the first 6 h after drilling to remove the vacuum (Table 1). This rate slowly declined as the tank's liquid nitrogen became depleted. The smaller Union Carbide tank lasted less than 1 day after vacuum loss. Tank 2 lasted about 18 h to complete evaporation, as did tank 3 (about 18 h to complete evaporation), despite an initially higher evaporation rate in tank 3 compared to tank 2. A difference noted between tanks 2 and 3 is that tank 3 was fit with an inventory rack system. The average evaporation rate (liters/hour) varies slightly as the tank is depleted of liquid nitrogen (see Fig. 2). Evaporation rate starts out high and then decreases to zero when the tank is depleted of liquid nitrogen. The formation of frost near the cap and sweating was observed within 3 h of vacuum loss (see Fig. 3).

Temperature probes were placed near the top (within 2") and near the location of where the specimens would be located in most tanks. In the smallest volume tank (LR-31; 30 L), the critical temperature of -130°C in the lower probe was reached about 8 h post-drilling. In the slightly larger MVE 47/11's, the critical temperature was reached after almost 27.6 h in tank 2, 20 h in tank 3 (with a rack), and it took over 35 h for the non-drilled but failing tank 4.

In relationship to nitrogen depletion, the critical temperature was quickly reached shortly after all of the liquid nitrogen had evaporated (see Fig. 4). In tank 2, the critical temperature was reached within 2 h of empty. In the damaged but intact tank 4, this occurred within 1 h.

In order to understand how these tanks are manufactured, we cut open one of these tanks (tank 3) to examine the connection of the neck to the inner and outer tanks (see Fig. 1).

Fig. 2 Liquid nitrogen evaporation rates of a small-capacity tank. The manufacturer’s stated evaporation rate was 0.39 L/day. Three hours after vacuum failure, the tank’s evaporation rate was 70 L/day, reaching a maximum evaporation rate of 90 L/day 6 h post-failure



Determining static evaporation rate of liquid nitrogen in a vacuum-compromised, large-capacity system

In the large, almost 700-L storage tank, the time from the alarm until the specimens would reach the critical temperature of $-130\text{ }^{\circ}\text{C}$ was about 15 h. It took a total of almost 31 h from alarm until liquid nitrogen depletion (see Fig. 5). Interestingly, the post-drilled evaporation rate of 31.4 L/day was only about 3 times that of the manufacturer’s listed pre-drilled evaporation rate of 12.5 L/day. Formation of frost on the tank’s lid was also observed (Fig. 3).

Static evaporation rate of liquid nitrogen in a vacuum-compromised dry shipper

Data for the dry shipper can be seen in Fig. 6. With no vacuum, the tank went from an evaporation rate of 0.15 L/day to over 11 L/day. The static hold time went from 22.5

days to less than 1 day. The tank temperature was above the critical temperature about 6 h after failure.

