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Design of a Hydraulic Weighing System for Alfalfa Silage at Macdonald Farm

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List of Abbreviations

ASABE	American Society of Agricultural and Biological Engineers
ASTM	American Society for Testing and Materials
BOD	Biological Oxygen Demand
CE	Conformite European
CFR	Code of Federal Regulations
CFU	Colony-Forming Units
COHSR	Canadian Occupational H&S Regulations
DM	Dry Matter
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
FDA	Food and Drug Administration
LLDPE	Linear Low-Density Polyethylene
NIOSH	National Institute for Occupational Safety and Health
OMAFRA	Ontario Ministry of Agriculture, Food, and Rural Affairs
RC	Ready Containment, LLC
RCRA	Resource Conservation and Recovery Act
SCBA	Self-contained Breathing Apparatus
SIA	Social Impact Assessment
ST	Sylvin Technologies
TLC	Theoretical Length of Cut
WSC	Water-Soluble Carbohydrate Contents

Abstract

In this paper, a system to accurately measure the mass of alfalfa silage within a tower silo is proposed. Currently, there are no methods to accurately measure the mass of silage, only comparison tables provided by the American Society of Agricultural and Biological Engineers (ASABE). There are many challenges to accomplish this task, and the hardest to overcome are a small 0.61 x 0.61 m entrance, fermentation and biological processes within the silage, and finding an accurate way to measure mass accounting for vertical forces acting on the silage. The paper discusses four approaches to this problem with two being of greatest value for a solution. The final selected design was a small, ring shaped, fluid filled bladder placed at the area of highest pressure at the base of the silo (at 55% of the total radius of the silo). The system was modelled and was predicted to have an accuracy varying with the height to which the silo is filled, and smaller than 7% if it was filled with 9 or more meters of silage. Unfortunately, a small

scale prototype was not able to be completed because of cost and logistical constraints, so further steps would include a physical model either large or small scale.

1. Introduction

1.1 Background

Silos are cylindrical or square storage units used to conserve livestock feed in the form of grains or silage (fermented feed). When used in optimal conditions, these storage facilities can provide cheap feed to horses, cattle and sheep. Wilkinson (2005) stated that they are an essential part of livestock and mixed farms, and have been used to store silage for over 3000 years. According to Reimbert (1976), the first silos were rudimentary and consisted in a shallow pit in the ground, in which fodder was simply covered in dirt. Modern silos are relatively tall structure, with a height typically ranging from 10 to 90 m. Reimbert (1976) says taller silos started being designed at the end of the 19th century when it was found that inferior quality fodder (the upper layer) remained the same regardless of the overall height of the structure, and that the quality of the lower layer increased with the height of the silo. These structures can be made of various different materials such as aluminium, stainless steel, masonry (concrete in particular) or wood depending on the specific application. From Chakraverty (2010), it is known that metal silos are prone to important temperature gradient and consequently a transfer of moisture across their structure, because of the high thermal conductivity of the material.

Wilkinson (2005) stated that silos can store a variety of different grains or silage, which is any wet biomass used for feed, and stored in sealed silos where fermentation will occur. For the present engineering design project, we will focus on Alfalfa silage (Lucerne or *Medicago Sativa*) which is a perennial plant used worldwide for hay production in which case it is baled, as forage or even as pasture. Cowan (2010) states alfalfa is very high in protein, various vitamins, calcium and carotene, which makes it a prime choice for animal feed. Generally speaking, alfalfa has a low ensilability potential compared to other species such as corn, ryegrass or grass. This translates itself by a slower fermentation and a final product that is poorly preserved, if the required measures are not applied, according to Wilkinson (2005).

1.2 Problem Statement

Current methods for the calculation of the mass of silage in a silo are inadequate. Typically, estimations are made based on initial moisture content of the silage, size and shape of the silo, and occasionally compaction sensors installed within silos. Modern techniques for estimating storage capacity are found in the ASABE standard D252.51 *Tower Silos: Unit Weight of Silage and Silo Capacities*. However, these are derived values, not direct data. This design aims to provide real time data about the pressure at the bottom of a tower silo. There is a known issue in this design as the storage of granular solids in a vertical silo causes lateral pressure to build from the top to the bottom of the silo. Chen (2016) explains there are many classical approaches to this design problem, mostly derived from plastic equilibrium equations with simplifying assumptions made. Equations from Reimbert (1987) will be used to account for pressure gradients in the silo. Appendix F shows variation of pressure as a function of time as described in Reimbert (1987). Biological production of effluent and gases during fermentation, aerobic deterioration, and field losses during handling of silage are major factors which affect the dry matter (DM), and the mass calculation in addition to the vertical forces. A system which delivers real time data is not only valuable for research, but allows for customers to maximize the amount of energy (and by extension, fodder) that can be given to livestock while minimizing costs (economic, environmental and social). The need for an accurate measurement of silage stems from the demand for high quality silage, and potential gains from obtaining data on the DM of silage in possession. Such a system would have to be accurate, food-grade, safe to handle, and engineered responsibly. This investment would enable farmers to accurately estimate how much matter is lost on the field, the amount of fodder that will be available to livestock for a given season, and get a prompt and fair estimate of the quality of the finished product.

1.3 Silage

A rapidly growing world population coupled with a significant increase in animal product demand (especially in low-income countries that undergo a steady industrial development and an increase in the quality of life) are synonymous with large scale, intensive livestock production, and thus a need for adequate feed for cattle, poultry and swine. Indeed, such systems are now necessary to sustain the aforementioned demand and ensure food security among populations, while optimal quality is ensured. Kaiser et al. (1997) says ensiled forages use for feeding cattle has been increasing steadily since 1975, and Cowan (2010) explains that high-quality silage can support intensive feeding systems imposed by current economic conditions, are cheaper than other feed sources such as corn, hay or direct pasture grazing and increase land and water productivity. Quality silage also has advantages over other methods in terms of nutrients: grass silage was shown to contain higher levels of protein and vitamin compared to the same product made into hay. Agro TechnoMarket (2011) explains that hay is often stored outdoors, and poor weather can create nutrient leaching from humid conditions, or bleaching caused by solar energy. Wilkinson (2005) describes silage as being storable for up to 5 years, and enables farmers to avoid wasting harvest surplus until it is required for feed, making it an excellent manner of preserving forage. It is also a versatile source of feed, as many different crops can be ensiled, such as corn, alfalfa, Italian ryegrass, and different species of clover amongst others. The choice of crop relies primarily on the local availability ensilability (potential of a crop to be adequately ensiled) and specific use of livestock. Nowadays, corn silage is extremely popular, has good quality and is quite high in energy and nutrients. According to Progressive Forage (2016), the United States corn silage production in 2015 was estimated at 125 million tons, which represents a total crop area of over 6 million acres. Data was also available for European nations, where corn silage represents approximately 50% of the total silage DM.

Although alfalfa is commonly considered to have a relatively low ensilage potential compared to other species such as the perennial ryegrass (*Lolium perenne*) or the tall fescue (*Festuca arundinacea*), alfalfa also has low DM and water-soluble carbohydrate contents (WSC). As an example, the perennial ryegrass stands at 200 g DM per kg fresh weight, and 35 g WSC concentration per kg fresh weight. Wilkinson (2005) gives values only reaching 150 g/kg FW and 9 g/kg FW for alfalfa. High WSC content is important when considering ensilage because a significant sugar content will lead to a superior finished product by facilitating the fermentation process. This implies that extra precautions and care in terms of harvest and storage should be taken in order to obtain high enough alfalfa silage yields. Orloff & Mueller (2008) recommends allowing harvested alfalfa batches to wilt until outdoors in windrows until the moisture content reaches 60 to 70%, which typically takes half a day to 24h. This step is crucial to reach a desirable DM content and avoid nutrient leaching from an excessive water content, which will allow farmers to obtain a well-preserved silage. Orloff & Mueller (2008) continues to state that moisture content should be monitored on a regular basis to ensure a uniform product. On the other hand, letting alfalfa harvest dry for too long is detrimental as respiration would cause notable energy losses in terms of carbohydrates being converted to carbon dioxide. Wilkinson (2005) explains that when the crop has reached the adequate moisture content, a metered-chop forage harvester (or silage harvester) is used to uniformly chop the forage to a desired length. This farm equipment can be calibrated to cut the forage to the right theoretical length of cut (TLC). Orloff & Mueller (2008) recommend a value usually ranging from 1.9 to 2.5 cm for alfalfa silage. Agriculture Canada (2008) explains that if the forage TLC is too high, it will be difficult to pack without air bubbles in the silo (poor compaction), inhibit fermentation and create molding. Adversely, a low TLC might increase fuel cost and decrease efficiency. After this step is completed, the alfalfa is ready to be loaded into silage trucks and placed in silos or pits.

1.3.1 Biological Processes: Fermentation

Pitt (1990), describes the biological process in four complementary phases: aerobic, lag, fermentation and stable phase. There is no doubt that fermentation is the fundamental phase which needs the most respect in order to obtain quality silage. Fermentation refers to the metabolic process through which organisms such as bacteria, yeast or other microbes break down carbohydrates found in a natural substance (in the form of starch, or sugar) to produce either and alcohol or an acid. After the alfalfa (or other silage) has been deposited in the tower, farmers must make sure that the mass is tightly packed and moist enough, but more importantly that the silage is kept under strict hermetic conditions. Indeed, in conjunction with inhibiting fermentation, allowing the circulation of air in and out of the vessel would encourage the formation of mold, which may destroy the acids formed and/or be toxic to livestock (Lamb, 1919). Pitt (1990) describes the first step as the aerobic phase, and resumes when the various microorganisms present have depleted the oxygen that was trapped between the silage particles. This process typically takes a few hours, and is accompanied by a slight increase in temperature caused by microbial production of water, carbon dioxide and heat. The lag phase occurs next, with anaerobic bacteria becoming active and multiplying overtime. Fermentation itself occurs when the plant sugars (cellulose, hemicellulose) are converted to acetic acid first, and finally lactic acid. FarmWest (1999) states lactic acid is more favorable than its counterpart, and its concentration typically averages 70% of the total organic acid weight inside the silo, as well as 6% total dry weight lactic acid. Fermentation can last anywhere from two days to two weeks, and finishes when the pH drops to about 5, and is too low to allow bacteria to thrive. This is where controlling the initial moisture content of fodder is crucial, as studies have shown that a starting MC of 70% or more can lead to formation of butyric acid instead of the aforementioned lactic and acetic acid, which is problematic because it gives an unpleasant sour aroma to the finished product. A high moisture content can also cause silage effluent. The last phase, stabilization translates itself by feeding out the fodder from the silo, and a stabilization of the pH. Great care should be taken in order to keep the mass in aerobic conditions. A diagram showing the phases of fermentation can be found in appendix C. Indeed, mold and yeast growth still need to be inhibited to avoid any damage in terms of silage quality, and DM losses. Orloff & Mueller (2008) recommend implementation of simple techniques, such as unloading small amounts of finished silage at a time (around 5 to 15 cm per day) or verifying and disposing of any spoilage.

1.3.2 Silage Effluent

A common effect of storing silage within a silo is silage effluent. Silage effluent is runoff from biological materials stored in a silo. The wastewater that comes from silage is highly concentrated in nutrients and thus poses potential problems to the surrounding environment. Gabrehanna et al. (2014) describes the consequences to untreated effluent runoff as eutrophication due to its high biological oxygen demand (BOD), increasing pH of surrounding soil and water, and corrosion to concrete and ferrous infrastructure, including the silo in which it is stored. Silage effluent represents a because its BOD can be 100 times greater than that of raw sewage and concentration of nutrients N, P and K are similar to that of liquid dairy manure. Ensiling the silage at the proper moisture content helps to reduce effluent. Tyson (2017) shows that storing silage at a DM content at 30% has a significantly reduced effluent flow. To reduce the severity of effluent from silage methods such as: managing the crop moisture content prior to ensiling, ensuring the proper infrastructure to store effluent and avoid runoff to potentially harmful sites, and including measures to treat and dispose of the effluent should be put in place.

