Detecting LN2 Tank Failure with a Digital Scale Alarm Monitoring System
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Abstract

Cryogenic tanks are insulated, vacuum-sealed pressure vessels widely used for storing live biological specimens including human reproductive cells and embryos. These samples are invaluable and irreplaceable, so it is important that the tank is kept at temperatures below -135°C. Liquid nitrogen is the most popular cryogenic fluid used to keep tanks cold; however, heat transfer, imperfect vacuum seals, and liquid tank venting are all factors that lead to liquid nitrogen depletion. Thus, it is imperative that cryogenic tanks are refilled periodically to replenish liquid nitrogen levels to prevent tank failure. In order to safeguard against failure, monitoring systems for storage tanks are essential. Liquid level monitoring systems currently exist but are primarily used for threshold monitoring. There is an unmet need in the cryogenic storage market for a system that warns of failures in advance rather than simply reporting when they occur. Because there is a direct relationship between the weight and the level of liquid nitrogen within a tank, an improved method to monitor liquid nitrogen tanks would be to measure the change in weight over time. The design team is tasked with developing a weight-based monitoring system for the client, Dr. Jeffrey Jones, whose clinic uses cryogenic tanks for storing biological specimens in liquid nitrogen. The monitoring system should continuously monitor the weight of the tank, log data, and send warnings regarding critical liquid levels, excessive leakage, and potential failures. The team plans to develop a "smart" system to detect external events to the storage unit (such as lid removal, LN2 refill, etc.) by analyzing patterns in the change of weight and temperature. This paper discusses the current state of liquid nitrogen monitoring, the motivation for building this weight-based system, and how this alternative design will help reduce the frequency of small cryogenic tank failures.

Table of Contents

1. Introduction

1.1 Motivation

The use of low temperatures in medicine and biological research has been present since antiquity; one of the more common applications in the modern age is the practice of cryopreservation, which utilizes low temperatures to preserve biological samples. Technology to cryopreserve and store human reproductive tissue has been used for over 40 years, which includes the use of liquefied gases to produce low temperature environments. This is most commonly achieved with liquid nitrogen (LN2) due to several useful properties; it is compact, easily transported, and has the ability to maintain temperatures around -196 °C, far below the freezing point of water [1]. LN2 is commonly used in cryogenic storage tanks, which are one of the most commonly used pieces of cryogenic equipment. In fact, storage tanks for the cryopreservation of eggs, embryos, and sperm are very prevalent in the cryopreservation market, which is expected to reach a size of USD 22.42 billion by 2021, at a compound annual growth rate of 6.74% from 2016 to 2021 [2].

Cryopreservation is expensive for the individual consumer - on average, it costs $10,000 to $12,000 per in-vitro fertilization (IVF) cycle, and $800 per year for storage of reproductive tissue [3]. People often entrust fertility clinics with their hope for children; any damage or loss to frozen samples not only results in the loss of individuals' progeny and related emotional trauma, but can include potential legal and financial ramifications for the organization responsible.

Storage tanks are not perfect, and neither are the human operators. At extremely low LN2 levels, the temperature rises suddenly and significantly, damaging frozen samples. This is commonly referred to as a tank "failure". A survey from 2005 showed that 11% (n = 97) of LN2 tank users had experienced some level of tank failure, either due to hardware failure or human errors [3]. Two recent failures involving the University Hospital Cleveland Medical Center in Ohio and Pacific Coast Fertility in San Francisco brought increased attention to the issue, as the incidents were very costly for both IVF clinics. Together, more than 6,000 human eggs and embryos belonging to over 1,000 families were lost between the clinics because low LN2 levels went unnoticed [4,5]. Some lawsuits are seeking millions in damages citing gross negligence, recklessness, and breach of contract; even if all suits receive reparation in just the cost of a new IVF cycle for each patient, the costs could still span from 1.2 to 6.0 million dollars [6].

In order to mitigate the risk of tank failure, most fertility clinics periodically inspect storage tanks containing frozen human reproductive samples to detect tank leakage or impending tank failure. Many inspection methods are labor intensive, imprecise, or subject to human errors. LN2 continuously evaporates at a slow rate, necessitating that tanks be topped off frequently to ensure tissues and cells do not get damaged as a result of low LN2 volume. However, LN2 tank failures are still being reported because these methods only provide warnings as events occur rather than in advance. As a result, there is interest in developing a “smart” system that more effectively monitors and records the volume of LN2 tanks with the potential to predict, determine, and alert users to potential failures in equipment. This “smart” system should also work with existing monitoring systems as an extra layer of protection.

1.2 Existing Methods

Fertility clinics usually implement a combination of monitoring methods to minimize risk of tank failure. These methods include traditional, manual methods such as the “dipstick” method. Others may be somewhat automated, which may be used to measure several different metrics, including tank temperature and LN2 level. Some of these systems include alarms to alert the user of low LN2 levels and tank failure. Existing automated monitoring modalities currently on the market include, but are not limited to: capacitance liquid gauges, ultrasound sensors, and temperature sensors. These methods all have their limitations, which include high cost, imprecision, and lack of information relaying capabilities regarding leak rate and the corresponding health of LN2 tanks. Note that weight is a novel method for monitoring LN2 tanks that has not currently been implemented. The reason for this is unclear.

1.2.1 Dipstick

The most common method used to monitor the level in LN2 tanks is the “dipstick” method, which is a manual method that consists of using a simple measuring stick and dipping it into the tank to see where the level of LN2 is on the stick (**Figure 1**). This is done on a daily basis at best and sporadically at worst, and levels are typically recorded and manually consulted to see if there are any alarming trends in LN2 levels. Though widely used, there are many problems with this approach; it is labor intensive, inaccurate, and most importantly, unable to detect sudden failures of the device. In particular, this manual method lacks automated monitoring, logging, efficient analysis of data, and the ability to alert users in case of failure.

Figure 1. A measuring stick is a simple tool used to measure LN2 levels, colored black so that the frost line is easy to see.
Image taken from:
https://liquidnitrogentank.com/How_to_Measure_Liquid_Nitrogen_Level.php

1.2.2 Capacitance Liquid Gauges

Capacitance liquid level gauges are useful for measuring the liquid level of cryogens due to their high sensitivity, low cost, low power consumption, and accuracy (**Figure 2**) [7]. The basic operation of these sensors comes from differences of the dielectric constant between liquid and vapor phases. Liquid level is a linear function of capacitance of the gauge:

$$L_f = \frac{C\ln(D_0/D_i)}{2\pi(\varepsilon_f - \varepsilon_g)\varepsilon_0} - \frac{\varepsilon_g L}{(\varepsilon_f - \varepsilon_g)} \qquad \textbf{(Eq. 1)}$$

$Where\ L_f = Liquid\ level\ in\ storage\ tank$
$C = Capacitance$
$L_g = Gas\ level\ in\ storage\ tank$
$L = Total\ height\ of\ storage\ tank$
$\varepsilon_f = Dielectric\ constant\ of\ liquid$
$\varepsilon_g = Dielectric\ constant\ of\ gas$
$D_0 = Diameter\ of\ outer\ electrode$
$D_i = Diameter\ of\ inner\ electrode$

As the gap between plates increases, the output voltage increases. Because changes in output voltage are directly proportional to the gap between plates and inversely proportional to capacitance, one can use **Eq. 1** to calculate liquid level. However, this method requires installing electrical components inside the tank, exposed to the extreme low temperature of liquid nitrogen, which increases risk of electrical problems and difficulty of maintenance. Also, having electrical current running close to biological specimens is not inherently safe either.

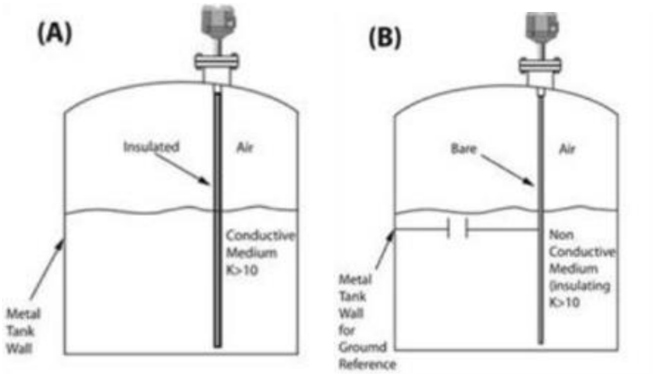


Figure 2: Capacitive level sensors measure the change in capacitance between two plates and can be used for fluids with high dielectric constants (A) or low dielectric constants (B). Cost: ~$100-500
Image taken from:
https://www.sensorsmag.com/components/a-dozen-ways-to-measure-fluid-level-and-how-they-work.

1.2.3 Ultrasonic Sensors

Storage tanks that use ultrasonic sensors are built such that they have a transducer mounted in the lid (**Figure 3, 4**). The transducer transmits ultrasonic waves and then receives those ultrasonic waves reflected back from an object. The time it takes between transmission and reception is used to determine the exact position of the object. In cryogenics, ultrasonic transducers are used to determine the liquid level in a storage tank. This method is accurate, reliable, and continuous; however, the cost is quite high, with the lid alone costing upwards of $1,000.

