Integrated Digital Scale and Data Logger with Alarm to Monitor LN2 Refrigerators
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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 -132°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 smart monitoring system that uses algorithms to predict failure. Because there is a direct relationship between the weight and the level of liquid nitrogen with 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, calculate the rate of loss of liquid nitrogen in real time, log data onto a remote platform, and send warnings regarding critical liquid levels, excessive leakage, and potential failures. 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 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 constitute the largest segment of the cryogenic equipment market based on product type, and the market 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].

Prominently used in fertility clinics, storage tanks containing frozen human reproductive samples are subject to daily inspection of the quantity of LN2 in the tank in order to detect tank leakage or impending tank failure. LN2 continuously evaporates at a slow rate, necessitating that tanks be topped off daily to ensure tissues and cells do not get damaged as a result of low LN2 volume. At low LN2 levels, the temperature rises suddenly and significantly, damaging frozen samples. This is commonly referred to as a tank "failure".

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]. Women, some of whom freeze eggs before undergoing medical procedures that render them infertile, entrust fertility clinics with their hope for children. Any damage or loss to these frozen eggs or embryos 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. 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 [3].

In order to safeguard against failure, monitoring systems for LN2 storage tanks are essential and widely used. Currently, there are many instruments and techniques used for LN2 level monitoring; however, LN2 tank failures are still being reported. 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.

1.2 Existing Devices

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

Accordingly, many LN2 tanks do implement automated monitoring systems, 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 monitoring modalities currently on the market include, but are not limited to: capacitance liquid gauges, ultrasound sensors, and temperature sensors. Unfortunately, some of these methods are costly, ineffective, and do not relay information regarding leak rate and the corresponding health of LN2 tanks.

1.2.1 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 3**) [6]. 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:

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

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

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.

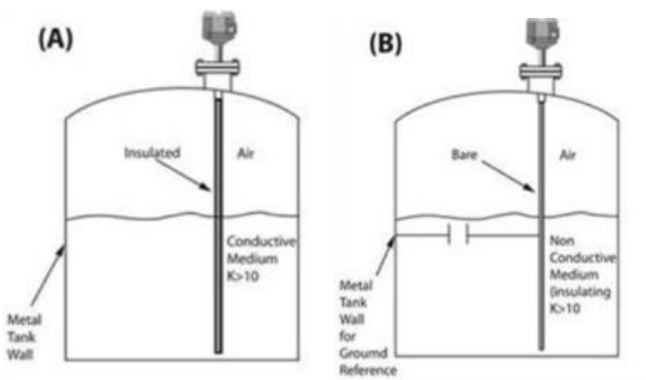

Figure 2: Capacitive level sensors measure the change in capacitance between two plates and can be used for fluids with high dielectric constants (A) or low dielectric constants (B).
Cost: ~$100-500
Image taken from:
https://www.sensorsmag.com/components/a-dozen-ways-to-measure-fluid-level-and-how-they-work.

1.2.2 Ultrasonic Sensors

Storage tanks that use ultrasonic sensors are built such that they have a transducer mounted in the lid (**Figure 4, 5**). 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.

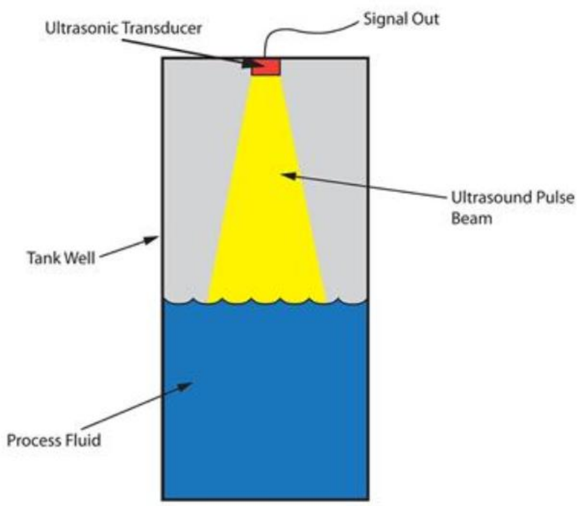

Figure 3: Ultrasonic sensors possess advantages such as simple structure and easy installation/maintenance, but are affected by temperature variations and electromagnetic interference.
Image taken from:
https://www.sensorsmag.com/components/a-dozen-ways-to-measure-fluid-level-and-how-they-work