1.3.3 Use of Additives

A wide range of silage additives or inoculants can be used in order to improve the overall fermentation performance by killing undesirable bacteria, reduce crop buffering capacity, obtain forage with a higher nutritional value for livestock or increase DM recovery in the silage. These compounds or substances are destined to direct the fermentation process by interacting with the bacteria present in the silage. McDonald et al. (1991) describes inoculants as biological or chemical agents, and classifies them as either absorbents, stimulants, inhibitors or nutrients depending on their effect on silage. Wilkinson (2005) says the first additives to be used for forage were a mixture of hydrochloric and sulphuric acid by Nobel prize winner A. Virtanen in the 1930s, which showed a significant grass forage silage improvement, by destroying undesirable bacteria. Another subcategory of chemical agents are acid salts, which have been quite popular among European nations since the 1970s. These include salts of formic, acetic, nitric or propionic acids amongst many others. Woolford (1984) shows that these compounds are effective at eliminating unwanted microorganisms such as clostridia, coliform bacteria as well as yeasts and molds by lowering the pH of the silage, and thus destroying these acid-sensitive organisms, and encouraging lactic acid fermentation. It was however demonstrated that powdered acid salts are less effective than their corresponding acid and must therefore be applied more frequently (Henderson, 1991). Biological additives refer to microbial inoculants or enzymes which function by directly improving the efficiency of the fermentation process (reduced nutrient loss during silage storage, decrease of pH, increased fermentation rate, and plant cell breakdown that facilitates fermentation in the case of enzymes). For example, Wilkinson (2005) showed that adding lactic acid-producing bacteria (lactobacillales, pediococcus) as an inoculant in grass silage such as alfalfa is proven to intensify fermentation, and therefore prevail over the crop's low ensilability potential. Nutrients such as molasses, whey or starch are also used to provide energy for the bacterial population in the windrow. As a general rule, additives should be considered and chosen carefully depending on the crop and its specific needs (requirement of fermentation stimulants or inhibitors, natural or chemical agents, safety considerations, crop ensilability, concentrations etc…) Orloff & Mueller (2008) say that order to compare options as objectively as possible, additives are compared using a mass of active ingredient used per unit mass of forage, which translates itself by a number of colony-forming units (CFU) per gram of forage for inoculants, for example.

1.4 Silos

Storage of feed and hay has been needed since man created more food than it could consume at a time. Each civilization had a method for storing excess food in case of emergencies. Modern technologies have greatly advanced mankind's ability and capacity to store excess feed in safe, environmentally conscious ways. Hay (1909) explains storage facilities are called silos from the greek "siros" meaning pit for holding grain, and come in many shapes and sizes. Some typical designs include bunker silos, tower silos, and even horizontal bag silos. A shift in modern silo design has been towards the use of bunker silos in lieu of older designs. Bunker silos are composed of open, large, and divided sections which are filled with material. They are easy and inexpensive to build, as well as fill and empty as long as heavy machinery is on hand. This makes bunker silos good for storing materials. Bunker silo management practices affect forage quality according to Ruppel (1995). Daily DM additions, initial particle size, and covering methods all affect output DM.

1.4.1 Tower Silos

During the turn of the century, use of square silos had started to diminish, according to Hay (1909). However, in Québec many concrete tower silos were built during the 1900s and these will be the focus of this paper. Bozozuk (1979) shows that from 1969 to 1979, approximately 1200 concrete cast-in-place and stave silos were produced in Québec. There are several thousand more created nationally across Canada. These concrete silos are generally well designed and last many years despite minor tilting or structural displacement challenges. Major issues concerning concrete tower silos concerns the strength of their foundations or the soils on which the foundations are constructed. Weak foundations or soil structure can lead to tilting and differential settlement according to Bozozuk (1979). Concrete tower silos may be top or bottom unloaded using built-in machinery, according to Macdonald farm manager Paul Meldrum. This makes them convenient for storing animal feed as they can be efficiently emptied with low risk of spoilage. Factors which impact DM in tower silos includes initial moisture content, internal and external temperatures, storage time, and particle size. Several concrete silos were built here at the McGill Macdonald farm, and the *Hydraulic Scale for Weighing Alfalfa Silage* was designed specifically for silo 5 at the McGill Macdonald farm. Blueprints for the silo and the 0.61 x 0.61 m entrance specific to the planning of this design can be found in Appendix A.

2. Project Vision Statement

For this project, our team aims at accurately designing and modelling a cost-efficient hydraulic system for the instantaneous weighing and measurement of alfalfa fodder mass in a silo, by applying engineering sustainability principle, assessing and managing risks factors that may arise from different sources (ergonomics, hazards, reliability, ethical and social considerations, etc..).

We will accomplish this study by first discussing the various parameters and processes that come into play during ensilage of alfalfa, that is physical, chemical and biological ones (fermentation, leaching, etc..) For this step, we will be looking at the system as a whole (crop, alfalfa and silo) in order to keep the scope as clearly defined as possible. We will then use the knowledge we acquired to make a full proposal for a hydraulic weighing system adapted to this particular application. Lastly, we will expose all the potential risk management issues one might encounter during the manufacturing process, and give an estimation of the cost such a system might have.

3. Selected Design

3.1 Initial Assumptions

A list of important assumptions have been made before designing this system, in order to simplify the tasks from a mathematical standpoint, and to help adopt good risk management practices early on in the project. The list is as follows:

a. Silo 5 follows the current CSBE estimates for maximum capacity for a 4.88 x 18.29 m silo, which is 255 tons of 60% moisture alfalfa hay (Jofriet 1982).
b. Pressure is not evenly distributed throughout the silo; there exists a pressure gradient due to frictional forces along the walls of the structure.
c. The vertical downwards pressure gradient follows the models given by Reimbert (1987).
d. The horizontal lateral pressure gradient follows the models given by Reimbert (1987).
e. Although there is a leveling arm at the top op of the unloader, it does not interfere with pressure measurements.
f. Outside temperatures will not affect the condition of the fluid within the bladder assuming it is not within 0.3 m of the silo wall according to Jiang et al. (1988).
g. Alfalfa silage is a good insulator and protects the bladder from outside temperatures.
h. The design will fail eventually.
i. Based on a series of calculations, we agreed that an acceptable percent error is 5-7%. This was later verified using our simulation.

3.2 Design Modeling

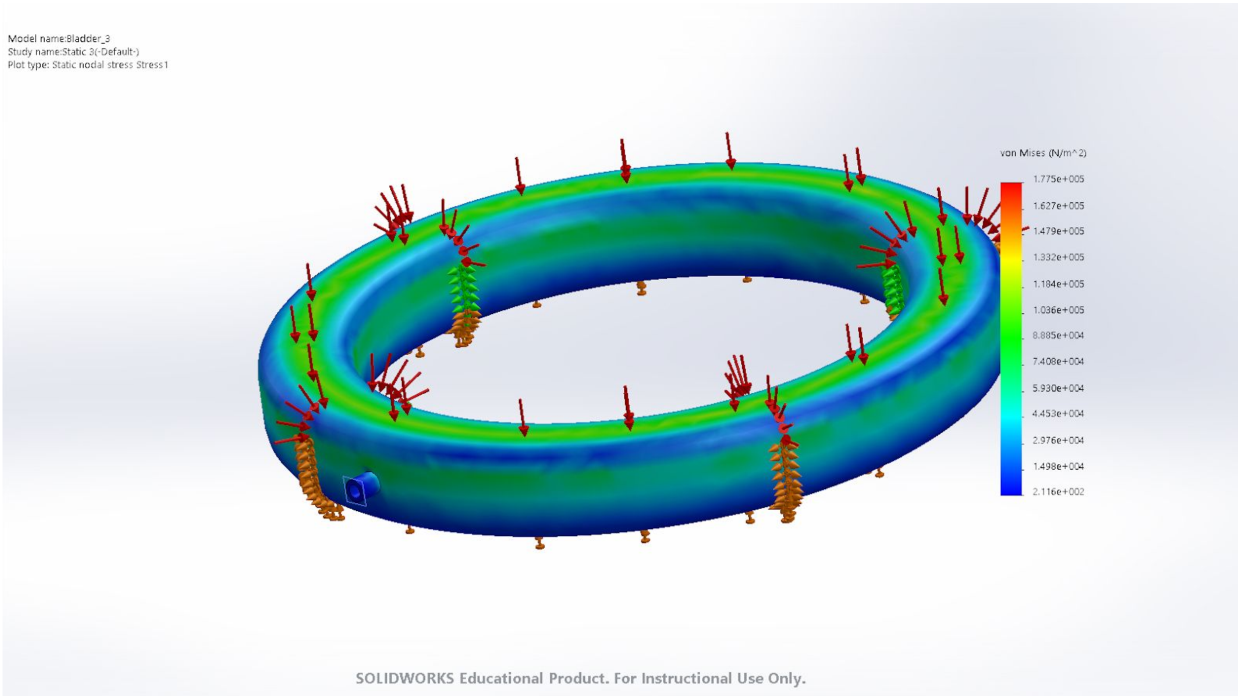

Figure 1: SolidWorks Model of the Selected Bladder, Showing Pressure Distribution

As illustrated above, the bladder design we have accepted is a hollow torus shape with an attachment on the front face for either a hose, so it may be used as a piezometer. Or, for a more accurate reading, a pressure gauge may be attached. This model was created in SolidWorks due to the lack of funding to create one in reality. The advantage of this, is that it allows us to subject our design to specific, calculated loads over its entire surface for a more accurate evaluation of when and where it will fail. As is noted by the scale to the right in Figure 1, this bladder design distributes the pressure evenly across all surfaces and shows no signs of puncturing or pressure points. This was a major selling point on selecting this particular design.

3.2.1 Mathematical Validation

A model was developed using the software SolidWorks, in order to prototype and predict the accuracy of the design. Using equations from Reimbert (found in appendix D), we were able to model the vertical and friction loads experienced by the silage on the silo to determine what type of pressures the bladder would experience at the bottom. These values were then fed into SolidWorks to test how the geometry of our bladder design would compress. As seen in Figure 1, the pressure is distributed evenly over all surfaces and no apparent punctures or pressure points can be seen. This is a positive confirmation that our design will not fail due to a singular point of weakness. Due to the circular shape of the design, many of the components will deform and compress equally.

In order to simulate the pressure distributions for Silo 5 at Macdonald farm, a Matlab Graphical User Interface was developed to accept various parameters from its user in order to determine the theoretical mass of ensiled material. This, however, was converted to an Excel program shortly after due to the lack of accessibility to and knowledge of Matlab from our client. In short, the program asks the user to input several variables including: the angle of repose of the ensiled material; the moisture content of the ensiled material; the height and diameter of the silo in question; and the maximum fill height that the silo can accommodate. Once these parameters are configured, a simple code determines the appropriate coefficient of friction to use and the bulk density of the material. These two factors are determined primarily from the moisture content of the material and have corresponding values based on work by Jofriet.

After obtaining the varying vertical pressures along the multiple heights of the silo, equation 5 in appendix D can be used to determine the height of displaced oil in the piezometer component of the design as seen in Figure 4. The maximum displacement of oil for Silo 5 is approximately 2.5 meters. Using this simple method, the farmer could roughly gauge the amount of alfalfa ensiled visually. This, of course is subject to a degree of error. Due to the shape of the silo, at a radius of 55% the silo's radius, the vertical pressure may be subject to a scaling factor of 1.2x its maximum value. As can be seen in Figure 19 in appendix F, as the height of the ensiled material increases, this error decreases. This proposes the question, "for what heights is the piezometer reading accurate?" In order to be within 7% of the actual value, it is suggested based on the Excel tables that this method is accurate for material ensiled above 9 meters. The closer to the max fill height of the silo, the more accurate the reading becomes. For this particular silo, as one approaches the 18 meter mark, the error reduces to roughly 4%. For a more accurate reading, it is suggested that the user of this design utilize a Bourdon pressure gauge in lieu of the piezometric reading.

3.3 Selected Design

3.3.1 Overview and General Challenges

While designing a system to measure the mass of silage, a series of engineering problems had to be overcome. Major design challenges included a 0.61 x 0.61 m entrance to the silo. This limited the options we had for any design solution that required large-scaled equipment to be installed inside the silo. The frictional force against the silo walls creating pressure gradients are a known factor that skews the results of direct measurement within silos. Lastly, working with animal feed poses two problems: the solution must be food grade, and cannot fail due to biological processes that occur within the silo. By using a food grade fluid filled bladder to measure the pressure at the base of the silo, most of the challenges are negated. Appendix B shows several diagrams of the bladder sitting at the bottom of the silo with a manometer attached to the side. Other design considerations are materials for the bladder and tubing, placement of the bag in the silo, and sensitivity of the pressure gauge.

3.3.2 Bladder

A ring-shaped bladder will fill the role of a deadweight tester by transferring downwards pressure from the silage to a fluid connected to a pressure gauge. Diagrams of the bladder in place can be found in Appendix B. The bladder will be installed through the 0.61 x 0.61 m door along the side of the silo. Because fluids are incompressible, pressure will be evenly distributed along the bag reducing point loads and risk of bladder puncture. By adjusting the size and shape of the tank, differences in pressure along the horizontal axis can be avoided. Ready Containment LLC (2017) (RC) produces bladders which are used for tasks such as transporting jet fuel, storing water, and impact testing. For these reasons, a bladder is a good choice for measuring the mass of silage in a silo.

The shapes and materials of bladders are typically rectangular and made of plastics or reinforced composite plastics, but are highly customizable. RC has already produced circular bladders for weight or impact testing. Circular bladders will reduce stresses on the corners of tank and help evenly distribute pressure throughout the tank. However, reinforcing a rectangular bladder with some bulkheads can also help evenly distribute pressure and reduce point loads on corners and seams. A recommendation from RC suggested using bulkheads to support the bottom and sides of the bag while allowing a hole at the bottom for valves to be attached to the pressure gauge. This will prevent point stresses and rupturing of the tank. RC also often uses coatings to reinforce their tanks. Coatings will impact the chemical resistance, tensile strength, and permeability of materials they are applied to. This is important for the design because the bladder will be in contact with strong acids from the silage fermentation. Resistance to lactic acid, acetic acid, and butyric acid are imperative for the function of this design, as they are produced in significant quantities during fermentation. PVC has moderate resistance to lactic and acetic acid concentrations of 25% up to 60°C according to Ipex (2013), and is a standard material available from RC. This will also help keep costs lower as custom bags are much more expensive.