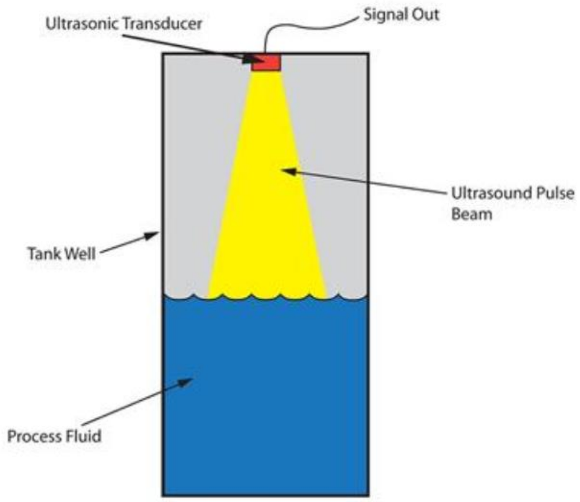


Figure 3: Ultrasonic sensors possess advantages such as simple structure and easy installation/maintenance, but are affected by temperature variations and electromagnetic interference.
Image taken from:
https://www.sensorsmag.com/components/a-dozen-ways-to-measure-fluid-level-and-how-they-work

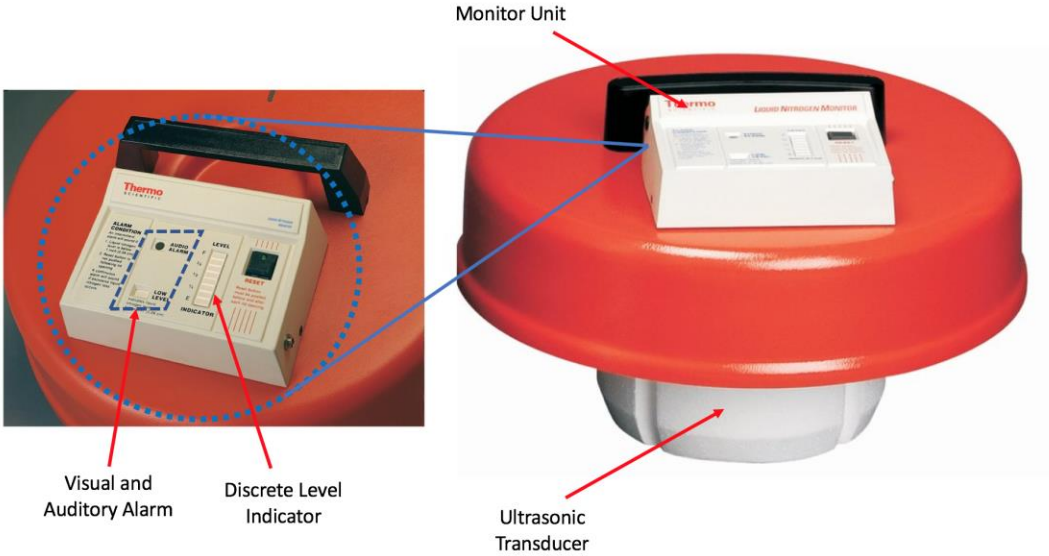


Figure 4: The Thermo Fisher Scientific Level Sensor features an ultrasonic transducer embedded into the lid. In addition, it features an on site monitoring unit with discrete level indication and alarms. There are no data-logging features.
Cost: ~$1000-1500
Image taken from:
https://www.thermofisher.com/order/catalog/product/CY509105

1.2.4 Temperature Sensors

Resistors, diodes, and thermocouples are popular and widely used examples of temperature sensors (**Figure 5**). They are typically made from pure metal and are used to record any voltage drop between the transistor base and emitter; voltage differences result in analog signals proportional to temperature. These temperature sensors are typically mounted on the lid of the tank. Although temperature is directly linked to specimen health, it is an inaccurate indication of liquid level because of the non-linear relationship between temperature and liquid level (**Figure 7**).

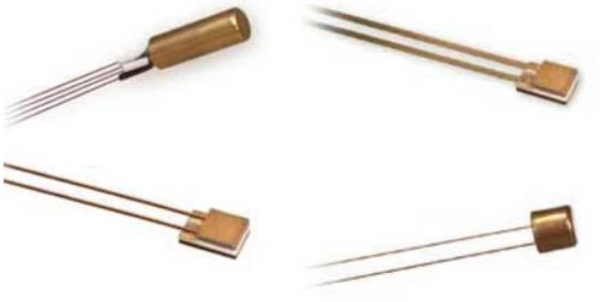


Figure 5: Resistors, diodes, and thermocouples are commonly used temperature sensors for cryogenic applications.
Cost: ~$50-100
Image taken from:

https://cryogenicsociety.org/26565/news/cryo_sensors_emerging_applications/

1.3 Problem Statement

Technologies used for cryopreservation can sometimes fail. This issue was highlighted by two recent failures in IVF clinics that resulted in serious legal, financial, and ethical repercussions. Though monitoring systems are used for LN2 tanks as a safeguard against failures, these technologies may be costly, ineffective, or unreliable. Moreover, they are unable to record and analyze data to predict potential failures.

The team performed preliminary research and surveyed three labs on the UW-Madison campus - Tibbetts Lab, Bio-Resource Lab, and Rapraeger Lab - currently utilizing LN2 monitoring systems to better understand the problem space and market need. We found a general consensus in the need for an automated system capable of continuous monitoring and sending alerts via text, email, etc. While current monitoring systems are able to accurately provide information on the relative levels of LN2, there is still a need for users to manually consult the devices and record information. Current systems also often utilize an audible alarm which is ineffective if no one is on site. Therefore, many of the current systems can benefit from better automation, data logging capabilities, and alert capabilities.

The most common method used by fertility clinics to monitor their LN2 refrigerators is using a simple measuring stick daily. This method is imprecise, labor intensive, results in the loss of liquid nitrogen and most importantly, is unable to detect a sudden catastrophic failure. Because there is a direct relationship between the weight and the volume of LN2 within a refrigerator, an improved method to monitor LN2 refrigerators would be to measure the change in weight over time.

The client approached the team with the desire to create a weight-based monitoring system, and tasked the team with designing and assembling the parts and equipment required to continually monitor and record the weight of a liquid nitrogen refrigerator (Worthington - Model VHC 35) used to store human eggs, embryos, and sperm. Specifically, the system shall be able to calculate the rate of loss of LN2, sync data to the client's existing Networked Robotics® (NR) data logging and temperature monitoring platform (called the Tempurity system), and control a local alarm system when a failure is detected. The client's existing Tempurity system automatically uploads temperature data to an online database, which would send alerts when a failure is detected. The team shall implement a weight-based monitoring system that automatically uploads weight data to the same database. The team plans to achieve this goal by implementing reliable sensor system and creating software featuring data logging and predictive alert capabilities.

2. Background

2.1 Cryogenic Fluids

Although more commonly used in the gaseous state, nitrogen is commonly stored and transported as a liquid, which is a more cost-effective method of product supply. Liquid nitrogen is a cryogenic liquid and can cause rapid freezing upon contact with living tissue. Storing biological samples at very low temperatures provides an indefinite longevity to cells, and the boiling point of LN2 (-196°C) is the preferred temperature for storing important specimens [8]. It is most often used because it stores samples below the glass transition point of water (-135°C) meaning that all biological activity stops and no degradation occurs, independent of storage time [SOURCE 999]. One limiting factor of LN2 is that it boils immediately on contact with a warmer object, and the temperature difference between LN2 and the surrounding environment is, even in relatively cold conditions, usually very significant. This is where the application of LN2 tanks becomes relevant. These tanks are one of the most common pieces of cryogenic equipment used in the preservation of biological samples. LN2 is stored, shipped, and handled in a variety of containers. One common aspect between them is the need to regulate pressure. A tremendous force can be generated if LN2 is rapidly vaporized in an enclosed space, so LN2 tanks often need to vent pressure and LN2 vapor. However, this results in loss of LN2, which necessitates frequent monitoring and periodic refilling. While cold storage devices (such as various freezers and refrigerators in the range of -70°C to -80°C) may be used, the temperature of liquid nitrogen is generally required for successful preservation of the more complex biological structures [8].

2.2 Cryogenic Storage Tanks

Cryogenic tanks are insulated, vacuum-sealed pressure vessels made from two interspaced layers of metal, typically aluminum or aluminium alloy (**Figure 6**) [3]. The space between the inner and outer chambers is a partial vacuum that insulates the tank. This vacuum acts as a thermal insulator; however, due to the extreme temperature difference between the cryogenic liquid and the ambient environment, heat transfer is inevitable and will cause the liquid to vaporize and pressure to build up. Vaporized nitrogen that collects in the inner chamber above the LN2 is vented from the tank via a pressure release valve. Vaporization rates depend on several factors including the cryogenic liquid itself, ambient temperature, and the condition of the tank's vacuum seal [9]. They can be as low as 0.4% or as high as 3% of the tanks' volume per day [10].

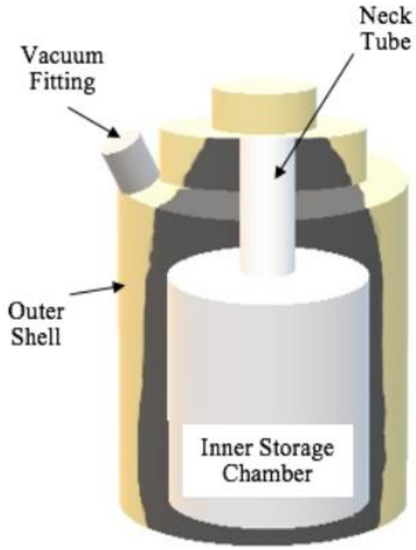


Figure 6: Small-capacity LN2 storage tank. The partial vacuum is between the tank's outer and inner shell. Samples are stored in the inner storage chamber.

Two major types of cryogenic tanks are used for the storage of human eggs, embryos, and sperm. Large high, capacity tanks can hold anywhere from 100 - 500 L of LN2 and are designed to store thousands of human samples [3]. They are often fitted with an autofill function that provides LN2 to the tank from a secondary supply tank when the internal sensor detects that LN2 levels are low. Small storage tanks are also used in cryogenics. They hold 30 - 60 L of LN2 and between 500 - 2000 specimens [3]. Small tanks generally have fewer functions than high-capacity tanks and do not utilize autofill technology. They are usually seated on a roller base to allow for mobility; however, mobility makes them more susceptible to failure by increasing the risk of tipping and mechanical damage. They offer clinics the advantage of hedging risk in case of tank failure by not being forced to "put all of there eggs in one refrigerator". A good 250 L tank costs about $10,000 while smaller 35 L tanks are estimated to cost about $1,000 [3]. A large clinic might utilize several high capacity tanks, or 20-30 smaller tanks.