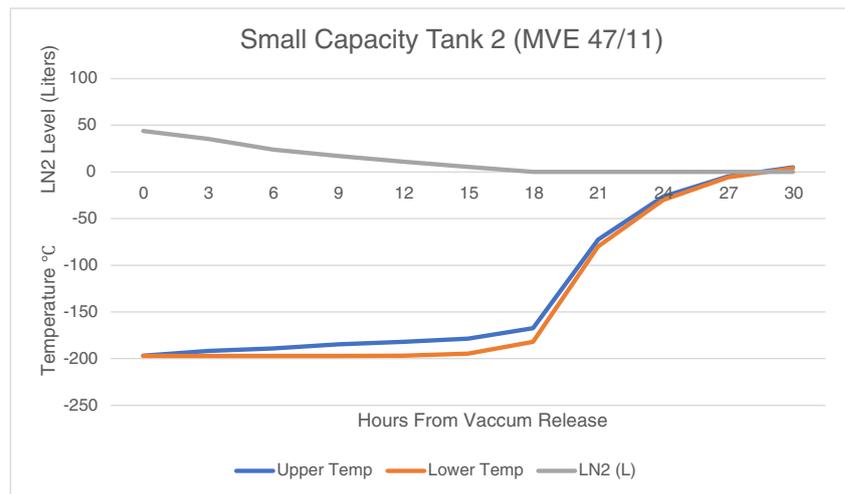
Discussion

Two recent, well-publicized failures in liquid nitrogen storage tanks have stimulated those storing human tissues to reexamine the safety of these tissues in tanks that were ostensibly designed for the storage of bull semen. In light of these failures, it is also prudent to consider the magnitude of responsibility a facility faces by undertaking cryostorage [7]. To date, there has been almost nothing published on the cause of nitrogen storage tank failure or the change in their performance when they fail. In this study, the vacuum insulation of donated storage tanks was defeated by drilling a hole through the vacuum port and allowing the vacuum to escape. The rate of liquid nitrogen evaporation was measured before and after

Fig. 3 One of the first signs of a failed tank—frost and sweating on the outside of the tank. This photo is of a small-capacity MVE 47/11 and a large capacity MVE 1840



Fig. 4 Graph of liquid nitrogen volume (green line) and temperature of the upper (blue line) and lower (red line) probes



vacuum removal in three types of tanks: small-capacity storage, large-capacity storage, and a dry shipper.

There are recognized limitations to this study, including the fact that the donated tanks varied by age, and included some tanks with pre-existing higher rates of LN2 evaporation, categorized as failing tanks. The authors also recognize that anecdotal observations or speculation may not be proved or disproved by this study; but many of these anecdotes proved true; rapid and unpredictable loss of LN2, individual performance characteristics of the tanks, and external indicators of failure, e.g., frost, sweating, audible movement of air via the site of damage as examples.

Regardless, the data provided by this study are unique and should be viewed conservatively, used as foundation data for further exploration by individual clinics, as circumstances allow.

All tanks, except the large-capacity shipper, had an initial manufacturer's evaporation rate of less than 1 L per day. When the actual evaporation rate was compared to the manufacturer's evaporation rate, it was slightly higher in all tanks. This was most likely due to the fact that these tanks were

either tanks that had been in service for many years or a failure in the tank was expected due to progressive increase in the liquid nitrogen evaporation rate over time. After the vacuum was released by drilling out the vacuum port, the liquid nitrogen evaporation rate increased dramatically to 30 to 40 L per day in the small and large capacity tanks and to over 12 L in the rather small nitrogen shippers. This rate of evaporation means that the small liquid nitrogen tanks would contain nitrogen for a little over 24 h after vacuum lost occurred and for less than 6 h with the dry shipper.

Of note, there was a difference in evaporation rates post-failure between two very similar tanks, tanks 2 and 3. Tank 3 had a much higher mean evaporation rate (see Table 1). Both tanks were model MVE 47/11, but note that tank 3 had been fit with a complete storage rack system: cannisters, canes, and goblets to simulate a full inventory. Base weight of this tank (empty) was 33.6 lbs and 44.8 lbs with the rack system and 122.8 lbs after LN2 filling; the tank was described as being fully functional prior to induced vacuum failure and manufactured in 1990 (5). The additional mass of the rack system—and the concomitant displacement of LN2,

Fig. 5 Liquid nitrogen usage (blue line) and temperature (red line) of a large-capacity MVE 1840 that has been drilled to release its vacuum