Placement and size of the bladder will determine how accurate the measurement of pressure is to the average pressure at the base of the silo. Reimbert (1987) says downwards pressure, as a function of the radius of the silo, builds to a maximum of 125% the total average downwards pressure, at 55% the distance of the radius, then drops to the minimum pressure against the sides of the wall of the silo as can be seen in Figure 15 of Appendix F. The build is gradual from the center, so placement of the bladder in a ring around maximum pressure is optimal. The size of the tank should be large enough to precisely measure the maximum downwards pressure, but not so large that the measurement will have a high error. Modeling provided the data needed to confirm these assumptions.

3.3.3 Hydraulic Tubes

Tubing is needed to connect the bladder component to the pressure sensor. Although a variety of plastics are used in tubing production, Parker Hannifin Corporation (2017) shows that high quality polyethylene tubing is functionally resistant to both lactic acid as well as acetic acid. Our selected tubing system is a series E (instrument-grade) linear low-density polyethylene (LLDPE) tubing. LLDPE is a copolymer of ethylene and an olefin (such as 1-butene, 1-hexene or 1-octene) which has a higher environmental stress-cracking resistance than other types of ethylene polymers. Another motivation for our choice is a lower overall cost than other ethylene polymers (TBL Performance Plastics, 2017). According to this manufacturer, the suggested applications of this material are chemical transfer, potable water systems and low cost, low pressure pneumatics, which justifies our choice. The fact that polyethylene is generally used in the food and beverage industry and that this tubing is very resilient to high pressure ranges and acids makes it a very good choice for the design. This tubing features 100% virgin resin polyethylene, is chemically resistant to fermentation by-products and provides long-term strength and dimensional stability. It also has a wide range of certifications, including but not limited to the ASTM D-1693 and FDA compliance for food contact. Our team chose the model E-108-XXXX in natural polyethylene, as this item offered the largest tube internal diameter, standing at 12.7 mm. This choice is mainly motivated by the fact that larger diameter for tubes enable more accurate readings and therefore helps minimize potential errors for our system. This was confirmed by a personal communication with a Parker Hannifin sales representative (2018). Other noteworthy specifications include a working pressure of 4.8 bar and a minimum burst pressure of 19.3 bar. Considering our calculations related to the theoretical pressure at the bottom of the silo, this tubing system can be safely used in our system with minimal damage risks.

Based on our SolidWorks design, we would need a tube length of approximately 5 m. According the Parker Hannifin Corporation (2017), this type of tubing comes in packages of 100, 500 or 1000 ft. The detailed cost estimate can be found in the following section.

3.3.4 Pressure Sensor

For the purpose of this project, we aimed at choosing a pressure system as simple and cheap as possible. Indeed, the goal for the weighing system is to be a universal and repeatable design that would target a broad range of users working with farming equipment, be easy to handle (good ergonomics) and minimize the risks linked to human errors. The final choice should also take into consideration sensitivity factors (i.e how precise our system should be). To do so, a variety of pressure measurement instruments were assessed and compared. According to the initial assumptions stated previously, the bottom of the designed silo would have a pressure of 25.616 kPa. Since we are in a medium range of pressure (comprised between 1.013 and 7,000bar) (Morris, 2001), pressure sensors used for sub-atmospheric or pressures higher than 7000 bars are to be discarded (they include McLeod and Pirani gauges, thermocouple gauges, or other electrical devices used for high pressures). Instead, our work focused on moderate pressure force collector type sensors which directly measure the strain caused by a mass and translate it to a pressure value without translation to an electric signal. Appendix D contains a brief description of all 4 types of instruments considered.

Our choice for a pressure transducer was based on different related variables: necessary accuracy, cost factors, maintenance, practicality and overall sustainability. Both bourdon tube and manometer types are appropriate for oils (and liquids in general) and are very easy to operate. Our final choice was an Omega brand digital pressure gauge, part number DPGM409-001BG . According to Omega Corporation (2017), this digital pressure gauge is made of rugged 316 stainless steel, and is specifically designed for usage in harsh environments, with applications including industrial or marine. The DPGM409-001BG digital gage has a broad range of working pressures, namely 0.25 mbar to 345 bar, with and boasts a high accuracy of ±0.08%. This translates to an accuracy of 0.001 bar or 0.01 kPa, which corresponds to ± 0.054 kg over a 18.6793 m^2 area. This great accuracy is essential for our designed bladder system to be as efficient as possible, and to enable the farmers to obtain reliable, repeatable in order to avoid potential silage losses. The pressure gauge also features a large 2.5 x 2.5 cm display for easy and accurate readings that decrease the likelihood of human errors. It has been tested to Conformite European (CE) standards. This is a rather versatile gauge, as it can either be powered internally (using two 3.6 V lithium 8.4 Ah batteries which can last up to 9 months at a time) or via an external DC voltage source. Based on where the system is to be used and the local power supply source, the user can therefore make an informed environmental choice about the form of power the gauge is to work with.

With the purchase of each of these gauges, a free configuration software is provided. This element would enable the farmers to easily connect the device to a computer in order to calibrate the apparatus, and for general data logging. For the particular silo that our design is based on (silo 5, at Macdonald campus farm), the algorithm that was created will therefore be used based on values obtained through the configuration software in order to provide farm employees with real time, accurate mass readings of alfalfa silage within the structure.

3.3.5 Fluid Selection

The fluid selection is based on the assumptions made regarding the silo and the general parameters under which the design operates. On top of that, our hydraulic fluid must be food-grade, in order to prevent and minimize any contamination of the surrounding crops, grazing areas and water bodies in case of spillage. The fluid must also be cost-effective, widely available and either disposable or reusable for other farm operations or resale to potential clients. Our decision was also based on the low potential for cavitation, low corrosion potential, and constant and low viscosity in the fluid column for optimum flow within the system. The corrosion aspect is particularly important, as fermentation byproducts are very acidic. The fluid life must also be as large as possible, in order for users to minimize maintenance during the time of operations, and obtain satisfying equipment performance. Last but not least, fire-resistance of the fluid is crucial, as silos can be subject to fires in certain contexts, which are mentioned in the social impacts of the present paper. Regarding the fluid's flammability and likelihood of fire hazard, two variables are commonly assessed. First, the smoke point is the temperature at which a fluid starts producing smoke, thus increasing the probability of a fire occurring. Moreover, the flash point is the lowest temperature at which a fluid produces vapors which can be ignited in the presence of an open flame (Doddannavar et. al, 2008). They should indeed be as high as possible, to decrease risks associated with the design.

It is understandable that our selected fluid cannot meet all the requirements exposed. Given the nature of the problem, our choice was based on the following high risk criteria:

a. Flammability/Combustion
b. Low environmental toxicity and small carbon footprint (local sourcing)
c. Equipment-compatibility: lubrication, corrosion
d. Appropriate range of temperatures
e. Long shelf life

For the suggested criteria, the selected fluid is flaxseed oil which proved to be the best compromise between all the desired properties. Also known as linseed oil, the yellow-toned substance is obtained from pressing of the seeds of the flax plant (*Linum usitatissimum).* Its applications include oil paints, as a finishing product for wood, and as a food product and dietary supplement (Ardec, 2015). Flaxseed oil is mainly composed of unsaturated fatty acids (namely linolenic, oleic and linoleic) at a proportion of 88.97%. The remaining 11.01% are saturated fatty acids (stearic and palmitic acids) (Popa et. al., 2012). This is our preferred hydraulic fluid for several reasons. First of all, the melting point of flaxseed oil is -24℃ which is advantageous in our case, based on the range of temperatures our system will be exposed to (ChemicalBook, 2017). Although some heat in the silo is generated during fermentation, having a melting point as low as possible is essential to ensure no solidification will occur during the time of operations, which could clog the hydraulic tubes and damage the system. Flaxseed oil has a very low melting point compared to other vegetable oils considered, such as canola and soybean oil (-10ºC and -16ºC respectively) which explains our choice (Engineering Toolbox, 2017). Moreover, flaxseed oil is known to be an outstanding rust protector, and is frequently used in combination with metals for rust prevention. This is an ideal property for the design since it contains metallic valves and tubing connections. One of the challenges faced when attempting to select a hydraulic fluid is the combustion and flammability aspect. Indeed, some vegetable oils are either flammable (flash point lower than 37ºC) or combustible (flashpoint between 37ºC and

93ºC) (CCOHS, 2017). Standing at 107ºC, the flash point of flaxseed oil therefore meets our team's requirements (ChemicalBook, 2017). Flaxseed oil is a drying oil, meaning that it hardens when exposed to oxygen, and subsequently forms a film or solid layer. This process is known as autoxidation, is exothermic in nature and is responsible for the oil going rancid. This is due to flaxseed oil's fatty acid profile exposed previously, and particularly its high unsaturated fatty acid content (Shahidi et. al., 2011). This is the main challenge of using this type of oil as our hydraulic fluid, and therefore extra precaution and care needs to be taken in order to ensure the bladder is completely air-tight, and that no light or moisture reach the tank (Shahidi et. al., 2011). Although flaxseed oil is sensibly more expensive than our second choice (canola oil), its thermal properties among other aspect, make it the most appropriate hydraulic fluid in our case, and its is preferable to choose a slightly more expensive oil to avoid maintenance costs, and increased failure risks.

Canada is the world's leading flax producer, with a yearly total output of 872,500 tonnes as of 2014 (Food and Agriculture Organization of the UN, 2014). This corresponds to 33% of the world's production. This suggests that the carbon footprint associated with obtaining this material would be small since the oil would be transported over relatively small distances. Our preferred supplier is TA Foods Ltd, situated in Yorkton, Saskatchewan, and our oil cost estimation is based on a personal communication with their sales representative.

4. Alternative Design Proposal

Multiple solutions were considered before a final design was selected. Three particular methods were investigated and will be described in the following section: a piston-plate deadweight tester, a large bladder design, and a multiple load cell design. Each method comes with benefits and challenges which will be discussed as well.

4.1 Piston-Plate Deadweight Tester

A piston-plate deadweight tester consists of a large metal plate covering the base of the silo, resting on multiple hydraulic pistons. This system would rest at the base of the silo with the mass of silage pressing upon it. Due to the acidic effluent produced during fermentation of silage, a polymer cover or resistant coating must be applied to the plate to prevent corrosion. The plate exerts a force on the pistons causing a displacement of fluid which are read on a pressure gauge. The gauge reading would then be compared with a table or put through an equation to convert to a mass. This design gives an accurate reading of pressure, based on the fact that similar systems are employed at the Macdonald farm to measure the weight of silage, trucks, or other farm equipment on a deadweight tester. Despite these benefits, a number of major challenges stand in the way of this design. As stated earlier, the corrosive nature of the effluent forces the use of a coating or polymer cover on the piston which will add costs and maintenance fees to the design.

Another major challenge is the sheer size of the design. The installation of a 4.9 meter wide plate to the base of a silo requires heavy machinery, offers high risk to those installing a heavy metal plate, and will certainly not fit through the 0.61 x 0.61 m entrance to the silo. Already these challenges defeat the solution. In addition to installation and corrosion troubles, this design requires a number of pistons to rest on the base of the silo creating major point loads on the foundation. Cracking of the foundation is absolutely unacceptable, and would cost the stakeholder tens of thousands in damage. The final obstacle to overcome would be drainage of effluent. The plate, covering the entire base of the silo, would have to be outfitted with drains to leak effluent, and risk exposing the pistons and tubing to corrosive effluent. This design was a good starting point for the development of an effective solution, but did not offer solutions to all of the challenges.

4.2 Large Hydraulic Bladder

The second design considered was a thin fluid-filled bladder covering the entire base of the silo. The silage presses upon the bag causing a pressure to develop in the fluid which is read to a gauge. The gauge reading must again be converted to a mass by table or equation. This design solves the installation troubles that the piston-plate method could not. An empty bladder can be fed through the entrance and filled *in-situ* with hydraulic fluid. This design will be considerably less expensive as it has fewer parts, and there is no need for an acid-resistant coating because polymers can be highly resistant to acids. This design also mitigates the risk of fracturing the foundation as pressure is evenly distributed across the base of the silo. There is also previous data on the use of bladders for impact testing and deep-sea fuel storage available from ReadyContaiment LLC which show the resilience of the bladders to withstand large pressures. The material selection for this design follows the same process as the final design because the components are identical; the only difference is the size. A large bladder still comes with challenges, however. A major hindrance to this design is, similar to the piston-plate method, its size. Even a very shallow (<10 cm) bladder would require over a hundred gallons of hydraulic fluid. Another challenge is the novelty of this design. Bladders may be used to read pressure elsewhere, but there is no literature on using them for silo mass specifically. The accuracy of this design, therefore, can be put under question. Mathematical modelling was key in the development of equations and prediction of accuracy for the design, and farmers will have to refer to tables or equations to get their data which is another obstacle. A final challenge for this design was the drainage of effluent. Methods which considered covering the base of the silo were henceforth disregarded, and small bladder designs and load cells were considered.