2.3 LN2 Leak Rate

A properly functioning tank will typically lose all of its LN2 after 20 – 120 days depending on storage tank brand and condition of the tank [11]. Lid removal during filling, leaking valves, imperfect vacuum seals, and liquid tank venting are additional factors that contribute to the natural LN2 leak rate. Thus, it is imperative that LN2 tanks are refilled periodically to replenish LN2 levels. Assuming that refilling is done every two weeks, then LN2 must be added 26 times per year for each tank. Clinics and laboratories often use dozens of tanks which correlates to hundreds of fillings per year. While manual monitoring may prove to be the most reliable method, it is simply not an economical or efficient way to deal with intrinsic LN2 leakage.

2.4 Monitoring Metrics

Monitoring systems used to measure LN2 levels largely involve temperature sensing and level sensing technologies. One of the main issues with temperature sensors is the gradient of readings that result from the vertical position of the sensor within the tank. As LN2 levels drop, the sensor can be in the liquid phase one moment and then in the gaseous phase the next. The effect is gradually warmer temperatures being reported as a function of decreasing liquid level. More importantly is the fact that storage tanks conduct the cold from the bottom of the tank to the top of the tank. This means that a tank can lose most of its LN2, yet still maintain the specimens at the appropriate temperature of -196°C. When the LN2 runs out, a rapid temperature change occurs (**Figure 7**) with very little warning, leaving the user with a very small window to replenishing the tank before the specimens are rendered unviable. The rapid warming of the tank also leaves clinics with little time to replenish LN2 levels before the tank fails.

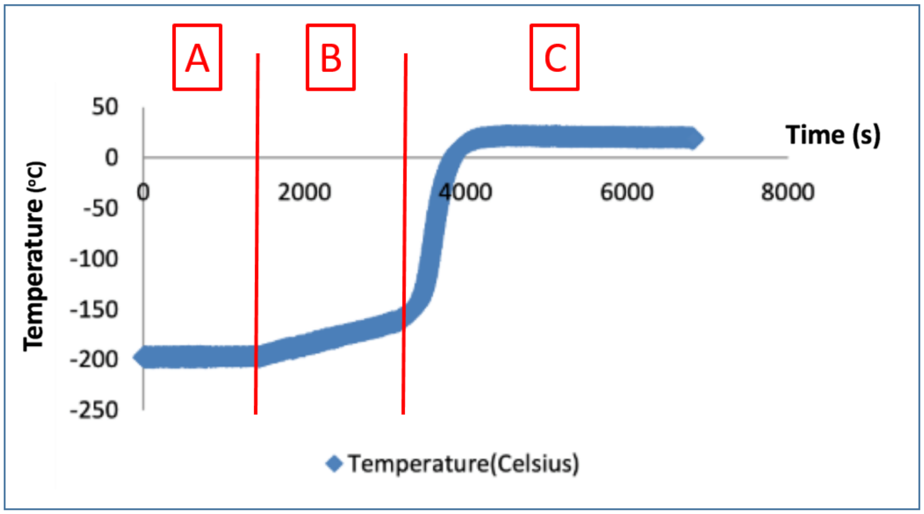


Figure 7: The temperature of a highly insulated tank rises from -150°C to 0°C in eight hours [11]. In section **A** of the plot, the tank has a substantial amount of LN2 in the tank and the probe is submerged in the LN2. In section **B** of the plot, the probe is in contact with both the liquid and gaseous phase of N2, and N2 is evaporating. In section **C**, the LN2 completely evaporated and escaped the tank, leaving the tank at room temperature (Image taken from NR).

Level sensing technologies generally require wires that must reach from the top to bottom of the tank. This extra set of wires adds a level of complexity to the tank. They are also difficult to secure to the inside of the tank and may interfere with moving samples in and out of the tank. For this reason, laboratories and clinics rarely monitor the liquid nitrogen level and more oftentimes implement temperature monitoring systems despite the fact that temperature monitoring is an imperfect system [11].

2.5 Client Information

Dr. Jeffrey Jones is an associate professor in the Department of Obstetrics and Gynecology and is the director of the Andrology and IVF laboratories at Generations Fertility Care [12]. He frequently practices cell preservation, via LN2 refrigeration. Because of his daily use of these refrigerators, he has proposed an improved method of LN2 refrigerator monitoring. He reached out to us to design and build an improved LN2 refrigerator monitoring system that has functional and convenient features that outperform competing monitoring modalities.

2.6 Design Specification

2.6.1 Client Requirements

Dr. Jones has specified a number of design requirements. Primarily, we must develop a long-term, continuous weight-based monitoring system for his LN2 refrigerators (Worthington VHC-35). Specifically, he would like a weight-based monitoring system integrated directly into the roller base (model 366783) supporting the tanks. His ideal method would be disassembling the base, integrating load sensors (strain gauges/load cells) into the individual parts, and reassembling the base such that the modified base is neither different in size nor shape compared to the original base. However, he is not particularly attached to this specific method of integration, although he would like to minimize major modifications to the original base. It is acceptable to find another method of integrating load sensors into the base so long as it is effective and non-intrusive to the system.

In terms of the functional features of the monitoring system, he requires that we continuously monitor the tanks over an extended period of time (on the order of weeks). In addition, we must incorporate continuous data-logging of the LN2 levels within the tank. The data must be stored into a remotely accessible database. Finally, we must record leak rate and extrapolate said leak rate to predict failure and send alerts for critical LN2 levels.

2.6.2 Physical and Operational Characteristics

The main purpose of this product is to continuously monitor LN2 levels within the tank and digitally log the resulting measurements over an extended period of time. The specific LN2 tank that Dr. Jones uses has a maximum weight of 45.5 kg (when it is full of LN2). As such, the monitoring system will have to be able to support the maximum weight ±10% of the tank, given that the tank will rest on top of the monitoring system.

The product shall neither compromise the integrity nor stability of the LN2 tank. In addition, the product will neither impede general functionality nor maintenance of the tanks. The system should be easily accessible and removable for the sake of both user safety and user experience.

2.6.3 Product Characteristics

Our goal as a team is to produce at least one fully functional model with all aforementioned features implemented into the system by the end of April 2019. We will have an allotted budget of $2,500. A fully functional model will encompass both hardware and software components; specifically, the system should include a method for monitoring LN2 levels and interface with the current temperature monitoring system to record and analyze data. Our target cost of development, material acquisition, and fabrications should amount to less than half of the budget. This will omit potential funding complications.

3. Preliminary Designs

3.1 Custom scale fitted to existing base

The existing roller base in this design has no modifications; rather, it will be used as a rigid attachment site for the external custom scale. The custom scale features load cells that will use each leg of the roller base to apply a normal force. The platform of the scale will be fabricated using stainless steel (**Figure 8** shows a transparent platform for the purpose of illustrating the placement of load cells). Although the base is mobile, it must be connected to a power source.

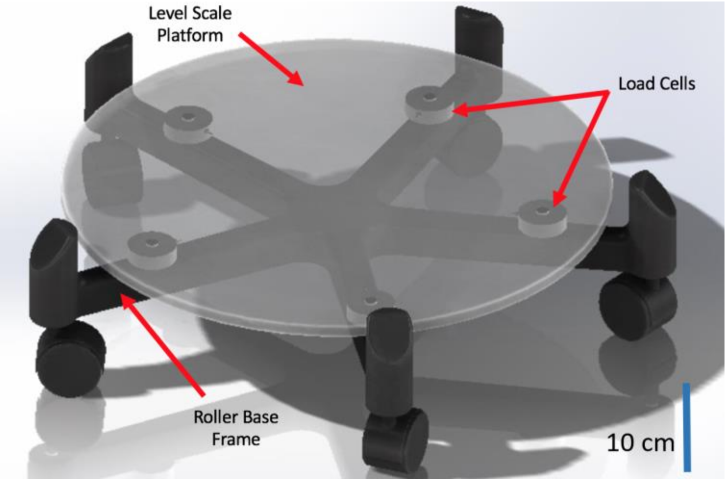


Figure 8: SolidWorks rendering of a custom designed scale, attached to the existing roller base.

3.2 Standalone scale with data logging capabilities

The standalone scale is completely independent of the existing roller base used to support the LN2 tanks (**Figure 9**). The scale features a ramp to allow for movement of the base onto the platform. In addition, the scale features an interactive LCD display. This display allows the user to indicate which tank is being monitored, what operations need to be carried out, and displaying data.

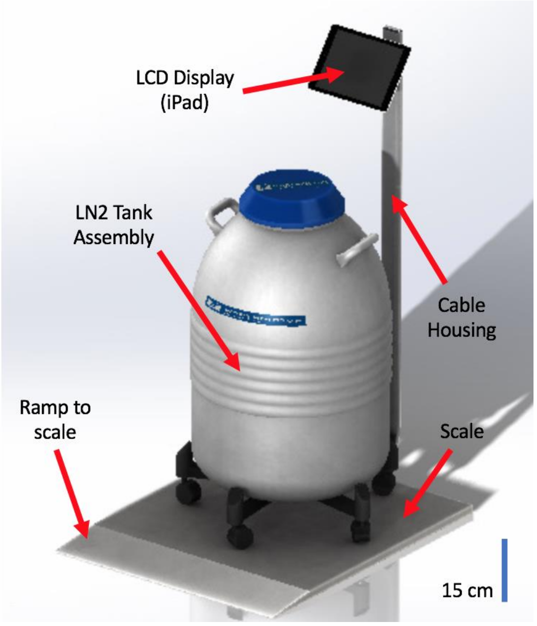


Figure 9: SolidWorks rendering of a standalone scale with an interactive LCD display.

3.3 Conversion of existing base into a weight monitor

In this design, the roller base will be reconfigured by embedding load sensors into each leg of the roller base, rather than utilizing and external scale like **Design 3.1** (**Figure 10**). The key advantage of this design is that the roller base will remain the same shape and size of the original base. Although the base is mobile, it must be connected to a power source.