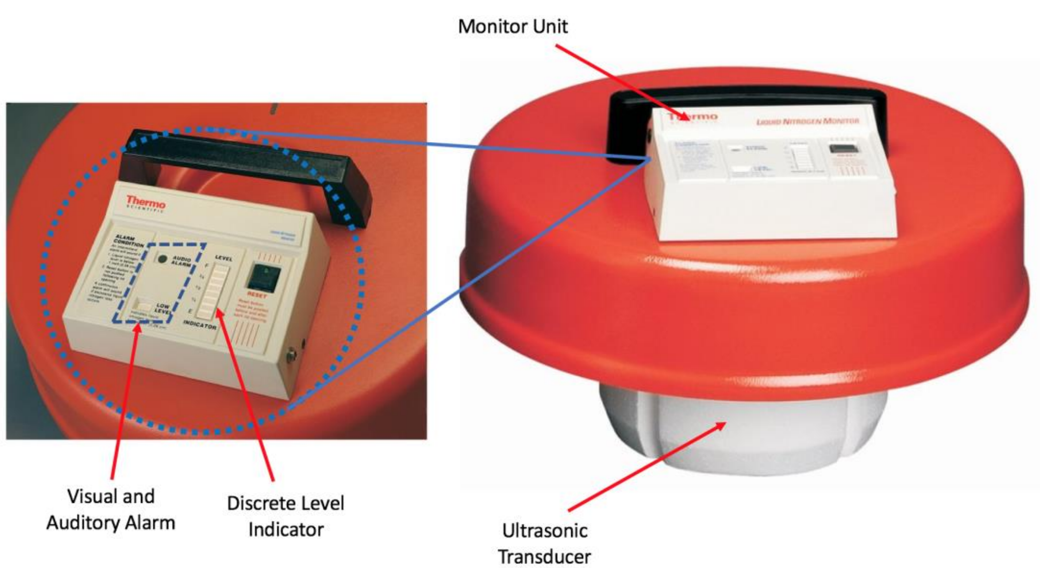

Figure 4: The Thermo Fisher Scientific Level Sensor features an ultrasonic transducer embedded into the lid. In addition, it features an on site monitoring unit with discrete level indication and alarms. There are no data-logging features.
Cost: ~$1000-1500
Image taken from:

https://www.thermofisher.com/order/catalog/product/CY509105

1.2.3 Temperature Sensors

Resistors, diodes, and thermocouples are popular and widely used examples of temperature sensors (**Figure 6**). 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.

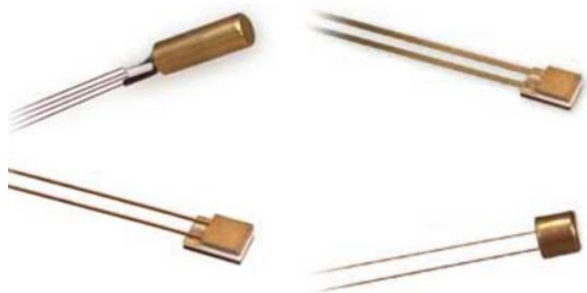

Figure 5: Resistors, diodes, and thermocouples are commonly used temperature sensors for cryogenic applications.
Cost: ~$50-100
Image taken from:
https://cryogenicsociety.org/26565/news/cryo_sensors_emerging_applications/

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 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 only utilize an audible alarm - which is ineffective if there is nobody in the room to hear it. 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 us 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® data logging and temperature monitoring platform, and control a local alarm system when a failure is detected. The ultimate team objective is to create an innovative design that satisfies general market needs, while applying the requirements and limitations of the client-specific problem. The team plans to accomplish this by implementing a more 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 is presumed to provide an indefinite longevity to cells, and the boiling point of LN2 (-196°C) is the preferred temperature for storing important specimens [7]. 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; however, 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 involve some sort of mechanism to vent pressure and LN2 vapor. However, this results in loss of LN2, which necessitates frequent monitoring and periodic refilling. While other devices (such as various freezers and refrigerators) may be used, the temperature of liquid nitrogen is generally required for successful preservation of the more complex biological structures to virtually stop all biological activity [7].