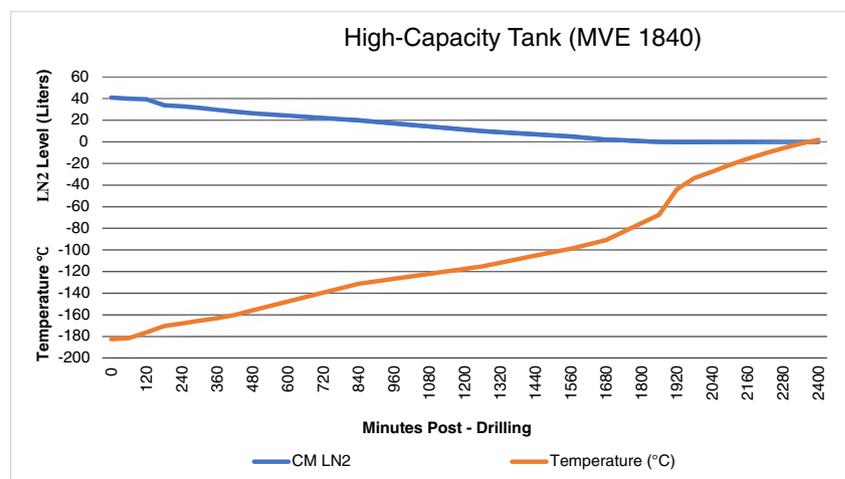
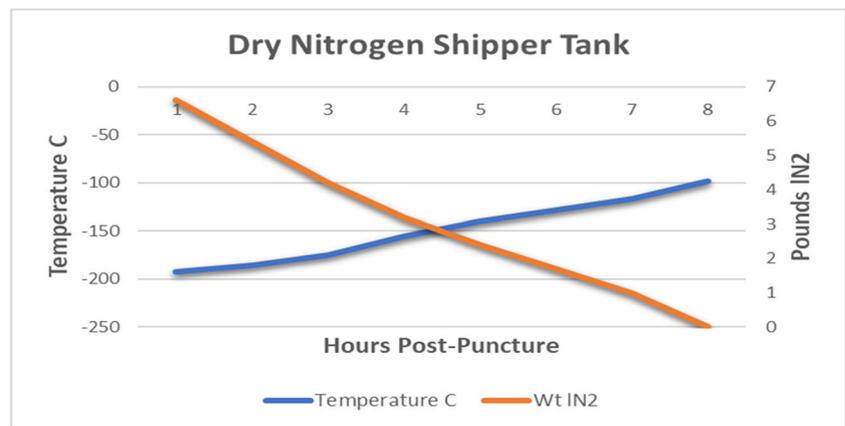


Fig. 6 Temperature (blue line) and liquid nitrogen usage (orange line) for a dry shipper tank whose vacuum has been released by drilling of the vacuum port



effectively reduced the amount of LN2 in tank 3—and may have influenced tank 3 initial and mean evaporation rates. This is a critical finding and speculation that requires more testing, even though time to complete depletion of LN2 in tank 3 was similar to tank 2.

We also observed that as long as there was some liquid nitrogen in the tanks, the temperature near the tissue would remain below the critical glass transition temperature of about $-130\text{ }^{\circ}\text{C}$. Once the liquid nitrogen was gone though, the temperature would quickly rise to room temperature within about 90 min (see Fig. 4). Even temperatures near the top of the tank changed very slowly after a vacuum breach. This has critical implications for how one should set up the probes that trigger an alarm. There is at least one manufacturer that sells a temperature alarm probe for cryotanks that is programmed to alarm when that probe gets to the temperature of $-150\text{ }^{\circ}\text{C}$. Our study indicates that for most applications of this alarm where it is placed about 2 in. below the styrofoam plug, the alarm would sound with only about 1.1 h (see Fig. 4, blue line) for a response before the specimens would be in danger of devitrification. For many clinics, this may not allow enough time to drive to the laboratory and rescue the specimens.

Though not evaluated in this study, a liquid level alarm or other mechanism, e.g., monitoring the weight of a tank, may be more effective than a temperature alarm, but one should thoroughly test any alarm system to failure in order to ensure that it will allow enough response time for a tank that fails. Our study indicates that if one could detect the early increases in nitrogen evaporation either with a nitrogen level alarm or a device that could measure the weight of the tanks, one would have about 18 h of response time (see Fig. 4)—plenty to handle most emergencies as long as a spare tank with liquid nitrogen was available. At least one temperature probe that is located close to the depth of the actual specimens should be used so as to be able to prove that specimens have not been exposed to sub-optimal temperatures that would allow for devitrification.