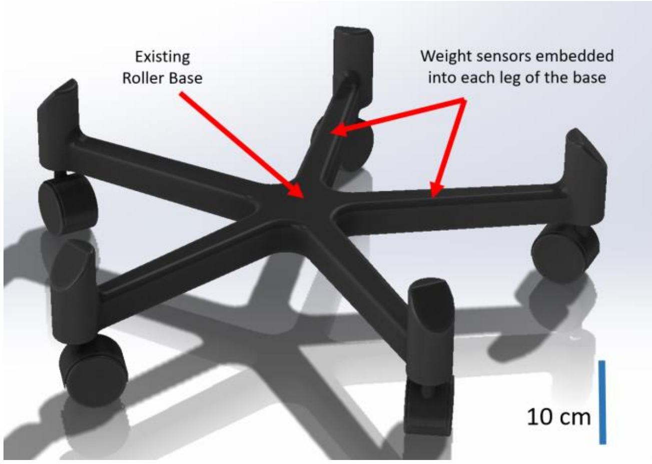


Figure 10: SolidWorks rendering of the existing roller base with weight sensors embedded within the base itself. Note that the size and appearance is no different that the unmodified base.

4. Preliminary Design Rationale/Evaluation

4.1 Design Matrices

In developing a weight-based monitoring system, the team performed several sanity checks to confirm that such a design would be the optimal way to satisfy the client's problem space. To do this, the team discussed several key issues, including: whether developing an alarm monitoring system is the best way to prevent LN2 tank failure, that weight is a more relevant and accurate metric (see Testing), how to best design a system in terms of hardware, and how data could be used to warn in advance rather than at the moment of failure. In other words, this section aims to address all available options for each aspect of the design to justify the team's approach.

4.1.1 Addressing Failure

The first point we want to address is how to mitigate the risk of failure in LN2 tanks. To do this, we need to thoroughly understand what "failure" is and how it occurs. Failure comes in various forms, but is most simply defined as the loss of sample viability. This occurs when the temperature rises past the critical threshold for storing biological samples at -135°C, which occurs from insufficient amounts of LN2. In turn, LN2 levels may get too low due to physical tank failures, which can result from gaseous leaking due to excessive pressure buildup or even a structural deformity in the tank. The key to preventing failures lies in making sure the temperature is always viable, and the key to making sure the temperature is viable is making sure there is enough LN2. In other words, we can prevent failure by either: constantly refilling tanks with LN2 (common existing method) or preventing LN2 loss altogether.

Redesigning the tank to be a perfectly sealed system presents the problem of excessive pressure buildup due to the warming of LN2 and its phase transitioning into gas. This can result in an explosion, resulting in failure. Gaseous leakage seems to be an acceptable compromise, although excessive leakage will result in rapid depletion of LN2 and can result in failure. If one were to focus on limiting leakage, they might choose to focus on redesigning the physical structure and ventilation of the tank itself. However, the average failure rate due to excessive leakage is extraordinarily low, indicating that the design of the current tanks are highly fine tuned and reliable [13].

This supports the idea that the optimal solution is the existing method of constantly refilling the tanks with LN2. The danger of this method is making sure that tanks are refilled on time, which can be addressed through the use of an alarm monitoring system that alerts the users when to do so.

4.1.2 System Monitoring Modality

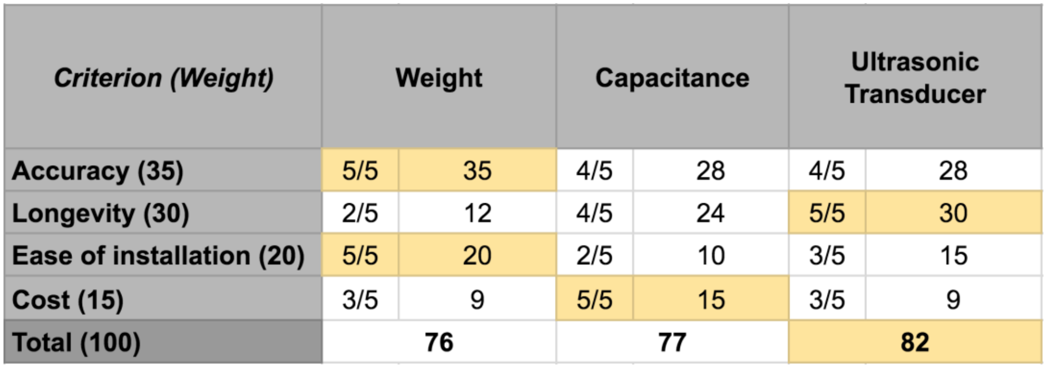
Existing products utilize a variety of sensors to interpret LN2 levels within the tanks such as temperature probes, capacitors, and ultrasonic transducers. Temperature probes are the most commonly used form of automated monitoring and are often coupled with other monitoring modalities including but not limited to capacitors and ultrasonic transducers. Therefore, we considered level sensing modalities in the form of weight acquisition, differential capacitance, and ultrasonic transduction that could be used in conjunction with temperature. We assessed these modalities based on the following criteria: accuracy, longevity, ease of installation, and cost (**Table 1**).

The most important criterion was the accuracy of the sensor. Load cells are highly reliable and are widely used, and therefore scored the highest. Capacitance is highly accurate in liquid level sensing; however, the extremely cold temperatures in an LN2 tank will affect the reliability of the capacitors. Ultrasonic transducers are highly reliable for proximity sensing; however, the presence of gaseous N2 can interfere with accurate level sensing.

Because the system must continuously monitor the liquid levels over an extended period of time, longevity is another key criterion that we must assess for each modality. Longevity was defined as the time interval from when the system is first installed to when it fails. Weight based sensing scored quite low in this category due to the fact that permanent deformation of the sensor may occur over the course of the monitoring period, resulting in miscalibration. Capacitors are known for performing consistently over long periods of time; however, the extremely cold temperatures have potential to affect the charging capacity of the sensor. Ultrasonic transducers are used in existing refrigerating systems, and are proven to perform over the course of a tank's lifespan.

A weight-based monitoring system would be the least difficult to install because it is an external device. In contrast, both capacitance and ultrasonic transduction would require installation within the interior of the tank. Capacitors would also need to be in contact with the liquid itself, resulting in further difficulty of installation.

Although ultrasonic transduction scored the highest overall, we must remember that we are designing a system specifically for our client, Dr. Jones, who wants a weight based monitoring system. As such, we choose to proceed forward in designing a weight-based system. Ultrasonic transduction is still a viable and promising option, and we should revisit the idea of using this sensing method in the future, once we complete the framework of our software and overall level monitoring system.



Criterion (Weight)	Weight		Capacitance		Ultrasonic Transducer	
Accuracy (35)	5/5	35	4/5	28	4/5	28
Longevity (30)	2/5	12	4/5	24	5/5	30
Ease of installation (20)	5/5	20	2/5	10	3/5	15
Cost (15)	3/5	9	5/5	15	3/5	9
Total (100)	**76**		**77**		**82**	

Table 1: Preliminary Design Matrix addressing the efficacy of each system monitoring modality to determine LN2 levels.

4.1.3 Implementation of Weight Sensors

Proceeding forward with weight-based LN2 level monitoring, we must assess the method of weight sensor integration with the system. As described in detail in **Section 3**, our original design concepts include developing a custom scale to be used in conjunction with the existing base (Design 1) and developing a standalone platform scale (Design 2). Our client's ideal design would be permanently integrating load sensors with the current roller base that he possesses (Design 3). We compared these concepts to determine the most effective method of integration (**Table 2**).

Data acquisition frequency was deemed to be the most important criterion due to the nature of our problem we are trying to solve (i.e. continuous level monitoring). Design 1 and Design 3 both scored high in this category because they are both permanent implementations of load sensors. Additionally, each tank would have its own monitoring system. In contrast, Design 2 would have transient monitoring, and would be used on multiple tanks, rather than a single tank.

In terms of longevity, Design 1 and Design 3 experience the recurring challenges faced by the potential unviability of long-term load application to load cells. Design 2 does not have to face this issue, and therefore scored the highest.

Ease of use and automation refers to the extent to which the user needs to interact with the system in order for the system to carry out its intended function. Design 1 and Design 3 require almost no user interaction, with the exception of periodic calibration. Design 2 requires user interaction everytime a new tank is being analyzed.

Assessing model compatibility is important due to the fact that we want our product to be used in a wide variety of models. Design 1 and Design 3 are specifically conceived for a specific roller base, and thus scored poorly. Design 2 is a non-specific concept and thus scored the highest.

It is clear to see that both Design 1 and Design 3 scored very similarly; but where Design 1 becomes a more viable option is in its practicality. Retrofitting load cells *into* an existing base would be time consuming, labor intensive, and difficult in general. In contrast, Design 1 is developing a dual platform attachment *atop* the existing base used to compress the load cells that bypasses the issues seen with developing Design 3. The score for Design 2 reflects its lack of requirement satisfaction, and can thus be omitted from further consideration.

To conclude, we will proceed forward in developing a custom weight-based monitoring system that will be integrated with the existing roller base via external attachment.

Criterion (Weight)	**Custom scale fitting existing roller base** 		**Platform scale w/ connecting ramp** 		**Conversion of existing base into a scale** 	
Data Aquisition Frequency (30)	5/5	30	2/5	12	5/5	30
Longevity (25)	3/5	15	5/5	25	3/5	15
Ease of Use/Automation (15)	5/5	15	3/5	9	5/5	15
Model Compatibility (10)	1/5	2	5/5	10	1/5	2
Ease of Fabrication (10)	3/5	6	5/5	10	2/5	4
Size (5)	5/5	5	3/5	3	4/5	4
Cost (5)	3/5	3	4/5	4	2/5	2
Total (100)	**76**		**73**		**72**	

Table 2: Preliminary Design Matrix addressing the specific method of weight sensor implementation.

4.2 Proposed Final Design

We will develop a custom scale (**Figure 11**) capable of continuous weight monitoring over extended periods of time. The scale will externally attach to the existing roller base. The system will continuously measure weight as a proxy for LN2 volume within the tank, and will record the levels over time. In addition to the proposed hardware design, software will need to be incorporated to enable predictive and alarm monitoring in the event of critically low LN2 levels or critical tank leak rates. Note, however, that the direct methods for implementing such predictive monitoring have yet to be determined. The team plans to use experimental data to develop tentative models (see Testing).