4.3 Load Cells

Load cells could also be employed in the design of a weighing system for alfalfa silage. A series of six or more button load cells would be placed around the ring of maximum pressure in the silo, at 55% of the total radius. The weight depresses a spring and creates a voltage differential within the cell. The voltage is interpreted by a computer, and a value is finally displayed to the farmer. The load cells would require a protective cover or coating to resist the effluent. Further considerations for this design would be to organize a method to accurately transfer the downwards pressure to the load cell such as with a plate. The electronic signal must be translated by a computer, and load cells are expensive. Therefore, this solution is less cost-effective, but a full analysis was not conducted. However, an electronic component to the design adds much potential for improvement such as mobile updates through an app, automatic adjustment of silage additives, or automatic data collection and interpretation. Also, load cells will not take up the entire base of the silo, and allow effluent to drain. This design alternative shows the greatest potential for further research and trials for implementation, but was not selected because of its high costs and long development time for an electronic display.

The design process for these solutions took time away from the final design, and, although they served as a basis for further development, could have been more quickly discarded during the process. Upon review, the only alternate design which merits further consideration is the load cell system. This would provide an accurate reading of mass in an easy to read display to the farmers computer or mobile device. However, the high costs involved with this design pushed the development of the small bladder solution which overcomes most of the challenges associated with the silage weighing system.

4.4 Alternative Fluids

Based on the challenges and important fluid aspects to bear in mind mentioned earlier, our team considered several alternative fluid before settling for flaxseed oil. Of course, the only fluids that were considered for this design are natural, vegetable oils. Indeed, our main motivation was to develop a weighing system as environmentally friendly as possible, and this should be undertaken using low-toxicity fluids that are readily available.

Canola oil was a good first option regarding our working fluid. According to Katragadda et al. (2010), canola oil has a very high flash point compared to our preferred oil, standing at 326ºC, versus 107ºC for flaxseed oil. This makes it a safe choice for an alternative design, as the likelihood of a fire spreading in the silo would be greatly diminished by using this oil. Canada is one of the world's top rapeseed producer along with mainland China, with 18.4 million tonnes of rapeseed harvested each year as of 2016 (Food and Agriculture Organization of the UN, 2018). According to the Canola Council of Canada (2018), the country also produces 3 million tonnes of canola oil each year. This makes canola oil an attractive option for several reasons. Firstly, rapeseed is readily available countrywide, and therefore its average price per kg is much lower than most other vegetable oils. To illustrate this, the average price of canola oil per kg as of 2017 was 0.99 Canadian dollars (Canadian International Merchandise Trade Database, Statistics

Canada, 2017). This is over twice as cheap as flaxseed oil, based on our economic impact calculations. Choosing canola oil would therefore be beneficial from an economic, but also social and ultimately environmental perspective. First of all, it would contribute to the consumption of local rather than imported resources, as well as the creation of more local jobs, therefore boosting the local economy and the existing large rapeseed market in Canada. From a environmental point of view, using canola oil would also have positive outcomes: GHG impacts can be significantly reduced by limiting transportation of goods, and thus the use of fossil fuel when possible. By implementing a simple EIA and a cradle-to-grave approach, the importance of sourcing local raw materials is easily understandable. The main reason why we decided to discard canola oil as our working fluid is its inappropriate melting point. At -10ºC, it was deemed too high for our particular application. As a matter of fact, temperatures in Sainte-Anne-de-Bellevue regularly drop to -10.3ºC in January (daily mean), while the average low temperature of this area is -15ºC in January according to Environment Canada (2017). Kung (2011) has explained that typical core temperatures associated with silo fermentation can reach 36ºC, while the temperature in the uppermost layers can go up to 55ºC under a set of particularly unfavorable circumstances (presence of air, poorly packed silage, etc…). Jiang et al. (1988) have also demonstrated that the state of the fluid is not affected by outside temperatures, provided it is located further than 0.3 m from the silo walls. However, the viscosity of a fluid is inversely proportional to the temperature it is subjected to. Hence, although for this design we assume that our fluid will not undergo freezing during the cold winter months, we opted for a fluid with a melting point as low as possible, to avoid high viscosities with could make pressure readings inaccurate, and damage the tubes and pressure gauge in the long run. Although opting for a more expensive oil makes the initial cost of the design higher, it is an economically sound decision, as this investment would drastically cut the subsequent yearly cost of operation and the long time return on investment would therefore be higher. It is important to note, however, that canola oil would be preferred if this design was to be implemented in another location, where the average winter temperatures are higher.

Soybean oil was also briefly considered. As it was stated earlier however, its melting point is -16ºC so this idea was rapidly discarded. On top of that, Canada produces very little soybean oil compared to the main worldwide leaders (China, the United States and Brazil) which would make it an inefficient, polluting choice.

5. Impacts and Further Considerations

An excellent way of ensuring a given design is as sustainable as possible is to assess all the impacts it has on an economic, environmental and social levels. In order to do so, a thorough assessment was carried out, largely based on the Social Impact Assessment (SIA) and Environmental Impact Assessment (EIA) methodologies. On top of that, elements from FIDIC's indicators. Tools to mitigate and manage the impacts and risks exposed are also provided by means of recommendations.

5.1 Economic Impact and Recommendations

Table 1. Cost analysis of the *Hydraulic Weighing System for Alfalfa Silage*

Item	Average Cost	Quantity	Total Cost	
			Initial	Recurring
	Canadian Dollars (CAD)	#	CAD	CAD/Year
Bladder [1]	$1050	1	$1050	N.A.
Flaxseed oil [2]	$2.00/kg	750L or 697.5kg	$1395	N.A.
Pressure Gauge [3]	$1025	1	$1025	$82.25
Pressure Hoses [4]	$0.935/ft	50 ft	$37.40	N.A.
Total			**$3507.40**	**$82.25**

[1] Sales Representative, Ready Containment LLC, personal communication (2017)
[2]Sales Representative, TA Foods, personal communication (2017)
[3] OMEGA Engineering Inc (2017)
[4] Parker Hannifin Inc (2017)

The total estimated initial cost for materials of the design is $3,507.40. This includes all the necessary components for our design to be operational. To this initial cost was added an average estimated yearly recurring cost. Recurring costs mainly concern the pressure gauge, and consist in the yearly average cost of the batteries needed for the Omega® brand digital pressure gauge, part number DPGM409-001BG, as per their catalogue. Potential additional costs could arise from a poor storage of the flaxseed oil. Indeed, studies have shown that flaxseed oil is fairly susceptible to oxidation, mainly triggered by heat, and exposure to oxygen and light. This is due to the high degree of unsaturation of the fatty acids present in this type of oil, according to Choo et al. (2007). A recent study by Tanska et al. (2016) has shown that effective materials for the storage of flaxseed oil are plastic-coated paperboard laminate, Tetra-brik Aseptic® and tin. According to Evergreen Packaging (2018), PVC has a very low oxygen transmission rate compared to other commonly used plastics, standing at 320 $cm^3.m^{-2}.d^{-1}$ It is important to bear in mind that flexible PVC is also opaque. We can therefore assume that the flaxseed oil inside our PVC bladder will be protected from oxidative stress for a duration equal or greater than its shelf life (about 12 months). However, estimating how long the oil will remain fresh in our system is difficult. Indeed, a lot of variables come into play, including the amount of oil, seasonal variations in temperatures and relative humidity, and so on. This is why the yearly recurring cost related to the oil replacement was not included in the summary cost table. Based on the unit price of flaxseed oil ($2/kg), it would theoretically cost $1,395 to replace the entire oil volume at any given time. In order to extend the oil's shelf life as much as possible, we recommend the silo operators to order it only when needed, to ensure optimal freshness and that sensitive design components such as valves and pressure gauges are not damaged. If this is not possible, the oil should be stored in one of the materials mentioned previously.

Another element to be determined a labor costs involved with the installation of the tank. The main factors which affect the installation costs are the time to set up the design and the difficulty associated with filling the bladder. This should be determined on-site, as the price could vary significantly based on the location, as well as other factors. A pump may also be required to facilitate the filling operation.

At an economic level, the design of a hydraulic weighing system is projected to be a cost efficient choice for long term use. Despite the fact that a substantial initial investment is required for the purchase and installation of this system, our design has potential to provide a significant ROI in several ways. Firstly, the mass of silage can be used as data, which collected over time can help pinpoint which seasons were the most profitable and why. This data will also help quantify losses and improve estimation techniques for the quantity of silage which is available over the course of storage. With this new data, planning techniques regarding feeding schedules, time to harvest, and optimal moisture content can be refined. Refining the process based on the mass of silage will result in less DM losses, reducing waste and providing more animal fodder, therefore increasing productivity. The mass also helps observe the fermentation process, which in turn can lead to a more efficient process overall in terms of alfalfa yield and quality. Operation costs associated with this design are very low; and once installed the sole expected costs are come from the electrical energy demand from the pressure gauge, as it was stated previously. Maintenance costs can also be anticipated, particularly if there is a leak in the bladder or hose connections, however the ease of installation and removal by draining the fluid avoids potential construction costs. Improving the efficiency and yields of farms would provide a benefit to local economy. The installation of this system would also increase the resale value of the property.

Our design has received interest from the company Silo J.M. Lambert, a company based in Drummondville, Québec that fabricates a wide-range of agricultural machinery, and specializes in silo fabrication. This design can potentially be attractive to a wide range of silo manufacturers across Québec and Canada in general, as it seems to be a very cost effective investment.

5.2 Environmental Impact and Recommendations

Identifying major environmental risks starts with classification of all of the materials. Of the parts in this design, the bladder and hydraulic fluid have the largest environmental impact. This is because the tank is made of complex polymers, and the large quantities of oil must be disposed of both safely and sustainably. These components are classified as high risk compared to the other components of your design. The pressure gauge and tubing have been deemed low risk because tubing is used in small quantities in this design and recycling streams are well known and the pressure gauge will have a long lifetime with proper care and maintenance. Now that high risk design components have been identified, they can be analysed for an elementary life cycle assessment. The elements can be sourced sustainably and properly recycled using a cradle-to-cradle perspective, leaving little to no negative environmental impact. Possible environmental benefits of this design stem from the data it will provide. As stated earlier, many classical approaches exist for the estimation of the capacity of silos, but real-time data will provide valuable information regarding the mass change during fermentation and moisture content loss during storage. This data can be used to help quantify greenhouse gas emissions, and provide valuable insight on how to reduce the environmental impact of silage making.

5.2.1 Bladder and Coating Impacts

In an effort to reduce the overall cost of production, RC's standard materials are used. This allows for the bladder to be manufactured of high quality or composite plastics such as ER-1000 fabrics, R-5 fabrics, polyurethane, PVC fabrics, and neoprene fabric. However, not all of these are suitable for the conditions at the base of the silo. PVC fabrics reinforced with E. I. du Pont de Nemours and Company (DuPont) Evalon® ethylene copolymer will be able to withstand the acidic conditions of the silo.

Traditional manufacturing streams for PVC can result in high levels of dioxin, furan, and other persistent organic pollutant production. Many of these toxins are produced when chlorine gas is exposed to organic compounds during the electrolysis of salt during PVC manufacturing. Other sources of pollutants include the electrodes responsible for electrolysis which may contain mercury and asbestos filters which help separate chlorine gas from the byproducts of salt electrolysis which are not always properly disposed of. These methods of PVC production are outdated, and modern electrodes and membrane filters are replacing toxic versions. More information on the production methods and environmental effects of PVC can be found in Thornton (2002). A green future lies ahead for PVC despite these setbacks in manufacturing, as companies innovate sustainable processes and alternatives to traditional materials and methods. Bio based polymers show increasing relevance to the polymer market as processes improve, and by 2021, 8.5 million tonnes of bio based polymers are forecasted to be produced annually, accounting for more than 2% of the global polymer market according to the Nova Institute (2017). Taking advantage of these polymers will reduce the carbon footprint of the design, and help comply with FDA regulations regarding food safe materials according to Sylvin Technologies (2018). New bio-based feedstocks allow for sustainability without compromising the performance of materials. Sylvin Technologies (ST) boasts increased strength to weight ratio, improved plasticizer migration, and greater customization in their entirely naturally sourced, 39 series bio based PVC. The bio based PVC from ST also has no phthalates, commonly used plasticizers with known negative environmental effects. By improving the sourcing of PVC, a more sustainable design can be developed. Collaboration between ST and Ready Containment LLC could lead to a bio based PVC bladder being manufactured.

