PROJECT 23: HYDRAULIC FLUID DISSOLVED GAS TESTER

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ABSTRACT

The goal of this project is to create a device that can accurately measure the gas content in hydraulic fluid for the EPA. The EPA's hybrid hydraulic system has the potential to increase fuel economy by over 50% in suitable vehicles, mainly large trucks that require constant accelerating and decelerating, such as delivery trucks. However, a large concentration of gas in their system has several negative impacts, namely cavitation, which can damage pump components. The main obstacle currently limiting mass implementation of this system is an inability to quantify when damage to the system is imminent, which is why they need an accurate and reliable measuring device.

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1. EXECUTIVE SUMMARY

One of the biggest challenges facing this generation is dealing with the upcoming energy crisis as a result of depleted fossil fuel sources. Part of the solution is increasing the efficiency of our motor vehicles to their peak potential. The U.S. Environmental Protection Agency's (EPA's) National Vehicle and Fuel Emissions Laboratory (NVFEL) is developing a hybrid hydraulic system capable of improving fuel economy in select vehicles by up to 70% [1]. The EPA is currently partnering with UPS, which currently has over 72,000 delivery trucks in the U.S. alone.

One of the main issues preventing the mass implementation of this system is when the nitrogen (N_2) used to store energy in high and low pressure accumulators slowly leaks into the hydraulic fluid, and over time can become problematic. As N_2 levels in the hydraulic fluid increase, so does the amount of N_2 that comes out of solution on the low pressure side of the system. Rapid compression of the N_2 that comes out of solution can cause cavitation, which can severely damage the pump and its components. The EPA needs a system that can measure the gas content of the hydraulic fluid and can thus identify when gas concentrations reach levels where cavitation becomes possible. Our goal is to create a device that can give accurate and precise measurements of the gas concentration in samples of hydraulic fluid.

The biggest challenge we faced is the lack of prior knowledge in the field of measuring N_2 concentrations. N_2 is an inert gas and has no negative health effects, so there has been little demand for measuring its concentration. Of the few designs we have seen that could measure N_2 concentration accurately, most are bulky and expensive, requiring advanced scientific knowledge of gas and chemical properties to build. The ability of our team to identify a method that will extract a hydraulic fluid sample, guarantee accurate (close to the actual measure of nitrogen gas in the sample volume) and precise (repeatable) measurements, and allow for proper disposal of is crucial to the success of our project, as well as balancing monetary and time constraints.

Our team first identified several conceptual methods of measuring the dissolved gas content in a sample of hydraulic fluid. Through a tree diagram and a series of Pugh charts, we decided on an alpha design consisting of a manual piston/cylinder device, with attachments for pressure and temperature measurement. After hydraulic fluid is transferred to the device (through a connection provided by the EPA), we can effectively measure the gas concentration by drawing a vacuum above the fluid, removing the gas, and measuring pressure, temperature, and volume.

Our device has evolved from the alpha model to a finalized design, and all manufacturing and validation has been completed. We have successfully achieved five of the eight engineering specifications given by our sponsor. The three we have not met include accuracy, steps in process, and test time, with the latter two increased to achieve a higher accuracy, which aside from safety was the most important criterion for our device.

Although the current uncertainty of the gas concentration given by our device is 14% versus the 2% engineering specification, we feel that it will still provide the EPA will their desired capability of detecting gas concentrations within a given sample of hydraulic fluid. In doing so, we believe our device will successfully assist the EPA in determining gas concentrations that prove problematic to their hydraulic hybrid system, and help predict when these problems occur.

2. PROBLEM DESCRIPTION

2.1. Motivation

As part of a continuous effort to reduce pollution by minimizing vehicle emissions, the EPA is working to develop a hydraulic hybrid vehicle suitable for delivery trucks. They have partnered with UPS in this effort. UPS has 72,000 delivery trucks in the United States, each of which has a fuel rating of about nine miles per gallon of gasoline. A hydraulic hybrid vehicle has the potential to increase the efficiency of these trucks by 50% or more [1].

Hydraulic hybrid vehicles reduce fuel consumption through energy storage; braking energy is stored in the high pressure accumulator, and later used for acceleration, whereas in a normal vehicle it is lost. The energy is more easily conserved in a hydraulic system than a battery (as with regenerative braking in hybrid electric vehicles), making hydraulic hybrids more suitable to stop-and-go vehicles such as delivery trucks or urban vehicles.

Hydraulic hybrid systems have an efficiency of approximately 70%. Energy is lost due to friction in the brakes, because the hydraulic system cannot stop the vehicle entirely by itself. While this is comparable to efficiency ratings in hybrid electric vehicles, hydraulic hybrid systems have a higher power density rating when compared to electric systems. This makes them more suitable for large vehicles which have high rates of energy input and output during braking and acceleration [2].

For delivery trucks in particular, a hydraulic hybrid system can increase fuel economy between 28% and 48% [2]. While electric regenerative braking can result in a 57% increase in fuel economy for city driving, current batteries are not well-suited for large vehicles for power density rating reasons previously discussed [3]. An electric hybrid system featuring an ultra capacitor would be necessary to favorably compare to the hydraulic hybrid system. However, such a system is still in the developmental stage. This strategy has been implemented in mass public transit (bus) trials in Europe [2].