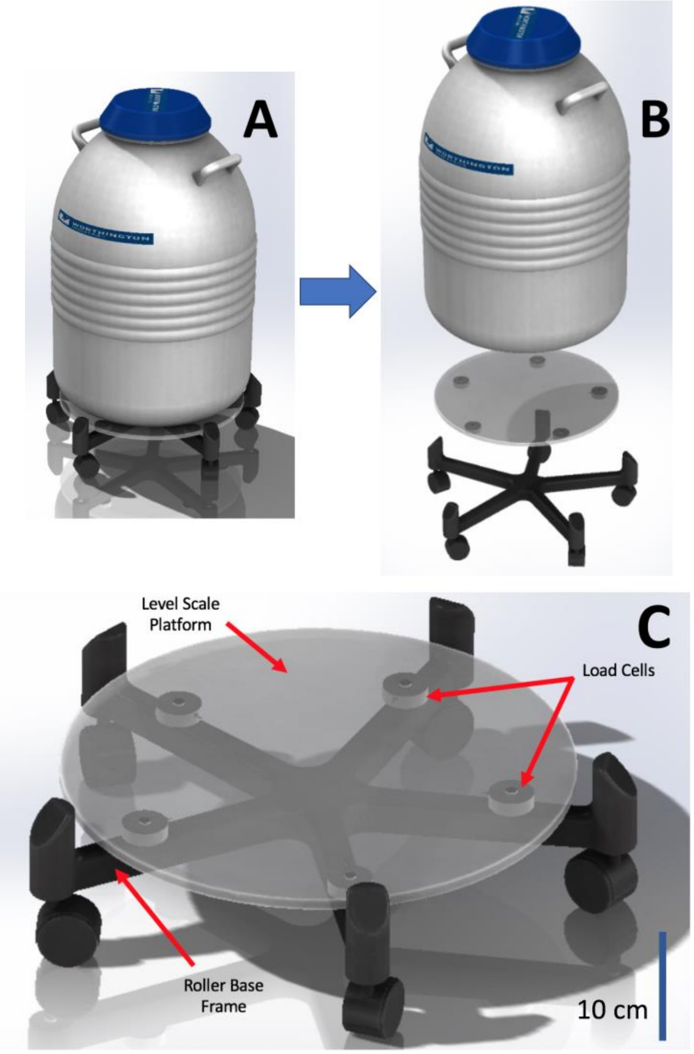


Figure 11: (A) Fully assembled roller base/weight sensor with the tank placed directly on the assembly. **(B)** An exploded view of Figure A, showing the individual components: roller base, weight sensor, and LN2 tank. **(C)** Annotations of the weight sensor integrated with the roller base.

Note: All images were rendered using SolidWorks.

5. Fabrication/Development Process

5.1 Materials

5.1.1 Hardware

The materials used in the design include a VHC 35 roller base, two beveled wooden disks, four 200 lb capacity compression load cells, a SparkFun OpenScale board, a Raspberry Pi microcontroller, and ten stackable PVC guide posts. The roller base is made from aluminum and has plastic wheels which allow for any 2-D motion (i.e. translation and rotation). The FX1901 load cells are optimized for laboratory or hospital use and designed to provide superior resolution. The OpenScale is designed to integrate input from multiple load sensors and contains an ATmega328P microcontroller to process, transfer, and format data.

5.1.2 Software

The current prototype uses a Python script to read from the Serial out of the SparkFun OpenScale and plots a graph of the measured data in real time (**APP 9.2**). This script is used purely for demonstration and proof of concept, to show that our design is capable of monitoring the system in real time. Note that the software of the final product involves integration with the client's current Tempurity System and the design of predictive algorithms. See **Section 7.2** for a detailed explanation of the team's specific objectives and future plans.

5.2 Methods

5.2.1 Roller Base Platform Scale

The platform scale was fabricated by evenly spacing four load cells radially between two wooden disks. One of the wooden disks (t = 1'' , D = 17.5'') was centered and secured to the VHC 35 roller base using five 2'' deck screws. A drill press was first utilized to ensure accurate hole positioning followed by a hand drill to secure the five deck screws to the base. The positions for the sensors were then marked on the second plate and four pilot holes were drilled. The second wooden disk was then clamped to the secured disk. Using the pilot holes as a guide, our team center punched the location of the load cells on the secured plate. At this time, two holes were also drilled for sleeves on which our team secured two ¼'' bolts and t-nuts on the first plate in order to align the sensors. The top disk was then removed and the load cells were glued in place. Due to the thickness of the wooden disks, PVC pipes were secured to the posts of the roller base in order to lengthen the original guide posts so as to prevent tipping and/or translation of the VHC 35 cryogenic tank. It should be noted the four sets of double stacked PVC pipes spray painted black are firmly secured to the base's original guide posts while the last double stacked PVC pipe spray painted blue is removable to facilitate loading and unloading of the tank.

5.2.2 Circuit Design

The overall circuit design connects input from the four load cells in parallel to the OpenScale board, which then sends the information to the Raspberry Pi through its Serial out for further data manipulation. Each load cell has 4 outputs that were soldered to wires so they could be connected in parallel on a Breadboard (**Figure 12**). The wires were shrink wrapped to help secure connections and improve wire management. Upon initial testing the team found that the voltage output of the load cells exceeded the maximum capacity input of the OpenScale, so a voltage divider was added using values of R_1 = 1k, R_2 = 10k to scale down readings to more appropriate values. The parallel output was then connected to the load cell screw terminals on the OpenScale board (**Figure 13**). The OpenScale is connected by micro USB to the Raspberry Pi, which uses a script to read and graph incoming data in real time.

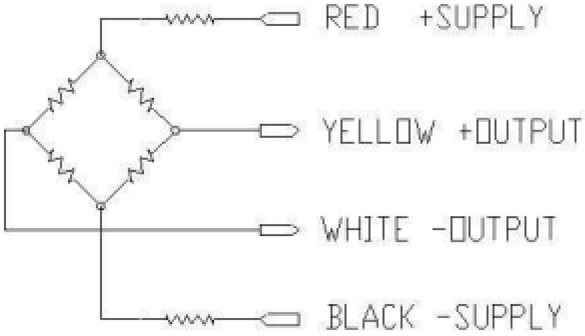


Figure 12: Wiring information for each of the load cells. Each of the outputs was soldered with additional wires (not shown) for connection to a Breadboard. Image taken from the FX1901 datasheet, originally created by the manufacturer, TE Connectivity.

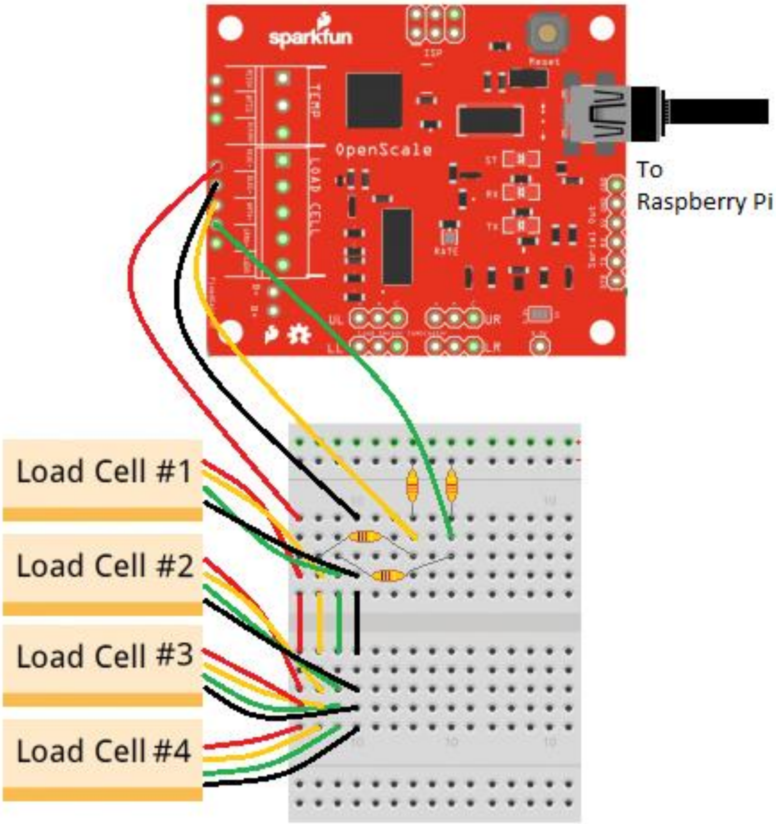


Figure 13: High-level schematic showing the setup of our circuit. Each output of each load cell is connected in parallel with the others. The colors correspond with the diagram in Figure 12, except that the negative output is represented by the green wire in this image. The supply wires are directly connected to the OpenScale screw terminals. The signal from the output wires are attenuated through a voltage divider before connection to the OpenScale. The OpenScale is then connected by micro USB to the Raspberry Pi.

5.3 Final Prototype

The final prototype varied significantly from the conceptual renderings in **Figure 11** of the proposed final design. The final prototype utilized sturdy and reliable materials to demonstrate a proof of concept (**Figure 14**). It features a roller base specific to the Worthington – VHC 35 and five FX1901 compression load cells. Four of these load cells were used in the final prototype, while one load cell was kept as a backup. The capabilities of this prototype feature continuous weight vs. time plotting. Each load cell has a maximum compressive capacity of 200 lbs, and can therefore bear a 800 lb limit (F.S. ≥ 8). Additionally, the added thickness of the custom scale is compensated by way of extended guard rails.

This is the first prototype that has been developed, and there are several areas of the design that can be improved in the next iterations (See **Section 7.2** for details pertaining to how we will improve the prototype).