According to VinylPlus (2014), PVC is a well understood material and has many processes available for recycling at the end-of-life phase of the design. Even flexible composite PVC fabrics have a high recyclability which is promising for the design. PVC recycling streams follow mechanical or feedstock pathways. PVC composite fabrics with or without coatings are used by Jutta Hoser to produce mats for greenhouse flooring. The flooring has a number of benefits to the consumer and provides a good end-of-life use for the bladder. Other mechanical methods include grinding and recycling into cement or wood composites. A particular method, VinyLoop®, is a patented process by the Solvay group which separates PVC from impurities by dissolving it in a solvent and recovering the mixture. This allows PVC to be recycled from composite wastes. Feedstock pathways aim to recover the carbon from PVC. Typical methods include gasification, hydrolysis, and dehydrochlorination. These methods are discussed in detail in VinylPlus (2014). There is no specific literature on the end-of-life uses for Evalon® coating, and VinylPlus does not offer more information on the disposal of insoluble composites in the VinyLoop process. However, DuPont offers a section on their website regarding sustainable bio-based polymers which may come to replace antiquated crude oil coatings.

5.2.2 Hydraulic Fluid Impacts

By the Environmental Protection Agency (EPA) through the Resource Conservation and Recovery Act (RCRA) contained in title 40 of the Code of Federal Regulations (CFR), spent linseed oil may be considered a hazardous material, although better judgement is required. Regulation for hazardous materials is clearly laid out in parts 264 in title 40. Full details of safety precautions observed regarding the bladder can be found at RC (2017) regarding secondary containment. Major concerns are spillage of hazardous materials and overflow of silage effluent. The EPA states that spillage and overflow must be drained away from the storage container into a collection basin which is large enough to hold any overflow, spillage, or possible precipitation. The silo design includes a drainage basin which will accommodate any spillage along with the effluent. Design measures have been made to ensure the bladder will be properly drained and safely operated. A food-grade hydraulic fluid was specifically selected because, assuming the design fails, the fluid will leak into the silage. By the design of the silo, silage effluent is produced and seeps through the silage into a collection basin at the bottom of the silo. In case of any leakage, oil will also pool in this collection basin, where it can be recuperated and recycled along with the effluent as nutrient supplements depending on the practices of the farmer. Leakage of food grade, biologic oil such as flaxseed into the silage is not of large concern to the farmer, and linseed oil is used as animal feed according to Riaz (2010). Other concerns regarding the hydraulic fluid are the disposal systems in place for oils. Linseed oil in particular can spontaneously combust if improperly discarded. Lazzari (1999) explains that degradation of linseed oil is an oxidative process followed by a polymerization and the oxidation of linseed oil is an exothermic reaction. A low flashpoint coupled with an exothermic curing process can cause spontaneous combustion, and fires are certainly environmentally disastrous. Therefore, care must be taken when disposing of linseed oil. From Pramanik (2014) and Riaz (2010), end-of-life uses for linseed oil include biodegradation into other useful polymers and blending it into other plastics. Linseed oil may also be used as animal feed, and the fluid may be mixed in directly with the silage when the design is no longer needed. Therefore, it can be concluded that linseed oil is a sustainable choice of fluid for this design.

5.2.3 Greenhouse Gas Emissions

According to Schmidt P. (2011), agricultural systems have been presented as major source of greenhouse gas (GHG) emissions, mainly due to the use of fertilizers, deforestation and enteric fermentation from ruminants. It was shown by Schmidt P. (2011) that greenhouse gas emissions for sugarcane silage stored over 66 days can amount to 2.08 L per kg of DM ensiled. There was a low correlation between DM disappearance and gas production during this study. This is of concern because this design will be providing data on mass change which is directly related to dry mass disappearance. However, this could have been due to experimental errors related to the methods by which gas production were measured.

According to Wilkinson (2015), losses of DM and metabolisable energy occur in silage making due to delayed harvest and also between field and feed trough due to fermentation and aerobic spoilage, as stated earlier. In van Schooten (2012), quantities of loss during storage were measured at 4.2 - 14.4% loss of DM. This percentage over 255 tons can mean a loss of over 36 tons of feed. Van Schooten (2012) further goes on to quantify the losses to 4,000 euros of labour and management costs. However, van Schooten (2012) concludes by stating that DM losses and decreased fermentation quality has a 1% increase in GHG emissions and a negligible net return on labour and management losses. Wilkinson (2015) recommends farm management techniques such as timeliness of harvesting and improving wilting time to improve DM losses within a silo. The proposed *Design of a Hydraulic Weighing System for Alfalfa Silage* will help improve on these techniques by providing real time data on DM losses within the silo. With this information, farmers can improve their harvesting time, initial moisture content, and wilting time. In addition to this, Wilkinson (2015) suggests feeding of up to one meter per week during the winter and two to three meters during the summer. Clearly these are height measurements within the silage. With the proposed design, this can be refined to an exact mass quantity which gives the farmer more accurate nutritional profile for their livestock. Using this data can help reduce GHG emissions by suggesting when high quantities of effluent or gases are produced in order to improve additive addition. Although van Schooten (2012) suggests negligible effects, savings of more than 4,000 euros easily accounts for the cost of the system, and, with real data on how to improve silage quality, more economic and environmental gains can be made using the proposed design.

5.2.4 Puncture and Leak Impacts

It is assumed that the design will eventually fail. Wear on materials is inevitable from filling of the silo or handling, and will create weak points in the bladder prone to failure. There will be no catastrophic damage to the silo or silage when the bladder fails because of the choice of fluid and low impact of a popping bladder. However, hundreds of liters of flaxseed oil will leak into the effluent containment system in the silo. The Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) outlines clear procedures to deal with silage effluent, which is high in biological oxygen demand. In the OMAFRA Factsheet 15-003, silage effluent must be collected in a containment tank or directly transported to an outdoor manure pit. It clearly states that underground tanks should not be connected to silage effluent containment as toxic gases are produced when manure and effluent are mixed. However, effluent is considered a nutrient, as it is high in available nitrogen and phosphorus, and is often applied to the farm. Macdonald farm follows a similar procedure to deal with effluent seepage.

Following a leak or puncture of the hydraulic bag, a the flaxseed oil will be disposed of in the same fashion. The can lead to a number of problems because of the flammability of flaxseed oil as well as its tendency to harden when oxidised. If the effluent is contained in a tank before being manually transported to the manure pit, the effluent tank may become clogged or overflow with flaxseed oil. Connecting the effluent seepage piping directly to the manure pit will mitigate problems with an extra containment tank. Communications with the farm manager Paul Meldrum and the client Maxime Leduc suggested that this is the method employed at Macdonald farm, and this is a major consideration for the suggested fluid-filled bag method. If the flaxseed oil makes it way to the manure pit, it is likely to float because of its low density relative to water or manure sludge. Crusts are commonly formed on top of manure pits, according to lectures in BREE 322 Organic Waste Management related to ASABE standards on manure pit operations. Specifically, standards EP 393.3 and EP 470 from ASABE regarding manure storages and storage safety are related to the proper management of manure. Despite the very low quantity of flaxseed oil in the total manure, it is likely to mix with the crust and harden when it oxidises. Manure pit crust management is typically farm dependent, but risks related to large quantities of flaxseed oil must be considered with installing this system. Typical solutions to crust formation are manual separation of the cake or thorough mixing of the tank. If the flaxseed oil crust is exposed to high heat for too long, the risk of flammability is significantly increased, as previously discussed. This could lead to catastrophic failures and high damages to the stakeholders. Completely mixing the flaxseed oil throughout the manure pit will help mitigate flammability risk, if possible, but the solubility of flaxseed oil into manure mixtures is not well studied. The quantity of flaxseed oil will have a negligible effect on the total volume of the manure pit, despite the challenges with disposal of fluid in the case of failure. This could bode well for a low impact in case of failure, but more testing and research on the flaxseed manure mixture is certainly of importance for the further environmental analysis of this design.

5.3 Social Impact and Recommendations

The first step towards a possible improvement of the social aspects involved is to identify the various stakeholders themselves. This step is of utmost importance, as it would enables the efficient targeting of the social indicators relevant to each group, and properly assess and manage the associated risks. The main group of stakeholders involved in our project are silo operations personnel, and any farm workers who would be in contact with material used to fill, empty or maintain the silage. Following the SIA model, it appears that the relevant social issues this project must focus on are risk and hazard assessment, both requiring occupational health and safety practices to mitigate. The main hazards associated with silos identified are: loading hazards, unloading hazards, fire hazards and maintenance hazards for the bladder tank system.

5.3.1 Loading Hazards

Concrete silos loading require special grain handling equipment. Indeed, this step is undertaken using elevators, portable augers, or high-speed mechanical conveyors and gear (NDSU). It also requires two or more tanker trucks or tractors that use PTO shafts in order to transfer the silage to a loading hose connected to the elevator or apparatus that will load the silo from the top. Dr. Grant Clark explained that PTO shafts are rapidly moving devices whose purpose is to transfer energy from the tanker truck motor to the auger or conveyor. To maneuver this system, farmers are constantly evolving in a highly hazardous environment. PAMI shows that PTO shaft is usually mounted with 3 safety shields, two at the extremities (tractor and implement shields), and another covering the shaft itself. PTO shafts and mechanical or pneumatic conveyors can however be the source of entanglement of clothing or hair in case safety standards are not carefully followed. This situation can also happen when the system is defectuous or lacks regular maintenance, or when the aforementioned safety guards are missing. Entanglement is a serious hazard and can result in grave injury such as dismemberment or even death. According to Josefsson et al. (2001), tower silo loading exposes farmers to an average of 188 h of entanglement hazard per year. Fall hazard is also noteworthy, as silo operators are required to climb a ladder located on the side of the tower during monitoring of the loading process, to clear a stuck pipe for instance. Considering silos are up to 90 m tall, this is another source of hazard that can cause death.

5.3.2 Unloading Hazards

There are two types of vertical silos: top and bottom-unloading. Josefsson et al. (2001) explains that bottom-unloading silos are seldom used as they need to be fitted within special silos usually modelled by the same manufacturer as the unloader. They continue to explain that top unloader silos are more widely used than their counterpart, and consist of a circular, metal structure mounted with a rotating auger arm that conveys grain to an exit point (chute) using a forage blower powered by a motor. The apparatus gradually moves down the silo as emptying progresses using a series of winches. This once again exposes operators to dangerous moving parts that can result in entanglement and trapping of body parts. On top of that, the external chute to the silage often passes through one of the doors of the silo along its walls. This implies that farmers regularly need to climb the structure to close a door at an elevated position, putting them at risk.

Another potential issue is the gas present within the silo, which farmers can be exposed to during routine operations such as loading or unloading. During fermentation, the nitrates present in the chopped alfalfa convert to nitrites, which in turn produces nitrous acid (HNO_3) by interacting with the silage. The Government of Alberta (2004) says that because of the exothermic reaction that is fermentation, this acid decomposes and produces nitrogen oxides (NO_x), such as nitrogen monoxide (NO), nitrogen dioxide (NO_2) and nitrogen trioxide (N_2O_3) among others. Out of these gases, NO_2 is the most abundant in sealed silos, and the most dangerous both for humans and livestock. It forms within hours after the silo has been sealed, peaking after a few days to concentrations reaching several hundreds of ppm according to Bolson (2010). The US National Institute for Occupational Safety and Health (NIOSH) (1976) describes this gas is odorless and colorless at low concentrations, and takes a reddish or brown appearance, as well as a bleachy smell detectable at concentrations above 0.1-0.4 ppm. NO_2 is a toxic gas, that can cause a variety of respiratory problems in people in contact with it by irritating the lining of the lungs. According to Environment Australia, at concentrations below 50 ppm, the symptoms usually involve coughing, a burning sensation, dyspnea or recurrent bronchitis in people regularly exposed to it. This can also cause fluid accumulation within the lungs and people exposed to it can pass away several hours later without noticing anything unusual. Concentrations above 50 ppm are immediately hazardous and can cause permanent respiratory damage and death within minutes according to NIOSH (1976).

Carbon dioxide (CO_2) is also a potential harmful product of fermentation. It indeed forms in great quantities and, being heavier than air, tends to accumulate at ground level. Asphyxiation in farm personnel can occur because of oxygen deprivation in this case, CO_2 being a confined space hazard.

5.3.3 Fire Hazards

Three elements are necessary to start and sustain fires in general: oxygen, a flammable matter and an ignition source. In silos, the flammable matter is the silage itself, and its flammability increases with a drier material, being particularly hazardous for forage with a moisture content between 20 and 45% (forage manual). Silo fires occur when enough heat is generated within, simultaneously with the presence of air. Indeed, Prather (1988) explains that a silage that is too dry, coupled with the heat generated from the fermentation process and a poorly designed system (air leaking through cracks within the structure or around the door, inadequate TLC) can trigger the combustion process, which can be very costly to farmers, and greatly increases the occupational H&S risks. This can cause the entire structure to collapse, and farmers virtually losing the entire capital invested in the silo and silage.