It is also important to note that dry shippers have a relatively short holding time due to the small volume of liquid nitrogen that they store (about 3.4 L). A loss of vacuum in these could result in the entire tank going dry within 5 or 6 h. One of the authors (KP) observed an incident where a brand-new, dry shipper that was shipped with tissue to another clinic only a few hundred miles away. When the tank arrived, it was warm and dry. The tank had failed, and the valuable tissues were not viable. When this new tank was tested, it was found to have an excessive nitrogen evaporation rate, most likely due to poor manufacturing.

In summary, when a leak occurs in a full, small-capacity tank, one has about 18 h in which to detect the failure and rescue the tissue. This assumes that the tanks are being monitored so that they can detect the increased evaporation rate that occurs in the first 3 h. A temperature probe located near the top of the tank appears to be inadequate for the rapid detection of a failing tank. One needs a system that will either detect this rapid change in evaporation rate or this rapid increase in nitrogen consumption [8]. Regardless, the entire system—tank, probe, and alarm—should be tested to failure to determine and ensure an adequate response time. Small-capacity tanks are very effective. So much so, that they can maintain a temperature below the critical temperature of the glass transition temperature as long as any liquid nitrogen remains in the tank. Hopefully, this study will provide much needed data to assist manufacturers to produce safer tanks and to improve working laboratory protocols so as to avoid similar incidents of embryo and ova loss as reported [9].

Acknowledgements A special thanks to those that donated tanks to this study: The World Egg Bank, Colorado State University's Animal Reproduction Laboratory, ReproTech, Ltd, Yale Fertility Center, and Kaiser Permanente Center for Reproductive Health.

Authors' contribution All authors contributed to the study conception and design and contributed to material preparation and data collection. All authors contributed to data analysis, with final review by KOP. All authors contributed to and had opportunity to comment on the original version of the manuscript.

Compliance with ethical standards

Conflict of interest There were no conflicts of interest reported by the authors, and no compensation was received by the authors for participation in this project. No commercial, State or Federal funding was utilized in this study; materials, monitoring devices, and tanks were available in-house or were donated for the purposes described in this manuscript.

References

1. Foote RH. The history of artificial insemination: selected notes and notables. *J Anim Sci.* 2002;80:1–10.
2. Polge C, Smith AU, Parkes AS. Revival of spermatozoa after vitrification and dehydration at low temperatures. *Nature.* 1949;164(666):70.
3. Pomeroy KO, Marcon M. Reproductive tissue storage: Quality control and management/inventory software. *Semin Reprod Med.* 2018;36:280–8.
4. Schiewe MC, Freeman M, Whitney JB, VerMilyea MD, Jones A, Aguirre M, et al. Comprehensive assessment of cryogenic storage risk and quality management concerns: best practice guidelines for ART labs. *J Assist Reprod Genet.* 2019;36:5–14.
5. Kelk DA, Liu Y, Nichols-Burns S, Lo J, Reed M, Pomeroy K. Analysis of a simulated liquid nitrogen storage tank failure. *Fertil Steril.* 2018;110(Suppl):e18–9.
6. Pomeroy KO. Liquid nitrogen storage tank failure: can we improve the current system? *Fert Steril Dialog.* 2018; <https://www.fertsterdialog.com/users/16110-fertility-and-sterility/posts/33372-pomeroy-consider-this>. Accessed 21 Oct 2019.
7. Moutos CP, Lahham R, Phelps JY. Cryostorage failures: a medico-legal review. *J Assist Reprod Genet.* 2019;36:1041–8.
8. Schiewe MC, Ochoa T, Whitney JB, Zozula S. Operational and performance qualification of 35 liter cryostorage Dewar tanks by weight measurement-fluid level correlations. *Fertil Steril.* 2019;111(Suppl):e29.
9. Alikani M. Cryostorage of human gametes and embryos: a reckoning. *Reprod BioMed Online.* 2018;37:1–3.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.