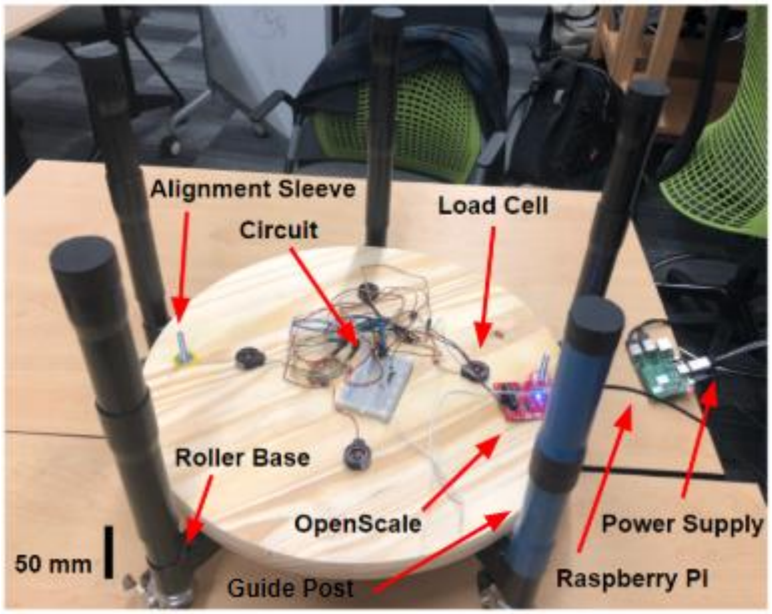


Figure 14: The final prototype is a functional custom scale that uses a Raspberry Pi to read the serial out of the OpenScale, which in turn reads the output from the four load cells.

5.4 Testing

The goals of initial testing are two-fold: to confirm that weight is a more accurate measurement for monitoring the condition of the tank than temperature, and to identify potential patterns between weight, temperature, and external events (such as the opening of the lid, removal of sample, etc.) for developing predictive algorithms and "smart" capabilities. The team obtained preliminary data with the help of the client, who set up the system used for testing. A dewar was filled with liquid nitrogen and left to stand undisturbed until failure. The weight and temperature were monitored and recorded using the NR Tempurity System over the course of a 30-day period, after which a graph was created to display the values over time (**Figure 15**).

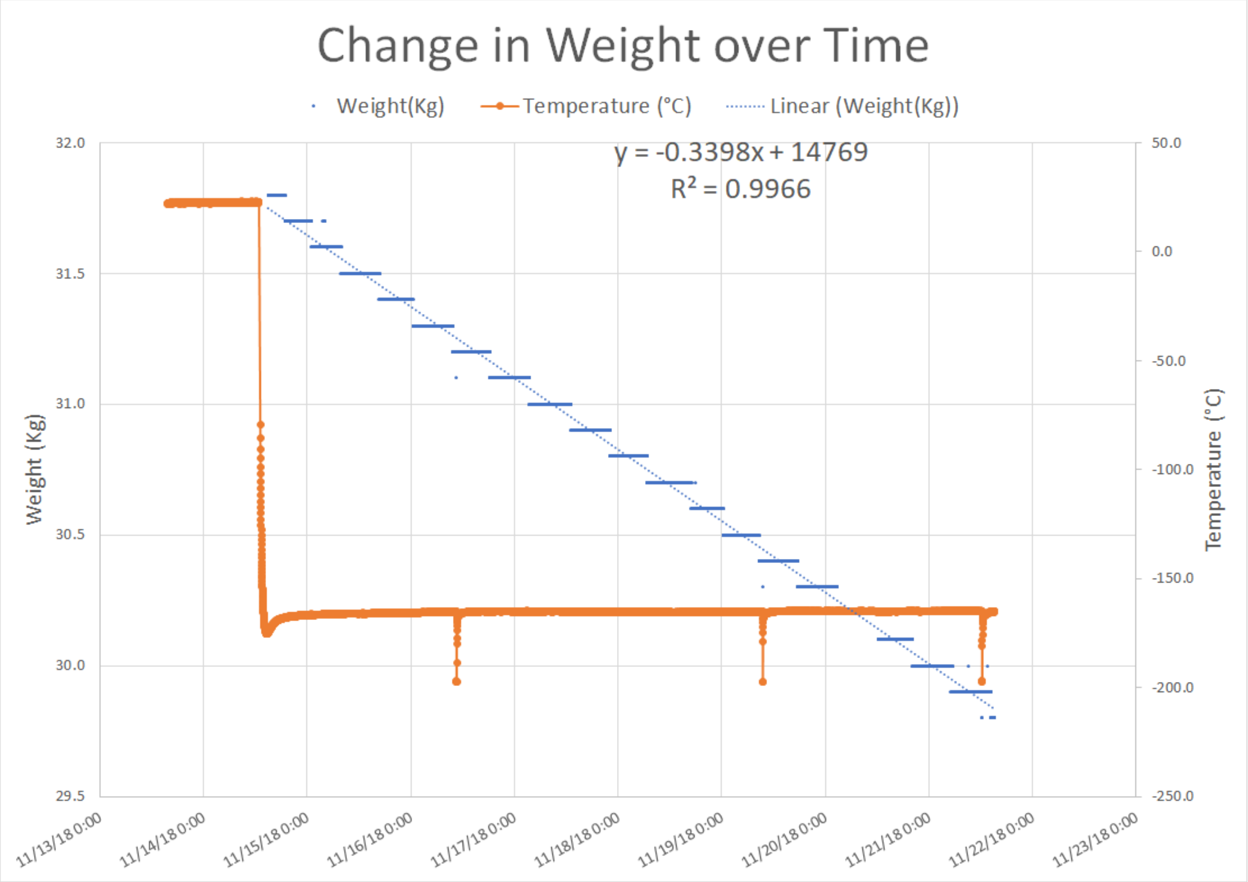


Figure 15: Data collected for the change in weight and temperature of a full LN2 dewar left undisturbed over a period of two weeks. The orange line represents temperature, and the blue line shows weight. Note that there is a relatively linear trend in the decrease of weight over time, with an R^2 value of 0.9966.

It was found that the temperature of the system remained relatively constant regardless of the amount of liquid nitrogen left in the tank - a finding supported by our preliminary research. This supports the idea that temperature does not really give any indication as to what is actually going on inside the tank, specifically in regards to how much liquid nitrogen is left. Temperature only changes at failure, so while temperature can be used to detect failure it cannot be used to warn against it. On the other hand, weight shows a relatively constant linear trend. It directly correlates with the amount of LN2 left in the tank, which helps confirm that weight is a better and more accurate way of monitoring the tank.

While our team chose to display the preliminary data in the form of weight over time, the graph can be modified to depict volume of LN2 in the tank over time and height of LN2 in the tank over time. Obtaining an expression for volume comes from dividing weight by the density of liquid nitrogen (**Equation 2**). Using the expression for volume of a cylindrical tank, our team then estimated the height of LN2 in the tank (**Equation 3**). Displaying LN2 height will eliminate the need for manually monitoring (“dipstick” method) utilized by many clinicians, as the data from both is equivalent. However, due to the fact that the VHC 35 LN2 tank is not perfectly cylindrical, the team standardized Equation 3 based off the assumption that the experimental height ($\hat{h}$) was a function of the theoretical height (f(h)) (**Equation 4**). Knowing that the tank is 32.4L full at a height of 16cm allowed the team to solve for a constant $\boldsymbol{\alpha}$ (**Equation 4**) used to relate experimental and theoretical height of LN2 in the tank. Our team found that $\boldsymbol{\alpha}$ = 0.2705.

$$Volume\ LN2\ in\ tank(L) = \frac{Weight\ (kg)}{.804\ (g/cm3)} \qquad \textbf{Eq. 2}$$

Equation 2: Weight to volume conversion using the density of LN2.

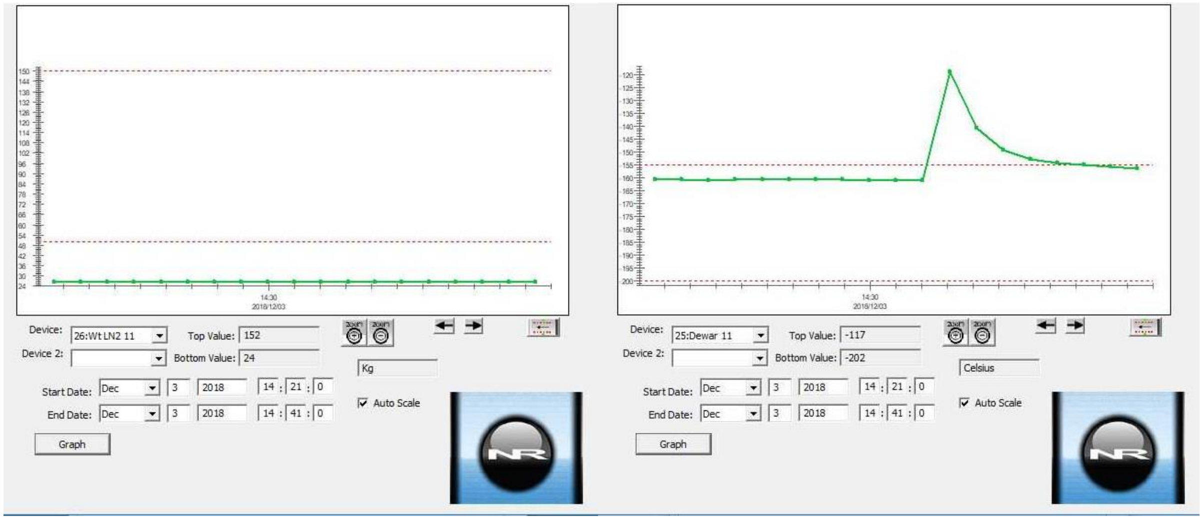
$$Theoretical\ Height\ of\ LN2\ in\ tank\ (cm)\ = \frac{Volume\ (L)}{\pi r2} \qquad \textbf{Eq. 3}$$

Equation 3: Volume to theoretical height conversion using geometrical relations of a cylinder.

$$Standardized\ Height\ of\ LN2\ in\ tank\ (cm) = \hat{h} = f(h) = \alpha \times h \quad \textbf{Eq. 4}$$

Equation 4: Volume to experimental (standardized) height conversion using geometrical relations of a cylinder and the constant $\boldsymbol{\alpha}$.