5.3.4 Puncture and Pressure-Related Hazards

As stated in the environmental impact section, puncture and leakages can be a serious flaw of this design. It would be responsible for the spillage of nearly 750L of flaxseed oil inside the silo. This can be a potentially hazardous situation for farm workers, for several reasons. First of all, the oil within the bladder would be at a pressure of approximately 25 kPa (assuming the silo was at full capacity) according to our design. If a small puncture on the surface of the bladder was to occur during or shortly after the filling operation, a stream of highly pressurized oil would be projected at high velocities across the inside of the silo, potentially injuring farm workers. According to Sampson (2011), high-pressure injection injuries are more often than not occupation-related, and mainly concern industrial equipment, often occurring with greases, oils or hydraulic fluids. This type of injuries usually happen on the limbs, hands and fingers area. The fluid under pressure usually creates very deep wounds, and can even require amputation in some cases, as the wounds fail to seem serious straight away and are therefore overlooked by victims. Inflammatory responses of the surrounding tissues subsequently occur, and are accompanied by deep tissue scarring, loss of limb function and in extreme cases, vascular complications and tissue necrosis. Secondly, a complete leakage of the bladder can also pose some risks. If the entire volume of oil was spilled during the bladder filling, farmers would find themselves in contact with a great volume of vegetable oil. Based on the internal silo diameter (4.877 m) and the volume of flaxseed oil (750 L), this would be more of an inconvenience than a real occupational risk. However, cleaning up this much oil would be a rather costly operation, and would take a great deal of time and effort. This should be avoided by following the recommendations suggested in the following part.

6. Occupational Health and Safety Guidelines

In order to mitigate the various occupational risks farm operators are exposed to when managing a silo, guidelines have been prepared based on a compilation from various reputable occupational H&S standards, guidelines and acts. The main objective is to avoid or minimize dangers to the health, safety and well-being of workers.

6.1 General Guidelines

- The Ontario Government (2017) specifies the employer has duties, which consist in protecting all his employees from potential hazards related to farm operations by providing: safety equipment, information and supervision.
- The employer must also ensure any worker appointed to a given task is competent: he therefore must provide regular training to farm operators, as well as familiarization with the official acts and regulations of H&S of the local government (i.e.provided by *Commission des normes, de l'équité, de la santé et de la sécurité du travail* (CNESST) in Québec)
- The Ontario Government (2017) also specifies employer must prepare an internal written H&S policy, and apply its content consistently. Regular reviews are also necessary.
- The employee has the right to refuse to perform tasks if he deems that the necessary equipment or information to do so in a safe way is not provided to him.

6.2 Toxic Substances

- According to NIOSH (1976) *Occupational Exposure to Oxides of Nitrogen* standard, access to the silo doors must be restricted when fermentation produces toxic gases, (first 3 weeks, based on when NO_2 emissions are most important). The following precautions are to be observed, according to NIOSH (1976) regarding silo safety.
- Electronically monitor the inside of the silo to ensure the concentration of NO_2 is below a threshold of 1 ppm when it is entered.
- If the silo must be entered during the critical period of NO_2 formation, ensure a silo ventilation blower is operating for at least 30 min prior to entering, and continuously until the working leaves it.
- When a worker is required to enter a silo where the concentration of oxygen and nitrogen oxide is unknown, respirators must be provided and properly used. Respirators that can be used include type c supplied-air respirators with full facepiece and helmet, as prescribed by NIOSH. This is a standard self-contained breathing apparatus (SCBA).
- A standby person must be outside the silo to monitor the activity and for emergency rescue in case of hazard.

6.3 Silo Fire Prevention and Management

- Prather (1988) suggests regular inspection of silos in terms of structural damages, cracks through the structure or improperly sealed silo which can result in poor aerobic conditions and risk of fires.

- Only load the silo with alfalfa at the proper wilting moisture content of 60%. Always calculate the moisture content instead of making assumptions, as this variable is not always reflected in the texture of the silage.
- Regular inspection of the bladder to ensure no spillage has occurred.
- Immediately call the fire department when a silo fire happens. Trying to extinguish the fire is often unhelpful as the it is usually difficult to locate it within the structure. Moreover, all silo doors must be closed promptly to deprive the structure of oxygen in order to avoid further fueling of the fire.
- Prather (1988) also suggests never attempting to extinguish a fire using water. In oxygen-limiting silos, this will only spread the flames further as explosions may occur. Large quantities of water being pumped into the silo can also result in significant lateral pressures in the silo which can damage its structure.
- NIOSH (1986) states that temperature sensors may be installed at different heights in the silo to detect potentially hazardous situations.

6.4 Fall Prevention

- The Canadian Occupational H&S Regulations (COHSR) (SOR/86-304) (2017). states that appropriate fall-protection systems should be provided to workers by their employer:
    i. Silo ladders should be designed and installed following the specific requirements set by the American National Standard for Ladders — Fixed — Safety Requirements (ANSI Standard A14.3-1984).
    ii. Grain bins or silos shall have both primary and secondary exits, the latter accessible from the roof, and leading to an exterior ladder.
    iii. Employees must keep contact with the ladder in at least 3 points at all times, and securely carry their equipment in pouches.
    iv. The ladders shall be isolated from weather conditions (snow, hail, rain) to avoid slipping.
- Standardized safety cages must be provided when the top of the ladder is higher than 5m above ground level, according to clause 18(1)(d) of Reg. 851 of Ontario's Occupational H&S Act (1990).
- Workers must wear helmets whenever they are using the silo ladders.

6.5 Farm Machinery

- According to ASABE's *Guarding for Agricultural Equipment Standard* (2003), all guards used in agricultural machinery shall be strong enough to withstand a static load of 1200N.

    i. In tanker trucks, tractors or loading devices, they must be rigidly fixed to the vehicle or apparatus, have no sharp edges and be operational under harsh weather conditions .
    ii. Guards must be attached to the machine with no possibility of removal without a tool. They should also be surrounded by a mesh that cannot be removed or distorted while the machine is running.
- Farmers shall under no circumstances enter the silo while the unloader is operating, to avoid grave injuries.
- Farmers shall not wear loose clothing while operating PTO-fitted machinery.

6.6 Puncture and Pressure-Related Hazards

- Appropriate safety equipment shall be provided to the workers during bladder-filling operations. These include helmets, footwear protections or steel-toe work boots, and cut resistant gloves.
- All the equipment involved in the filling operations (pumps, hoses, bladder material, tubing system) should be regularly tested for potential damage to the material or obvious punctures.
- If applicable, the manufacturer of each of the aforementioned should provide farm workers with detailed safety precautions to follow in case of punctures.
- Prevention is essential: one of the employer's duty is to prepare detailed health and safety procedures to follow in case of pressure-related issues. Employees should be regularly trained to avoid such issues.
- Leak tests shall be performed on a regular basis. Although many leak-testing devices are available on the market today, a simple and affordable way to ensure the pipes and other elements of the design are not damaged is to consistently and regularly monitor the pressure using the appropriate software provided by Omega. Using a simple algorithm and logging software, the silo operators can be notified when the pressure in the bladder drops suddenly.

7. Conclusion

The objective of this project was to design an accurate method to mass alfalfa silage *in-situ*. Based on thorough research on the physical properties of silos and silage, a complete system was devised. A small torus-shaped bladder will transfer fluid to a pressure gauge and read out to a built-in electronic display. This design is simple and elegant. Ease of installation and operating, and low social, economic, and environmental impacts were the key factors to this design. After the components and impacts were analysed, a detailed overview of OSHA standards was presented in order to ensure proper handling and operating of the system in the context of silos and high risk situations. The adherence to these protocols is imperative to mitigate risks and ensure proper use of this design. Moving forward, there are aspects that can be further developed. With adequate funding, ideas such as bio-based polymers for the bladder material, innovative technologies and cellular applications for ease pressure readings, and potential improvements based on acquired data.

A prototype was considered for this design. It would consist of a hollow concrete cylinder, mimicking the shape of a silo as well as the internal friction forces between the sidewalls and the silage. The scale would be kept the same. Silo 5 at the Macdonald farm has dimensions 14.12m by 4.88m. This gives a scale of roughly 2.9:1. For practicality in construction and testing, our prototype would measure exactly 0.88m tall with an inner diameter of 0.3m. A miniature bladder would be placed at the bottom, attached by tubing to an exterior manometer. Drawbacks to this design would be slightly inaccurate pressure readings due to tubing connections.

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Appendix A - Silo Blueprints

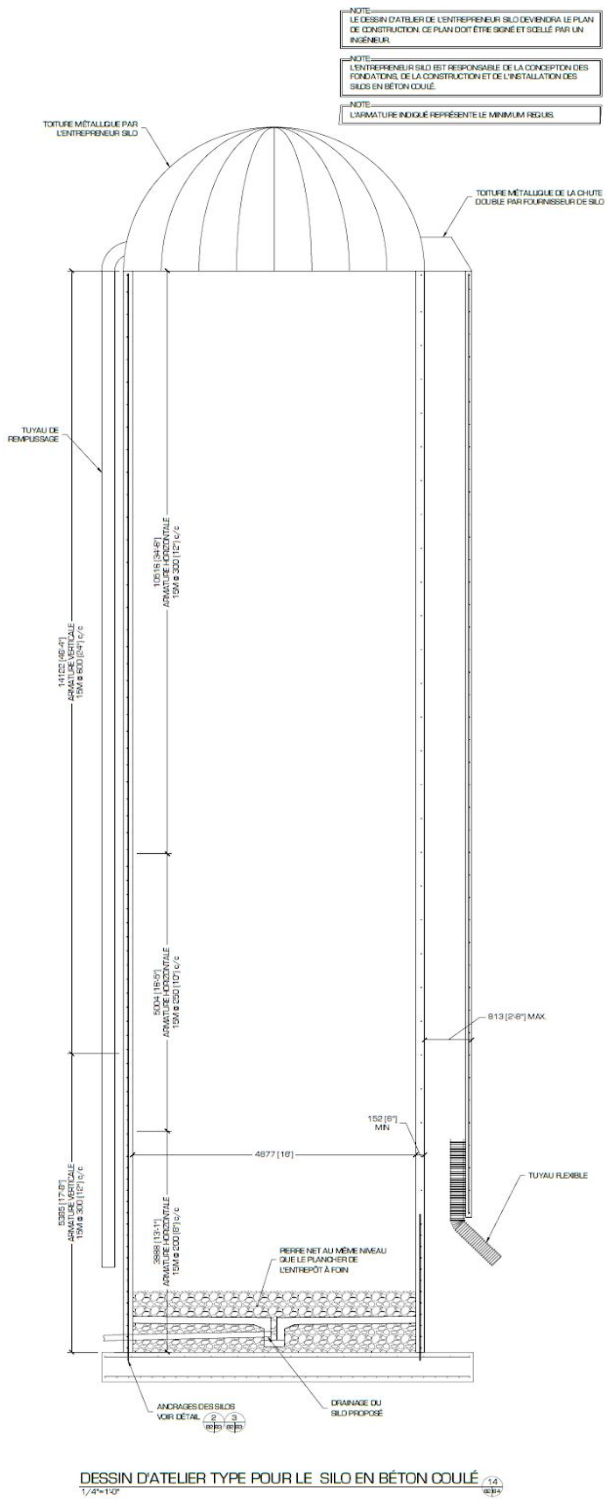

Figure 2. Blueprint plans for Silo 5

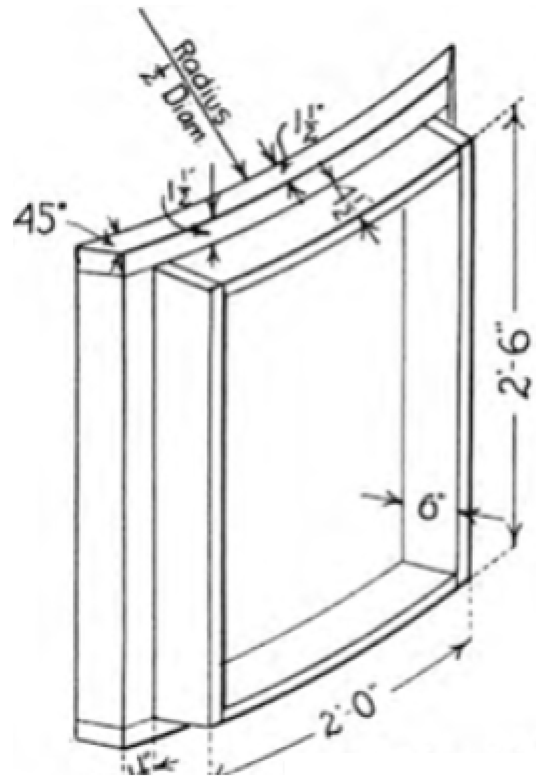

Figure 3: Silo doorway specifications

Appendix B - Bladder Schematic

Figure 4: Isolated Bladder and Tubing

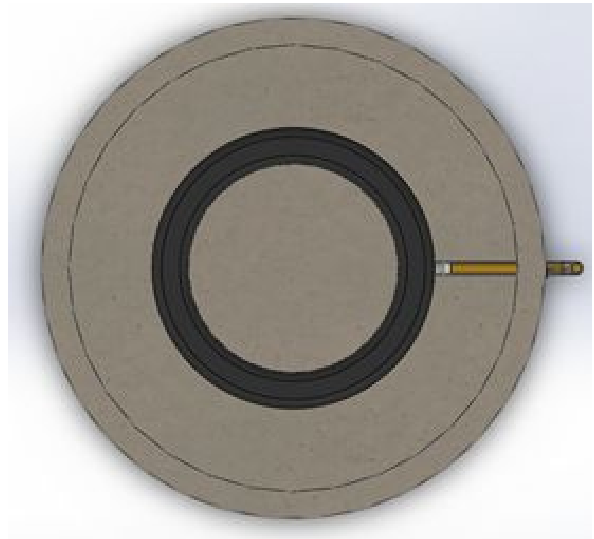

Figure 5: Vertical View of Bladder in Silo

Figure 6: Horizontal View of Bladder

Figure 7: Isometric View of Bladder

Appendix C - Phases of Fermentation and Moisture Content in Silages

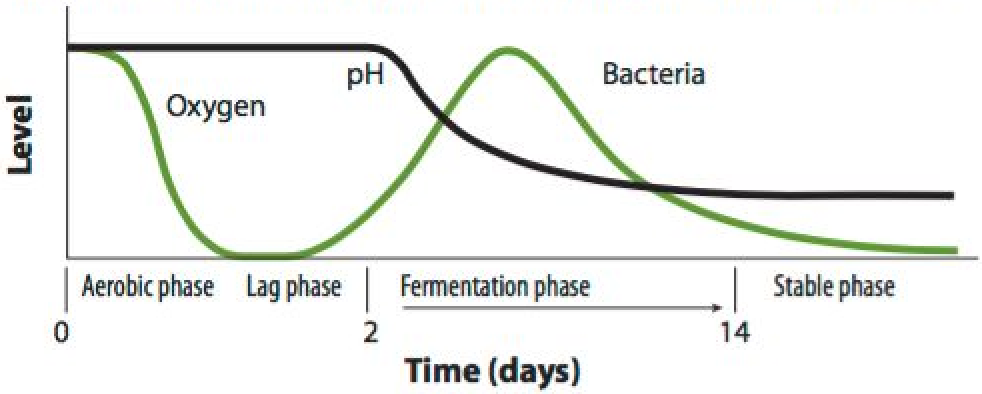

Figure 8 : Sequence of phases during the ensiling process (Pitt, 1990)[1].