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 [8]. They can be as low as 0.4% or as high as 3% of the tanks' volume per day [9].

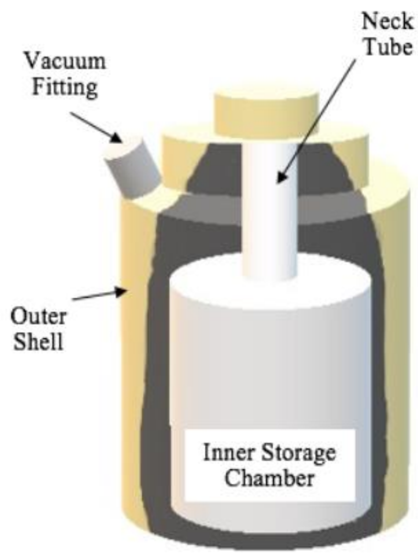

Figure 6: Small-capacity LN2 storage tank. The partial vacuum is between the tank's outer and inner shell. Samples are stored in the inner storage chamber.

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 [10]. 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**). The rapid warming of the tank leaves clinics with little time to replenish LN2 levels before the tank fails.

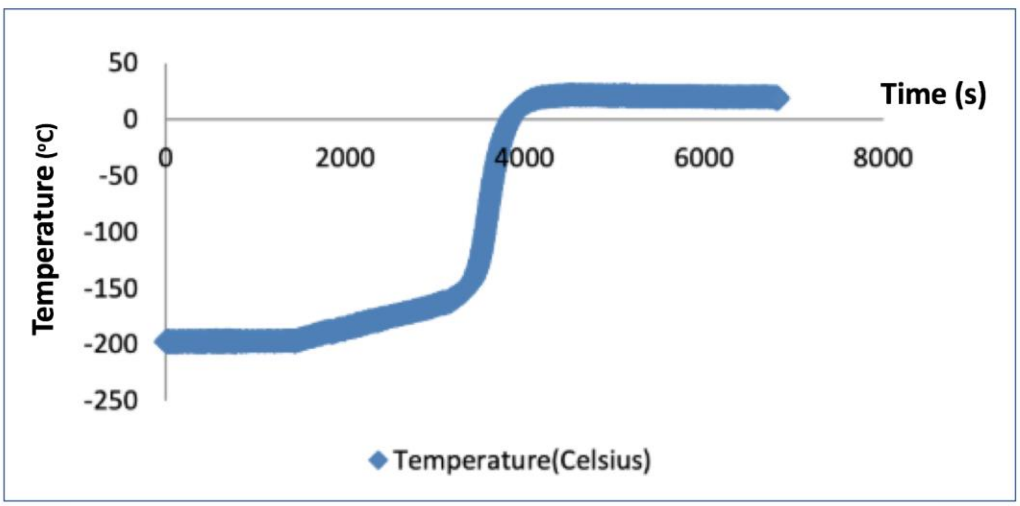

Figure 7: The temperature of a highly insulated tank rises from -150°C to 0°C in eight hours [10].

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 [10].

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 [11]. 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 may have to be able to support the maximum weight ±10% of the tank, if the monitoring system in any way has to support the tank's weight.

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 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

All weight based designs feature data logging and monitoring. The recorded weight will be sent to a database that features threshold monitoring, leak rate tracking, and failure prediction. These monitoring features will be accessible via an on site monitor and/or remote access through 3rd party devices. See **Section 4** for a detailed description of the decision making process, resulting in the following design concepts.

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 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.