The true value of our system lies in being able to use that data to develop “smart” capabilities. For example, because the rate of change is generally constant we can potentially predict the amount of LN2 at any future time or assess the health of the tank if the rate is different from what we expect. The general idea is that by analyzing patterns in the change of weight (in correlation with temperature) during external events (such as lid/sample removal), we can create a system that recognizes occurrences of those events. To test the proof of concept, weight and temperature data were recorded using the Tempurity system during removal of a sample from an LN2 tank and graphed (**Figure 16**).



Device: 26:Wt LN2 11
Device 2:
Top Value: 152
Bottom Value: 24
Kg
Start Date: Dec 3 2018 14 : 21 : 0
End Date: Dec 3 2018 14 : 41 : 0
☑ Auto Scale

Device: 25:Dewar 11
Device 2:
Top Value: -117
Bottom Value: -202
Celsius
Start Date: Dec 3 2018 14 : 21 : 0
End Date: Dec 3 2018 14 : 41 : 0
☑ Auto Scale

Figure 16: Data collected for the change in weight and temperature of an LN2 dewar when a sample is removed. The left graph shows the weight of the tank during the event, while the right graph shows the temperature. Data is collected and displayed using the Network Robotics Tempurity Monitoring System.

The temperature behaved predictably; there was a sudden increase in temperature during the event because removing a sample exposes the inner environment of the tank to the warmer room temperature outside. However, there was no observable change in weight. This is most likely due to the fact that the scale used only measures up to 0.1kg accuracy - the weight of the sample is less than that. This test should be reconducted using a scale with increased accuracy (i.e. ±0.01kg or ±0.001kg) in order to obtain more conclusive results.

The team also conducted basic testing on our final prototype to confirm that it worked. This was done simply by calibrating our scale and placing objects of known weight on it to measure accuracy. Note that while most of the testing will be used for predictive models, other testing should be done to verify the accuracy and longevity of the custom hardware we build.

In conclusion, our testing to this point has provided evidence that weight is a more relevant, accurate way of monitoring LN2 tanks. Additional testing must be done to investigate the patterns of weight and temperature during external events, which can be used in developing a “smart” system with predictive capabilities, as well as the quality of our particular build (See **Section 7.2** for a more detailed list of future testing).

6. Discussion

6.1 Implications

While the development of a more reliable monitoring system has obvious applications to the given problem statement and client problem, such a device could theoretically be applied to any type of storage unit. Weight is a universal property specific to the material, and is therefore not only a more general metric than temperature or level, but a more reliable way to measure the amount of material left. A weight-based monitoring system is not necessarily limited to liquids, and could be applied to a wide variety of industries and organizations that utilize storage units and related monitoring systems. This may range from large-scale processing plants that need to store various chemicals, to transportation-based industries that need to monitor fuel usage, to bars (and even house parties) that could benefit from knowing when to refill a keg.

However, the true value of our project and proposed design involves creating a “smart” system with predictive capabilities that can warn of failure in advance, rather than when it occurs. By correlating patterns of weight and temperature during external events such as sample removal, we can potentially record events to create a more accurate model of prediction as well as more efficiently timed alerts. Data logging capabilities would be useful for administrative purposes in terms of general record keeping and data analysis. Our system could even additionally be used as a means of assessing the overall health of the tank - any LN2 storage unit is going to degrade over time, and a system that is capable of monitoring the natural leak rate can help users determine whether their system is compromised. The team believes the design could be used not only by the client and other fertility clinics, but in biological research that might require cryopreservation of biological samples. In addressing the specific needs of the client, the team plans to use a market approach to develop a system that can satisfy general market needs; one of the most important steps moving forward is to have many individuals test and use our design to provide proof of concept.

6.2 Ethical Considerations

There are few ethical considerations in the design of a monitoring system for LN2 storage units. In general, one should consider that the cryopreservation of biological samples is necessary for various basic and applied scientific research, whose results may ultimately be used in applications that benefit human society. On a smaller scale, storing reproductive tissue may raise ethical concerns because in the event of LN2 tank failures, an individual’s progeny is directly lost, which can have serious repercussions on future livelihood. Not only that, but the organizations that are responsible for such failures may suffer from financial and legal consequences. Therefore, in designing a monitoring system one must endeavor to create a device that is reliable, accurate, and robust in order to prevent failures that may otherwise hinder beneficial scientific research, to help safeguard institutions against financial and legal consequences, and to protect against potential individual trauma. The design and development of a better monitoring system helps to improve the standards of LN2 storage, and should be taken into account when considering the ethical implications of this work.

6.3 Sources of Error

The critical component of a weight-based monitoring system will be the load cells. Therefore, the load cells should be foremost considered for sources of error. One of the most common causes of load cell malfunction is overloading. When working in the proper operating range of load, a load cell deforms elastically, which means that it would return to its original state and retain all weight measuring capacity when the load is removed. However, excessive load could cause a load cell to deform plastically, which means that there would be permanent deformation and damage to the load cell, resulting in inaccuracy. Occasionally, a liquid nitrogen tank may be lifted up and later put back onto the scale. If the operator accidentally drops the tank onto the scale, the impact that this creates may surpass the actual weight of the tank, thus exceeding the capacity of the scale.

Apart from overloading, moisture is also a common cause of load cell malfunction. Moisture in the environment can cause erosion of the electronics and the mechanical structure of the load cells. This may cause a short circuit or failed structure. Furthermore, because our application uses liquid nitrogen, accidental spills during refilling may also cause damage to the load cells. Load cells most commonly have a metal structure. Due to the extremely low temperature of liquid nitrogen, if a load cell comes into contact with liquid nitrogen, the low temperature could cause contraction in the metal structure. Normal room temperature would then cause expansion. Such contraction and expansion cause significant stress in the structure, and repeated contraction and expansion would result in deterioration of the mechanical strength of the load cell. In addition, all load cells require periodic calibration to maintain accuracy. ISO 9000 and most other standards specify a maximum period of around 18 to 24 months between re-calibration procedures, and annual calibration is usually considered best practice in industrial application [14].

An additional source of error is related to the accuracy of the Tempurity weight monitoring system. Currently the Tempurity system only records weight data to ±0.1kg. The current prototype, however, displays the weight to ±0.01kg. The inconsistency between the data logging system and the prototype makes it difficult to identify changes in weight during times when samples are added or removed from the tank, as individual samples weigh on the order of grams. This indicates that the resolution of the Tempurity system may need modification to detect small incremental changes in weight. Reporting to the hundredths of a digit in weight will also be important for increasing accuracy in reporting the evaporation rate of the tank.

7. Conclusions

After extensive literature review and preliminary considerations, the team designed, fabricated, and tested a weight-based monitoring system for LN2 tanks based off *Preliminary Design 1*, which consists of having a custom scale mounted on top of the VHC 35 roller base. A weight based system provides a more reliable method of monitoring the amount of LN2 because weight is directly proportional to volume. Moreover, it is external to the tank and does not require internal probes, meaning that it can easily be used in conjunction with temperature probes as a redundant monitoring method for safeguarding specimens.

In summary, the results of initial testing exhibit a linear trend for change in weight over time with temperature remaining relatively constant for any amount of LN2, indicating that weight is a more relevant, accurate way of monitoring LN2 tanks. While it may be clear qualitatively, more extensive testing is desired in order to quantitatively prove that a weight-based system can detect abnormalities in advance of changes in temperature. Yet unevaluated is LN2 evaporation rate and changes in weight due to external events, so these aspects of the design specifications remains undetermined.

7.1 Expenses

The cost analysis of each material includes raw materials and materials for testing procedures. Costs were determined from preliminary research. The roller base, load sensors, wooden disks, PVC guide posts, and circuit materials cost a total of $490.32 to fabricate and assemble (**APP Table 1**). This was well within the allotted budget of $2500.00.

7.2 Future Work

Moving forward, the team would like improve the aesthetic and scalability of the hardware. We plan on replacing the wooden disks with thin metal plates, creating a more compact circuit with a printed circuit board, and adding a housing unit to store loose circuitry. In addition to improving overall aesthetic, using thin metal might reduce variability of readings of lighter items. Moreover, it will eliminate the need for additional material including the PVC guide posts, increasing the scalability of the design. The team is also interested in quantifying the scale's accuracy over extended use. While it is anticipated that static loading will not affect accuracy, this needs to be tested and verified.

In addition to creating a more robust prototype, the team has two main tasks for the software of the final product. The first task, as specified by the client, is to integrate the existing hardware with NR's Tempurity System (**Figure 17**). This requires purchasing NR's NTMS4 (Network Telemetry Monitoring System) hardware which would give the team access to a network-based data collection and monitoring of real-time weight data platform. Further discussion with NR regarding intellectual property (IP) may need to be discussed next semester before incorporating any NR hardware. The second task and main objective for the software is to use weight data over time to develop a predictive algorithm that can identify abnormalities in advance of a temperature rise. This first requires obtaining a data set of continuous weight and temperature values corresponding to the client's VHC 35 tanks. Ideally, data collection would begin when the tank is completely filled and end when the LN2 is completely depleted and the temperature begins to rise - simulating a tank failure. Once the data is obtained, the team will work to correlate specific weight values with external events such as LN2 filling and sample addition/removal or critical threshold temperatures such as -135℃, the critical transition temperature for biological specimens [15]. Moreover, the team intends on using the data to accurately record the rate of loss of LN2 every minute. A real-time evaporation rate could be a useful measure for anticipating tank failure as well as for quality control testing of the LN2 tanks to ensure they maintain LN2 as specified. The ultimate goal is to make the system web-enabled or Bluetooth-enabled. Utilizing weight-temperature or LN2 evaporation rate thresholds; for example, the team can notify clients via email or text message regarding the status of their LN2 tanks.