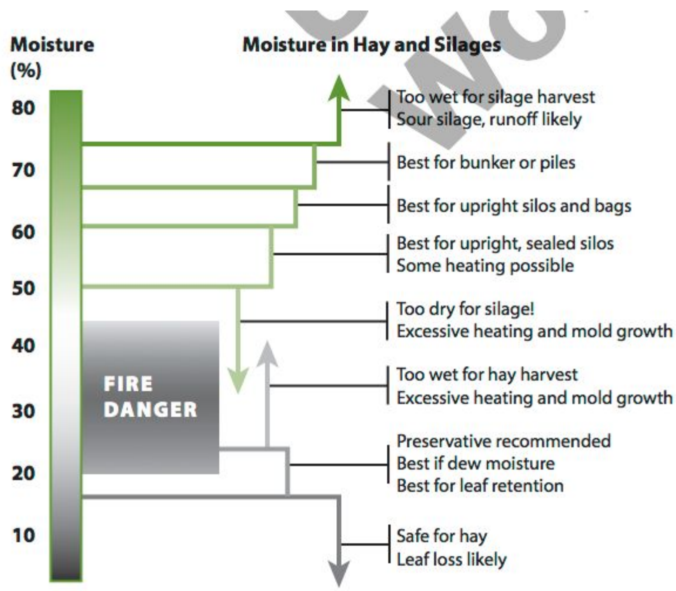

Figure 9 : Moisture Ranges for Preservation of Alfalfa as Hay or Silage (Pioneer Forage Manual: A Nutritional Guide, 1990).

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Appendix D - Sample Calculations

Following the initial assumptions under *Selected Design*, it can be concluded that the mass of silage in a silo can be determined using a pressure sensor at the bottom of the silo. Equations (**5b**), (**10**), (**12**), and (**13**) from **Reimbert** (1987) proved relevant to this design and were used to provide a calculation using the measurement of pressure at the bottom of the silo, the height of silage, and an estimated angle of repose for alfalfa hay. Experimental data will prove useful for determining the true angle of repose for alfalfa hay in silo 5.

The mass of silage in a silo can be calculated as follows:

$$Q_{max} = q_z * S + \frac{\gamma \bullet S \bullet z^2}{z+A} \qquad (1)$$

Where

Q_{max} = mass of silage in a silo (kg)
q_z = mean vertical pressure at depth z (kg/m^2)
S = surface area of a horizontal slice of the silo (m^2)
γ = bulk density of silage (kg m^{-3})
z = height of silage (m)
g = acceleration due to gravity (m s^{-2})
A = characteristic abscissa of a vertical silo (m)
h = height of upper ensilage cone (m)
$tan\varphi = \mu_k$ = internal coefficient of static friction (unitless)
Q_0 = weight of upper ensilage cone (kg)
R = inner radius of the silo (m)
W1 = weight of silage before drying (kg)
W2 = weight of silage post drying (kg)

The procedure for calculating the mass of silage is as follows:

i. Weigh out 100 g of chopped silage. Spread on a microwave-safe dish.
ii. Place in heated microwave oven for 2 minutes or until dry. Reweigh silage and continue until similar readings are obtained or charring occurs.
iii. Calculate moisture content. Moisture content will determine bulk density of ensiled material according to Jofriet (1988).
iv. Calculate A using equations (**12**) and (**13**)
v. Calculate Q_0 using equation (**5b**)
vi. Calculate Q_{max} using equation (**10**)

A calculation deriving the estimated bottom pressure for the weight of silage in silo 5 was completed using ASABE estimates for capacity, an estimate for angle of repose by S.C. Negi (1988), and bulk density formula for alfalfa hay from Day (1966).

Initial and Boundary Conditions:

$z = 18.2880\ m$
$S = \pi \bullet R^2 = 18.6793\ m^2$
$^{*}\ tan\varphi_0 = \mu_k = 0.4$
$\gamma_{alfalfa\ hay} = 669.703\ kg\ m^{-3}$
$R = 2.43840\ m$
$h = R\ tan\varphi_0 = 1.69\ m$
$^{**}\ g = 9.80906$

$$Q_{max,estimate} = \gamma \bullet z \bullet S = 234771.57\ kg \qquad (2)$$

$$Q_0 = \gamma \bullet S \bullet \frac{h}{3} = 7011.77\ kg \qquad \textbf{(5b) Reimbert}$$

$$A = \frac{Q_{max,estimate} - Q_0}{\gamma \bullet S} = 4.2\ m \qquad \textbf{(10) Reimbert}$$

$$q_z = \gamma \bullet S \bullet [\ z\ (\frac{z}{A} + 1)^{-1} + \frac{h}{3}\ ] = 2607.876\ kg/m^2 \qquad \textbf{(12, 13) Reimbert}$$

$$Q_z = q_z * S = 49177.781\ \text{kg} \qquad (3)$$

$$\text{M.C.} = [(w1-w2)*100/w1] \qquad (4)$$

*Obtained from experimental data by Negi (1988)

** Acceleration due to gravity in Montreal from wolframalpha.com

Equations for piezometer reading in reference to Figure 11 below.

P_A = pressure within bladder (Pa)
γ = specific weight of fluid (KN/m^3)
h = change in height of fluid in pipe (m)

$$P_A = \gamma * h \qquad (5)$$

Appendix E - Transducers

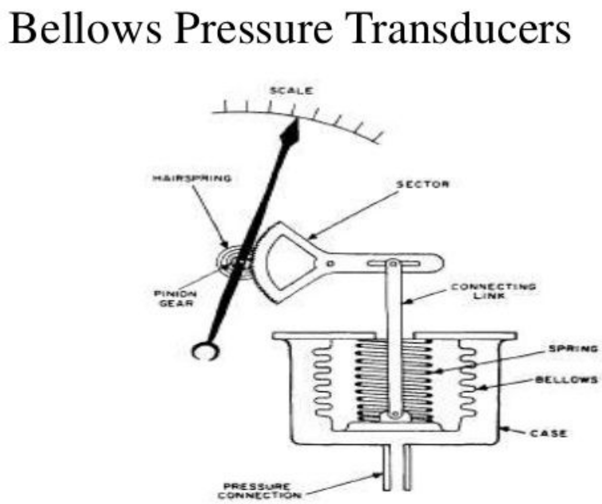

Figure 10: Bellows. A spring-loaded device that counterbalances a deflection caused by pressure. The value is transmitted to a pointer via a simple connecting link. Relatively low pressure differentials are appropriate for bellows (Benedict, 1984).

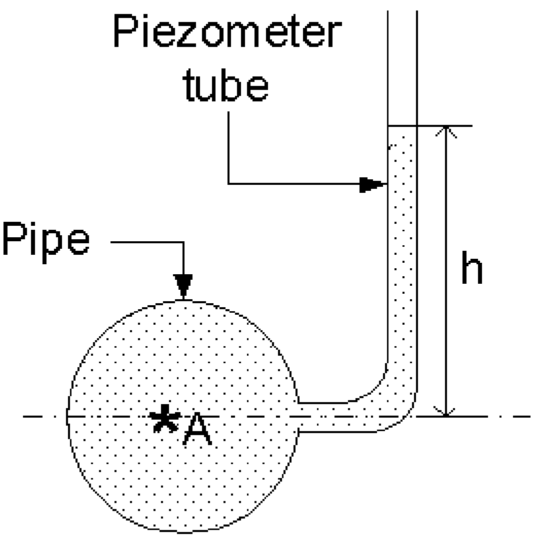

Figure 11: Piezometer: Well-type, inclined type. Uses a column of liquid to measure differential pressure (fluid vs. atmosphere) using basic fluid mechanics principles. The well-type refers to the standard U-shape device and requires no calibration. The inclined-type works based on the same principle but has a better accuracy as the inclined leg has more graduations (Benedict, 1984).

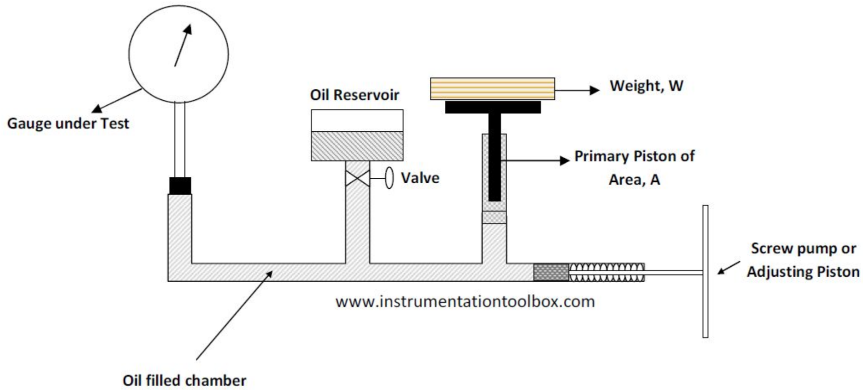

Figure 12: Dead Weight Gauge. A method that involves using a known quantity of weight to calibrate a pressure gauge. This involves a cylindrical piston design that displaces an amount of gas or oil to cause movement in the pressure gauge.

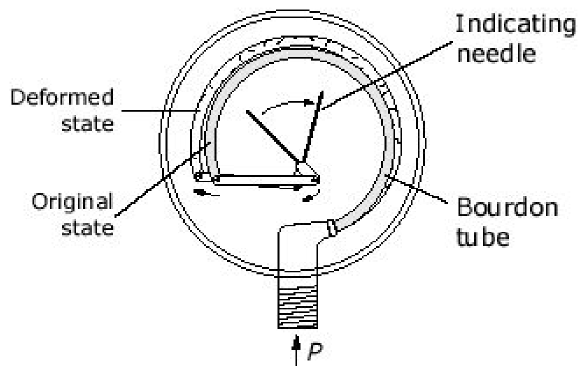

Figure 13: Bourdon Tube. Flattened spiral, helical or c-shaped tube that regains its straightened shape under application of fluid pressures. The measure of pressure is proportional to deflection of the free end. Spiral and helical types are preferred for pressures above 60 bar.

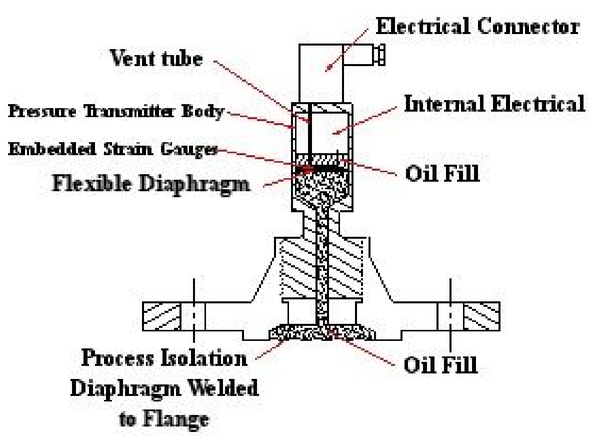

Figure 14: Diaphragm Gauge. Common gauge for both liquid and gas measurement. Consists of flanges enclosing a non-circular diaphragm moving up or down depending on the pressure exerted. The pressure value can be read on a pointer. Can measure pressures ranging from 16 mbar to 25 bar.