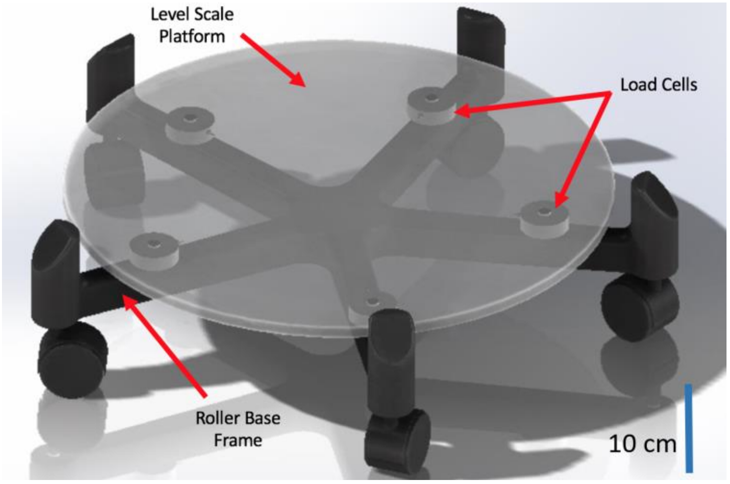

Figure 8: SolidWorks rendering of a custom designed scale, attached to the existing roller base.

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. 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.

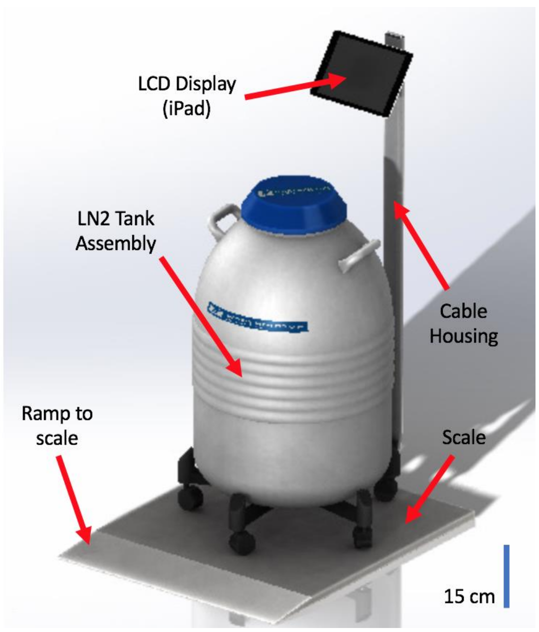

Figure 9: SolidWorks rendering of a standalone scale with an interactive LCD display.

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. 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.

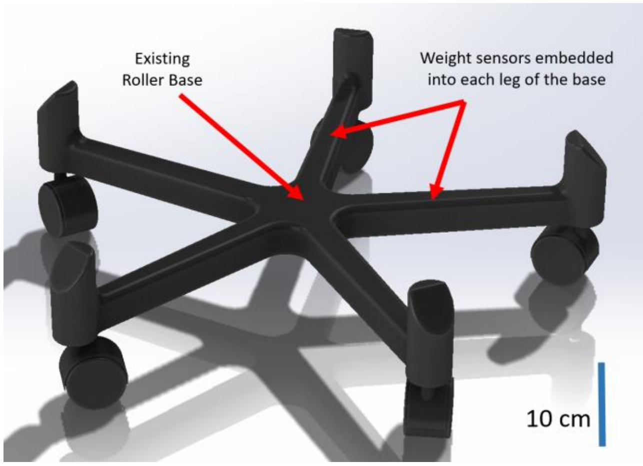

Figure 10: SolidWorks rendering of the existing roller base with weight sensors embedded within the base itself. Note that the size and appearance is no different that the unmodified base.

4. Preliminary Design Rationale/Evaluation

4.1 Design Matrices

4.1.1 Addressing Failure

The first question we need to answer about mitigating the risk of failure in LN2 tanks is what part of the overall system needs to be redesigned. Though our client has proposed the development of a weight-based monitoring system to detect tank failures, it is necessary to determine whether this is the optimal approach to the entire problem space. One option is remodeling/improving the overall design of the tank. Specifically, we must consider if it is a viable option to address the leak rate directly, by manipulating the integrity of the system itself. A second option is to assess the viability of developing a new system that would completely omit the risks of failure seen in existing refrigerating systems. A final option is to accept the potential failure of the existing system, but incorporate a monitoring system to inform the handler about the integrity of the system and predict failure before it happens.