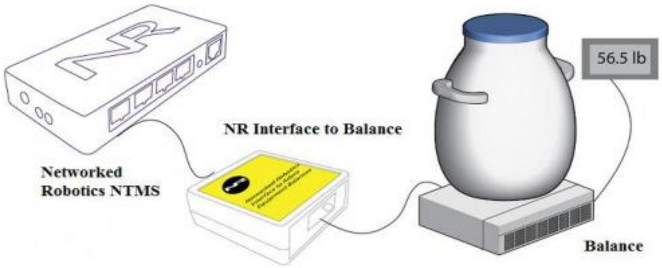


Figure 17: NR interface to custom scale, which is used to communicate with the NTMS. The NTMS is a standalone ethernet network device that collects data to send and store in the Tempurity Server (Image taken from NR).

Throughout the process of refining hardware and developing a continuous web-enabled, data-recording alarm monitoring system, the team should also continue to conduct market research with the goals of better understanding the root problem, potential customers, and to determine whether any market needs can be applied to our current design to create a more robust and versatile product.

7.3 Acknolwedgements

Our team would like to thank Dr. Jeffrey Jones for the opportunity to work with him in designing a weight-based LN2 continuous monitoring system. We would also like to thank our advisor, Sarah Sandock, for her assistance, weekly guidance, and involvement in the project.

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9. Appendix

9.1 Expenses

Item	Description	Supplier	Part Number	Link	QTY	Cost	Date	Total
VHC 35 roller base	Roller base used to support a single LN2 tank	Worthington Industries	366783	https://www.nxp.com/docs/en/data-sheet/MPXA6115A.pdf	1	$268.00	10/19/2018	$268.00
TE Connectivity FX1901 Series 200lb load cells	Load cells ranges of 200lb compression; enables force sensing in "smart"	TE connectivity	FX1901-0001-0200-L	https://www.digikey.com/product-detail/en/te-connectivity-measurement-specialties/FX1901-0001-0100-L/223-1530-ND/5277313?utm_adgroup=	5	$30.75	10/28/2018	$139.8

	consumer and medical products			Sensors%20&%20Transducers				
Sparkfun OpenScale	Reads multiple types of load cells and offers a serial menu to configure calibration value	SparkFun	SEN-13261	https://www.sparkfun.com/products/13261	1	$29.98	10/28/2018	$29.98
Raspberry Pi microcontroller	Small single-board computer	Jeff Tsai	N/A	N/A	1	N/A	N/A	Previously Owned
Wooden Disks	t/Dm=1’’/17.5’’	Home Depot	N/A	N/A	2	$12.84	11/23/2018	$25.68
Deck Screws	2’’ length	Home Depot	N/A	N/A	5	$0.60	11/23/2018	$3.00
Washers	⅜’’	Home Depot	N/A	N/A	8	$0.36	11/23/2018	$2.88
Nuts	⅜’’	Home Depot	N/A	N/A	8	$0.42	11/23/2018	$3.36
Bolts	⅜’’ thread; 1 and ½’’ stainless steel bolts	Home Depot	N/A	N/A	4	$0.60	11/23/2018	$2.40
Nuts	¼’’ bolt; 2’’long (guide sleeve)	Home Depot	N/A	N/A	2	$0.66	11/23/2018	$1.22
T-nut	¼’’ galvanized t-nt	Home Depot	N/A	N/A	2	$0.50	11/23/2018	$1.00

PVC extension tubes	Used to create a guide post to prevent LN2 tanks from tipping	Home Depot	N/A	N/A	10	$1.30	11/23/2018	$13.00
							TOTAL	$490.32

Table 1. Finalized expenses report

9.2 Product Design Specifications (PDS)

Function: The device shall monitor and record the weight of the LN2 tank, and integrate with Networked Robotics current monitoring system “Tempurity” to log data and send alerts about LN2 levels and leak rate.

Problem Statement: The most common method used by fertility clinics to monitor their liquid nitrogen refrigerators is to measure the level of liquid nitrogen using a simple measuring stick every few days. This method is imprecise, labor intensive, results in the loss of liquid nitrogen and most importantly, is unable to detect a sudden catastrophic failure. Because there is a direct relationship between the weight and the level of liquid nitrogen within a refrigerator (volume), an improved method to monitor liquid nitrogen refrigerators would be to measure the change in weight over time. Our team is tasked with designing and assembling the parts and equipment required to continually monitor and record the weight of a liquid nitrogen refrigerator (Worthington - Model VHC 35) used to store human sperm, eggs and embryos.

Client Requirements:

- The device shall be able to continuously measure and record the weight of a LN2 tank
- The device shall be able to determine the volume of LN2 based on the measured weight
- The device shall be able to calculate the rate of change of LN2 in the tank
- The device shall be able to identify alert thresholds for LN2 volume and rate of change
- The device shall be able to communicate data to the current “Tempurity” monitoring system
- The device shall be able to send alerts about LN2 levels
- The device shall be implemented on the roller base of the LN2 tank
- The device shall not compromise the integrity/stability of the LN2 tanks nor hinder the functionality of the LN2 tanks
- The device shall give an indication of the health/efficiency of the LN2 tank
- The device shall include a physical display showing the current weight of the tank

Design Requirements:

1. Physical and Operational Characteristics

a. Performance Requirements:

- The device shall be able to continuously monitor the weight of LN2 tanks over an extended period of time.
- The device shall be subjected to weights of up to about 45.5 kg.
- The device shall be placed on a roller base and be able to withstand simple translational movement.

b. Safety:

- The device shall not compromise the integrity/stability of the LN2 tanks.
- The device shall not impede the general maintenance of the LN2 tanks, which includes cleaning, lifting, and filling of the tank.

c. Accuracy and Reliability:

- The device shall be implemented so that the loads are evenly distributed about the roller base; the device shall accurately record the weight of the liquid nitrogen in the tank within ±0.1%.
- The device shall have a safety factor of at least 5, due to the fact that the tank may be tilted, in which case the weight of the entire tank is transferred to only one leg of the five-legged roller base.
- The device shall be able to reliably monitor the weight of the LN2 tank through continuous use.
- The device shall record and communicate weight data to the current monitoring system every 10s.
- The device shall require minimum easy recalibration after prolonged use ≥2 years.

d. Life in Service:

- The device shall remain functional for at least 5 years.
- The device shall retain its structure and function over continuous use.
- The device shall retain accuracy for a period of at least 6 months before calibration is necessary.

e. Shelf Life:

- The device shall be created with materials that will allow the device to be usable for a large timeframe (> 5 years).

f. Operating Environment:

- The device shall operate in a cold room in temperatures ~20°C.
- The device shall be able to withstand and accurately read compressive loads no more than 45.5 kg.

g. Ergonomics:

- The device shall fit on the 19’’ roller base used for VHC 35 LN2 tanks.
- The device shall be reusable and portable for daily use.

h. Size:

- The roller base fits tanks 19’’ or less in diameter. The device shall work with roller bases of at least this size and possibly be flexible enough to work with other sizes.

i. Power Source:

- The device will be a mobile unit, and thus will require a battery operated power source rather than fixed-source power cords.
- Because the device will be “ON” indefinitely, power cords may be used during extended periods of immobilization in order to limit battery consumption.

j. Weight:

- The device shall have a capacity appropriate to that of a full LN2 tank, which weighs approximately 45.5 kg [1].
- The weight of the device itself shall be less than 25 pounds for easy movement and use.

k. Materials:

- The device shall be made with materials that are resistant to shock and corrosion from chemicals such as steel load sensors (either plated or stainless) so as to optimize precision and accuracy throughout its lifetime.

l. Aesthetics, Appearance, and Finish:

- The device shall encompass a digital display to allow the user to easily see readouts.
- The device should fit seamlessly with the roller base.
- The device should be easily recognizable to allow for easy location of the device during maintenance and calibration.

2. Product Characteristics

a. Quantity:

- At least one working model should be fabricated and assembled.

b. Target Product Cost:

- The current funding is approximately $2500.
- Target cost of development, material acquisition, and fabrication should be approximately a factor of 2x less than the allotted budget, in order to eliminate the need for further funding.

3. Miscellaneous

a. User-Related Concerns:

- Because the tanks are occasionally lifted up, there is chance that a tank may be accidentally dropped back onto the base. Therefore, the device should be able to withstand the impact resulting from such drops.
- The device should be easily accessible for the user to conduct maintenance and calibration, in order to reduce potential complications or injuries.

b. Competition:

- Current refinements in digital electronics is, in effect, making level sensors the popular market option for monitoring liquid nitrogen levels [2]. Operation is largely capacitance-based using cryogenic liquid as the dielectric.

9.3 Final Prototype Python Code

```
# Code by Jeffrey Tsai
# Last modified 12/3/18
import serial
import datetime as dt
import matplotlib.pyplot as plt
import matplotlib.animation as animation

ser = serial.Serial('/dev/ttyUSB0', 115200)
for i in range(8):
     s = ser.readline()


fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)
xs = [0]
ys = [0]
data_point = 0
prev_point = 0
```

```
# Function called periodically from FuncAnimation
def animate(i, xs, ys):
    global prev_point
    s = ser.readline()
    t = s.decode("utf-8")
    n = t.index(',')
    y1_data = t[0:n]
    y_data = float(y1_data)
    if y_data < ys[0]:
        ys.insert(0, y_data)
    else:
        ys.append(y_data)
    xs.append(i)

    # Draw x and y lists
    ax.clear()

    if y_data>prev_point and abs(y_data-prev_point)>0.02:
        ax.plot(xs, ys, "g-")
    elif y_data<prev_point and abs(y_data-prev_point)>0.02:
        ax.plot(xs, ys, "r-")
    else:
        ax.plot(xs, ys, color="blue")

    prev_point = y_data

    # Format plot
    plt.xticks(rotation=45, ha='right')
    plt.subplots_adjust(bottom=0.30)
    plt.title('Weight over Time')
    plt.ylabel('Weight (lbs)')

ani = animation.FuncAnimation(fig, animate, fargs=(xs, ys),
interval=800)
plt.show()
```