Appendix F - Pressure Graphs

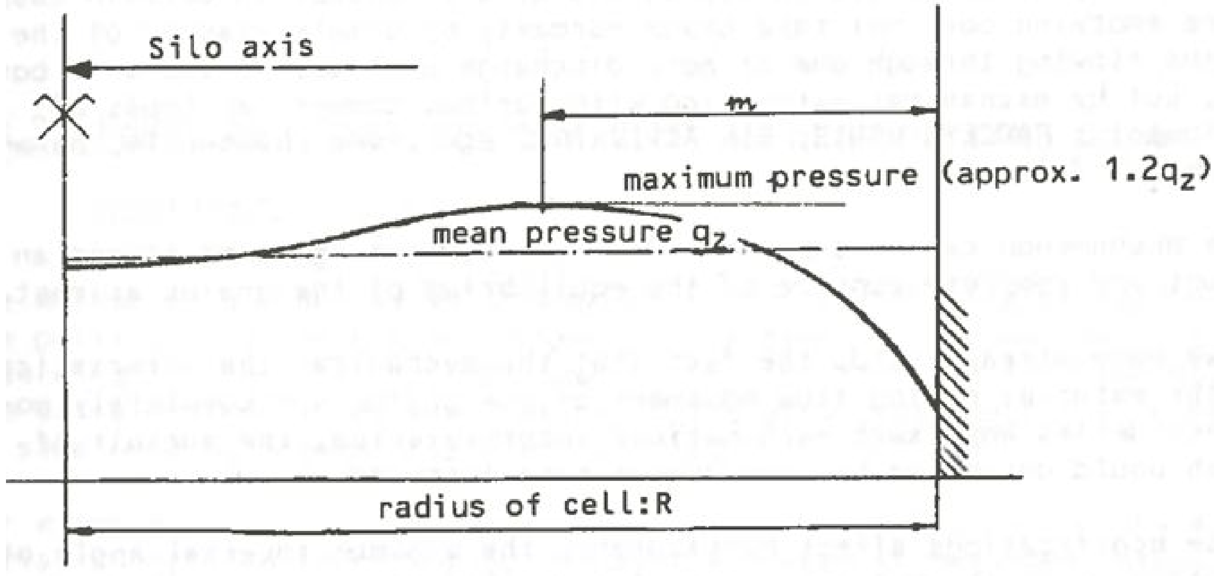

Figure 15: Pressure variation as a function of distance from the center of the silo. Reimbert (1987)

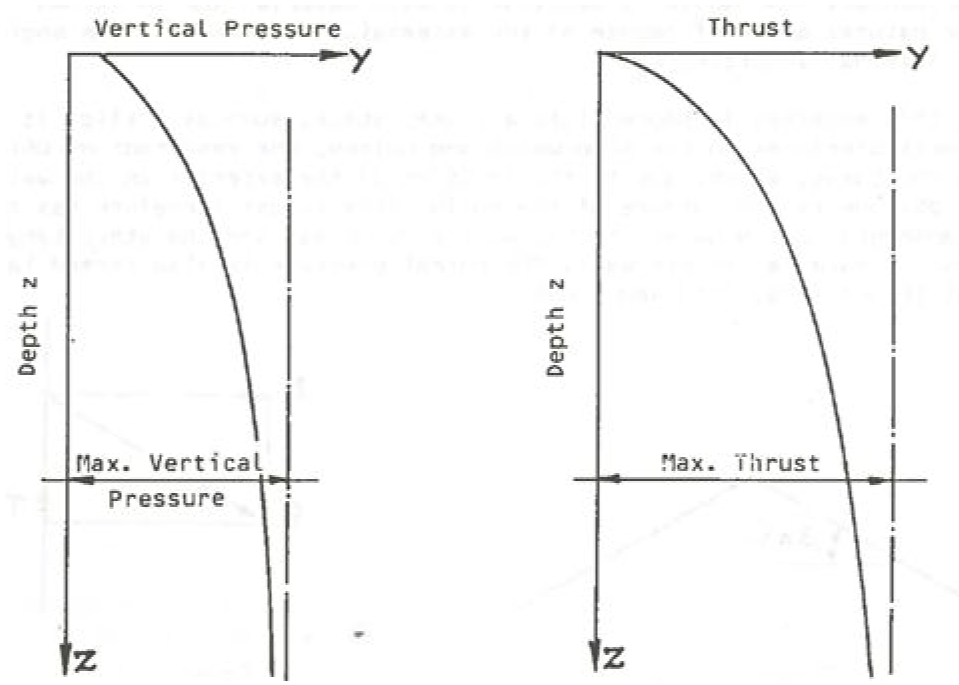

Figure 16: Vertical pressure and lateral thrust as functions of depth of silage 'z'. Reimbert (1987)

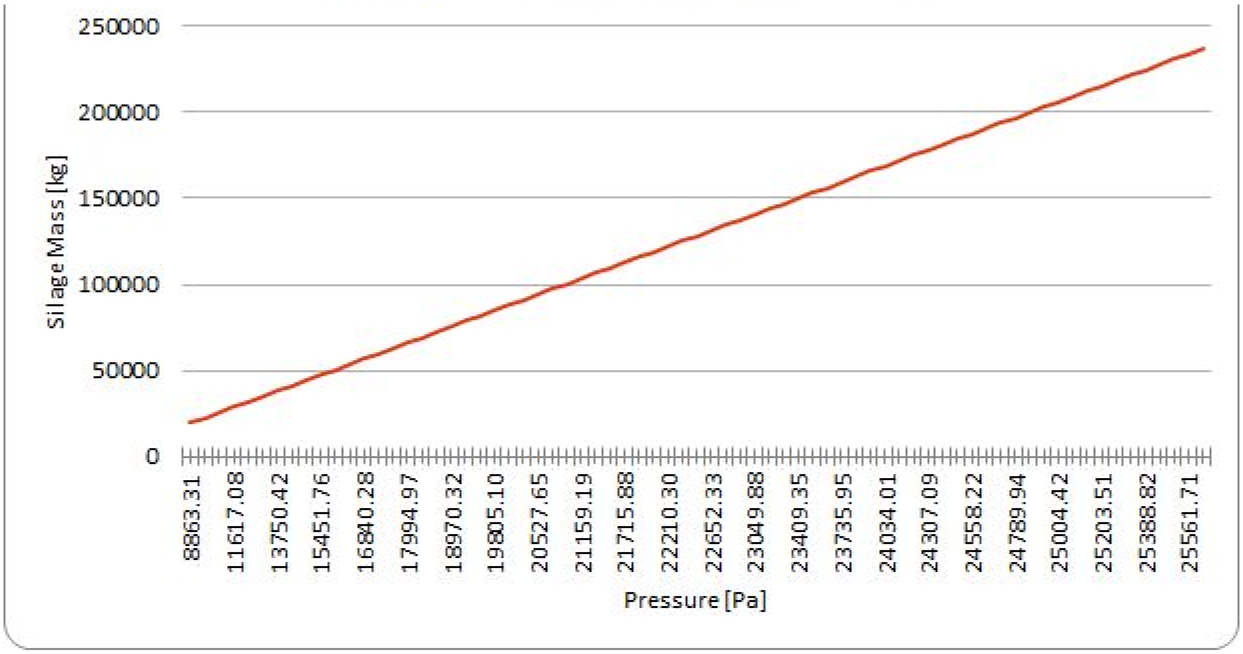

Figure 17: Mass of Silage vs. Gauge Pressure

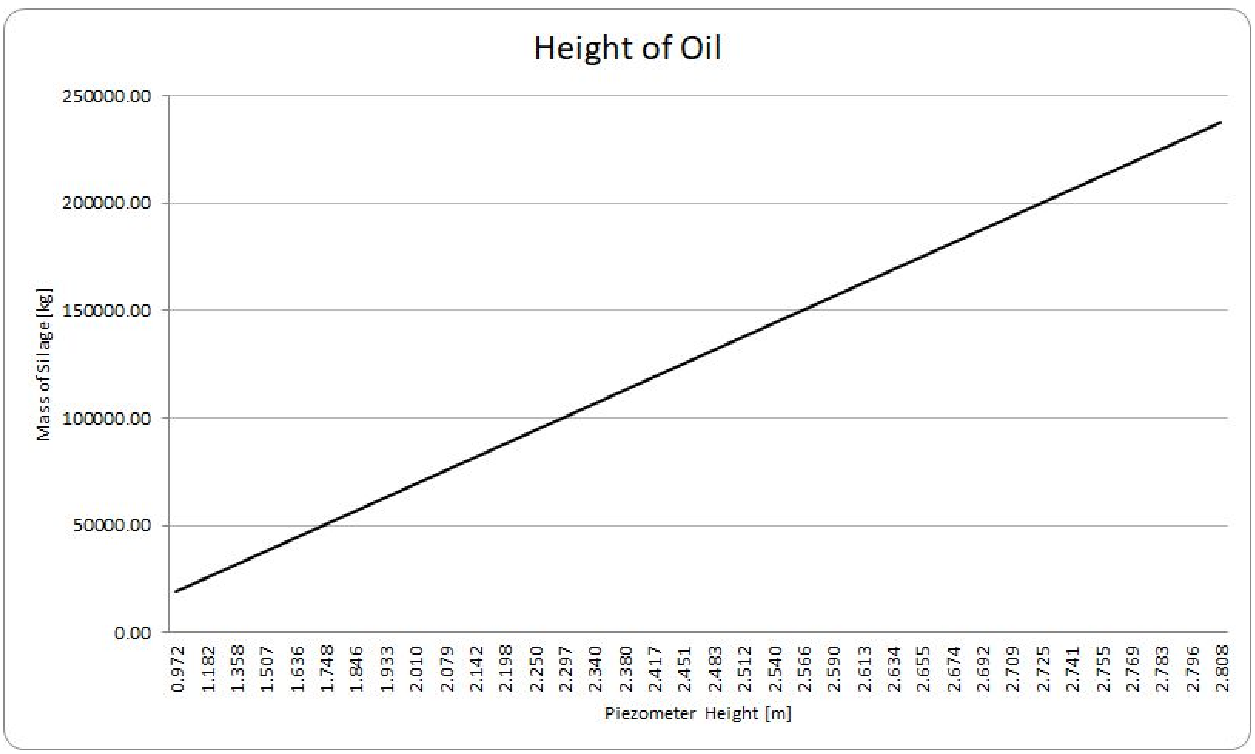

Figure 18: Mass of Silage vs. Piezometer Height (Height of Oil)

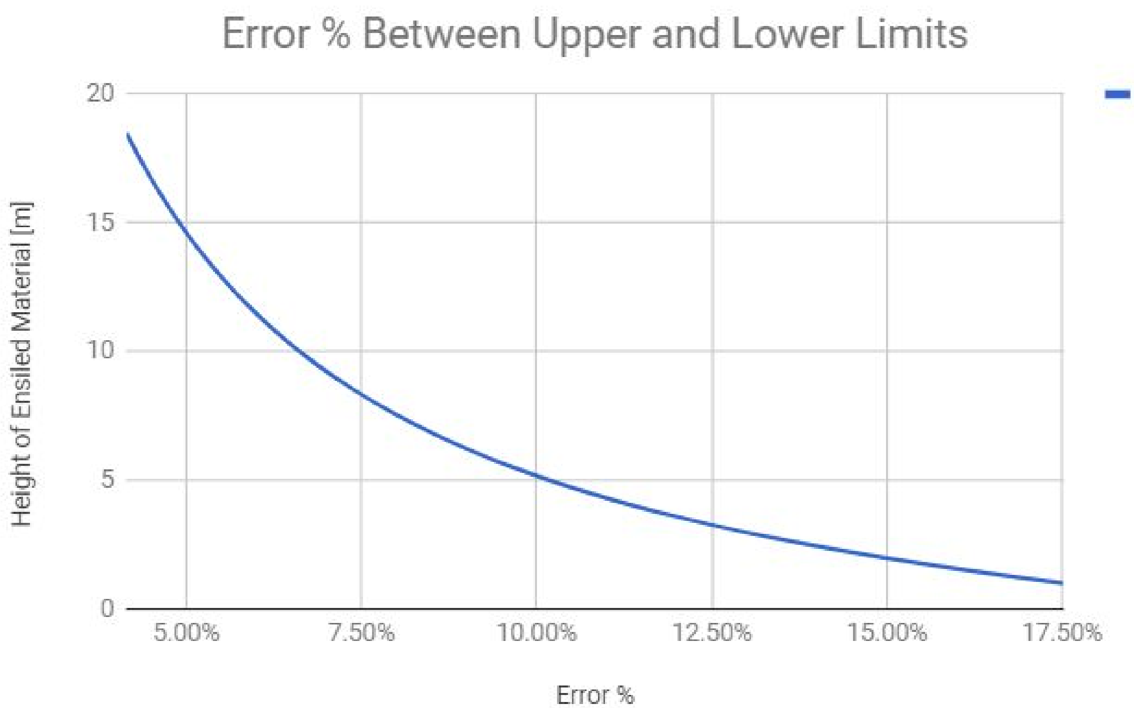

Figure 19: Height of Ensiled Material vs. Error