Tank failure comes in various forms, such as excessive pressure buildup and gaseous leaking. Redesigning the tank to be a perfectly sealed system presents the problem of excessive pressure buildup due to the warming of LN2, phase transitioning into gas. This can result in an explosion, which is obviously a catastrophic failure and will render all samples unviable. As such, gaseous leakage is an acceptable compromise. However, excessive leakage will result in rapid depletion of LN2, and can result in failure.

As previously stated, the average failure rate is extraordinarily low, indicating that the design of the current refrigerating systems are highly fine tuned and reliable [12]. The most common source of failure results in excessive gaseous N2 leakage. However, due to the fact that gaseous N2 leakage is required in order to prevent pressure buildup, it is questionable whether or not there is a valid justification for manipulating the existing designs. Likewise, developing a brand new system that is capable of cooling the system to -196°C without encountering the aforementioned risks of failure would be costly, time consuming, and highly labor intensive. Therefore, the most practical method appears to be safeguarding against failure because it would be difficult, if not impossible, to eliminate the potential for failure altogether. After analysis of the various aspects of cryopreservation, including the design and structure of storage units, the cryogenic fluid used, and the data on causes of past failures, the team has decided to pursue the design of an alarm monitoring system.

4.1.2 System Monitoring Modality

Proceeding forward with a monitoring system, we must determine the most effective method of monitoring the LN2 levels within the tank. Existing products utilize a variety of sensors to interpret LN2 levels within the tanks such as temperature probes, capacitors, and ultrasonic transducers. Based on our client's interest in weight-based level monitoring, in addition to the leading products on the market, we considered sensing modalities in the form of weight acquisition, differential capacitance, and ultrasonic transduction. We assessed these modalities based on the following criteria: accuracy, longevity, ease of installation, and cost.

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. 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.

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 to be developed 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 an attachment for the existing base 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

After a critical analysis of the exact issues that lead to failure in LN2 refrigerating systems, we were able to conceive a viable design that would rectify the issue. Specifically, we will develop a custom scale 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. The system will be capable of not only sending alerts in the event of critical LN2 levels, but will also be capable of predicting failure of a system based on critical leak rates.

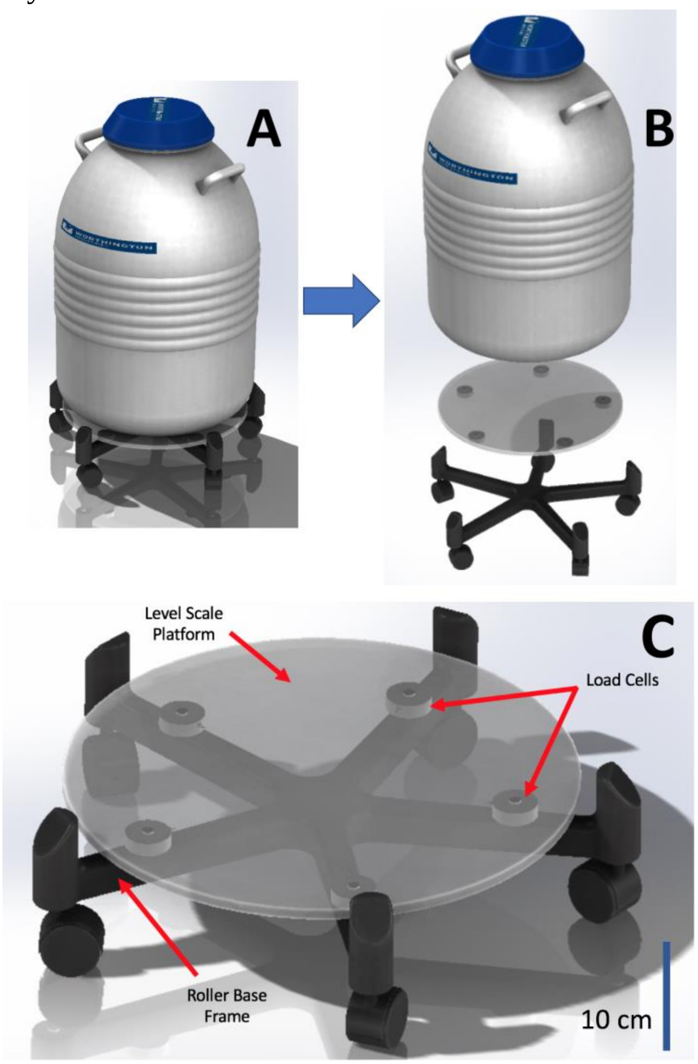

Figure 11: (A) Fully assembled roller base/weight sensor with the tank placed directly on the assembly. **(B)** An exploded view of Figure A, showing the individual components: roller base, weight sensor, and LN2 tank. **(C)** Annotations of the weight sensor integrated with the roller base.
Note: All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

5. Fabrication/Development Process

5.1 Materials

The proposed final design will feature both hardware and software components. In terms of hardware, the materials used in design include a roller base, load cells, a VHC 35 cryogenic tank, and a platform for the tank to sit on. The roller base is made from aluminum and has plastic wheels which allow for any 2-D motion (i.e. translation and rotation). The load cells should be made from materials that are resistant to shock and corrosion from chemicals. Steel load cells (either plated or stainless) may prove to be a viable option that will optimize precision and accuracy of the scale throughout its lifetime. The platform plate will also be made from stainless or plated steel.

The main component used in software development will be a Raspberry Pi microcontroller. This microcontroller will be used in conjunction with Networked Robotics NTMS4 unit, the specifics of which we are currently unsure of and will require third party collaboration with Networked Robotics.

5.2 Methods

The hardware will be designed and assembled before the software. Though the team will need to further explore load cell options, material for the platform, and exact methods of fabrications, the major steps in the fabrication process include: machining a lightweight rigid platform for the tank to reside on, attaching load cells to the base, and using cords and wires to connect the system. The machining of the platform and assembly of the load cells will likely be done using resources from the UW-Madison TEAM lab.

Testing is needed to validate the accuracy of the individual load cells as well as the orientation and arrangement of the load cells. The load cells will be connected to the microcontroller using wires. An amplification circuit for the signals from the load cells may be needed before signals are read by the microcontroller, depending on the amplitude of output from the load cells. The team has determined the microcontroller will likely be connected to the Networked Robotics interface using an Ethernet cable, since the interface is already using Ethernet ports for communications and the Raspberry Pi microcontroller also has an Ethernet port.

The next step will be to develop software that the Raspberry Pi microcontroller runs for weight measurements, calculating leak rate, data logging, and communications. This may require third-party collaboration with Networked Robotics.

5.3 Final Prototype

The final prototype will undergo multiple design iterations and vary significantly from the rendered images of the proposed final design (**Figure 8**). Several elements of the design were not rendered for the purpose of illustration and also the lack of a concrete implementation strategy. For example, the exact method of attachment to the roller base was neither rendered nor described because we have yet to receive a physical version of the roller base. Additionally, wiring was not portrayed due to the fact that we lack information regarding exactly how many sensors we need, sensor models, power source, integration platforms, etc.

Once we begin material acquisition and fabrication, necessary adjustments to the design will become apparent. The final prototype has the potential to be a fully developed product, but could also be a stepping stone to a further refined product.

5.4 Testing

As previously mentioned, the viability of load cells under long-term load application is relatively unknown. As such, we will conduct experiments to determine how long a load cell can maintain the weight of an object before becoming permanently damaged or losing its ability to accurately assess weight. If we are to find that load cells are an impractical fit for long-term weight monitoring, we will reassess our preliminary designs and proceed accordingly. If we find that load cells are, in fact, a viable option for long-term weight monitoring, then we will proceed with validation testing.

After fabricating our custom weight monitor and associated software, we will subject the system to various test trials. The premise of validation testing is filling a vessel with fluid, placing the vessel on the scale, and monitoring the leakage of the vessel. We will manually log the volume (**Eq. 2**) of the fluid in the vessel at incremental time intervals and use our manual log as the gold standard for the leak rate. We will then assess the system's ability to accurately monitor and record leak rate according to **Eq. 3**.

$$\text{Volume} = \text{Weight x Density} \qquad \textbf{(Eq. 2)}$$

$$R_{leak} = \frac{\Delta W}{\Delta t} \qquad \textbf{(Eq. 3)}$$

$$R_{leak} = leak\ rate$$

$$\Delta W = change\ in\ weight$$

$$\Delta t = duration\ between\ measurements$$

However, in order to verify the accuracy of measurements the team should attempt to characterize and quantify the LN2 leak rate of the tank for various aspects. For example, we might consider quantifying the difference in LN2 loss from opening the lid compared to the loss from pressure ventilation. Literature values will be important in determining whether our system accurately reports and analyzes data. In addition, these values will allow us to test whether or not the predictive capabilities of our device are correct. Even if the team is unable to find archived data, we might consider doing our own testing to characterize the various sources of LN2 leak.

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.

The value of our project and proposed design involves creating a system with a more accurate and reliable hardware setup, as well as the development of accompanying software to record and analyze data as a means of predicting potential failures and commenting on the overall health of the storage unit. 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 as outlined by preliminary survey results.

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 be many times 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 recalibration to maintain accuracy. ISO9000 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 [13].

7. Conclusions

In consideration of the client request and preliminary market research, the team has determined that the best approach to addressing the issue of LN2 tank failure is to design a more reliable and predictive monitoring system. The client currently uses a temperature-based monitoring system for LN2 refrigerators. However, temperature is not a reliable way of predicting LN2 tank failures, because temperature has no significant correlation with the amount of LN2 in the tank. Weight provides a more reliable method of monitoring the amount of LN2 because weight is directly proportional to volume.

The client has proposed the use of a weight-based monitoring system for LN2 tanks. Moving forward the team has decided on the use of Design 1, which consists of having a digital scale mounted on top of the roller base of the tank. According to the product design specifications, the system should be able to continuously and accurately monitor the weight of the tank over extended periods of time. The system should integrate with the client’s current temperature monitoring system to record and analyze the data to send alerts about potential tank failures. The value in our system is in developing a more reliable system of sensors and developing novel software to predict failure and send alerts. Furthermore, such a system has applications to various other storage units used outside the presented problem space.

7.1 Future Work

Future work involves several major components: testing proof of concept, manufacturing prototypes, software design and integration, as well as continued market research. The team will begin with acquiring and assembling necessary hardware after finalizing design decisions. Because the team has decided to develop a weight-based monitoring system, the team plans to purchase load cells and subject them to a series of tests (specifically interested in reliability of measurement over extended use) as proof of concept for use in the final design. The team will also evaluate a few different options for the material of the plate in terms of mechanical strength, ease of fabrication, and cost. The final hardware product will be a scale that can be easily installed and integrated to the existing roller base. Upon completion of a working sensor, the team will design the software required to sync data with the existing hardware interface (Networked Robotics NTMS4i) that uploads data to an online data logging platform. The software will also be capable of calculating leak rate by taking the derivative of the weight measurements over time and triggering a local alarm system when excessive leaking is detected. Throughout the process the team should also continue to do market research with the goals of better understanding the root problem, and to determine whether any market needs can be applied to our current design to create a more robust and versatile product.

7.2 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

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 alert threshold for LN2 volume and rate of change shall be customizable and set by the user
- The device shall be able to communicate data to the current "Tempurity" monitoring system
- The device shall use the current monitoring system 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 each leg of the roller base; the device shall accurately record the weight of the liquid nitrogen in the tank within ±5%.

- 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 only require minimum or easy recalibration after prolonged use.

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.
- Glass level gauges and floats are examples of established level-sensing technology used to continuously monitor LN2 levels.
- Displacers, bubblers, and differential pressure transmitters are examples of hydrostatic devices used to continuously monitor LN2 levels.