2.2. Background

As seen in Figure 2.1 on page 10, the hydraulic system contains two accumulators: one with high pressure and one with low pressure. The hydraulic fluid is separated from the working gas (nitrogen) by a rubber bladder, which allows the nitrogen gas to easily contract and expand. Energy is stored and released in the nitrogen bladder as the hydraulic fluid enters and exits the high-pressure accumulator.

Additionally, in the EPA's hydraulic hybrid system, all of the power from the engine goes to the hydraulic pump, creating more potential for energy savings. The speed and load of the engine are completely independent of the wheels [5]. This is known as a series hydraulic circuit.

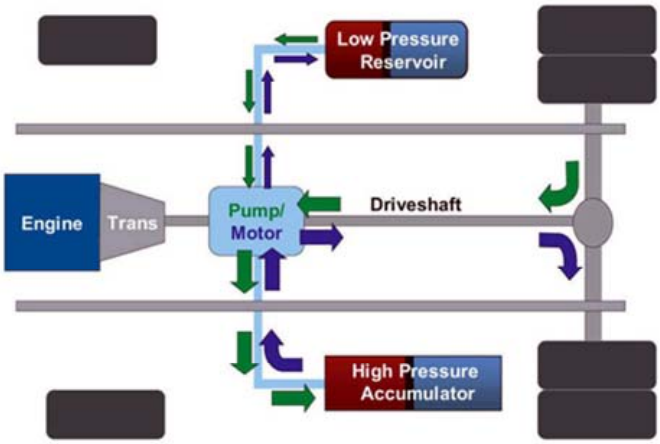


Figure 2.1: Hydraulic hybrid vehicle circuit [4]

Braking triggers fluid flow from the low pressure reservoir into the high pressure accumulator, where the energy is captured in the nitrogen gas bladder. Upon acceleration, the energy is released and fluid flows from the high pressure accumulator to the low pressure reservoir, powering the driveshaft and transferring torque back to the wheels [2].

In order for the hydraulic system to function properly, the pressure in the high-pressure accumulator must be between 2000 psi and 7000 psi. The pressure in the low-pressure accumulator must be between 60 psi and 200 psi [5].

2.3. Design Problem

The hydraulic hybrid system does have tradeoffs. The rubber bladder containing the nitrogen gas, while easily contracted and expanded, is semi-permeable and can allow nitrogen gas to seep through. When dissolved nitrogen gas accumulates in hydraulic fluid, it can release pressure, cause cavitations, and significantly increase temperature, all of which lead to losses in efficiency and possible damage to the hydraulic system.

The EPA does not know exactly how much nitrogen will cause these problems, because they cannot measure the amount of nitrogen gas in a sample of hydraulic fluid. We have been tasked with developing a laboratory instrument accurately measuring the amount of nitrogen gas in a given small sample of hydraulic fluid.

2.4. Impact of Successful Design

A successful measurement tool for the amount of total gas present in hydraulic fluid would contribute to reducing the emissions of UPS trucks in the United States. However, this instrument would also provide great insight into gaining a precise knowledge of the amount of nitrogen needed to cause damage in hydraulic fluid. Additionally, if the instrument could be used to consistently monitor hydraulic hybrid vehicles and their safety, then hydraulic hybrid vehicles may be implemented for other uses such as sanitation vehicles, urban vehicles, and other stop-and-go applications.

3. PROJECT REQUIREMENTS AND SPECIFICATIONS

The customer requirements have been outlined by Dr. Andrew Moskalik of the EPA and are focused on safety and the accuracy and precision of the measurement. The requirements are outlined in Table 3.1 on page 12, and are listed in descending order of importance. Our engineering specifications were given by Dr. Moskalik. Also, we have created a QFD, which can be seen in Appendix A, to better understand how the project requirements relate to the given specifications.

3.1. Project Requirements

Given that our device will be used by the EPA for laboratory tests and not continuous data collection or experimentation, it is important that it be efficient in many ways. The design of the device must be such that we provide a small, inexpensive, accurate, and easy-to-use device. In doing so, other resources such as time, funding, and labor can be devoted to more vital activities within the EPA's overall goals, rather than being consumed by a simple measurement process.

3.1.1. Safety

The most important aspect of our design is safety. The overall safety of the product in its use and interaction with users is mandatory. Any product submitted which poses a threat of any sort to other devices, humans, or the overall EPA environment is entirely unacceptable.

3.1.2. Accuracy and Precision of Measurement

Once the design is ensured to be safe the next focus is on the measurement. Accuracy must be high in order to help the EPA best understand the properties of dissolved gas in hydraulic fluid, and determine the extent of damage that can result from it. The precision of these measurements must be considered in our design. If we are unable to reproduce an accurate measurement then our device will give inconclusive results to the EPA.

3.1.3. Quantifiable Output

The device must have an output that is easily translated into a meaningful value of the amount of gas in hydraulic fluid. We have been given freedom to determine the units and output style. It is not mandatory that the output be the concentration itself. Further calculation by the user is acceptable.

3.1.4. Portability

If the system is not in-line, it is desirable for the device to be portable. This means that it must have a low weight, small size and basic ergonomics need to be considered. A portable device requires a minimal power input, preferably that of a small consumer battery.

3.1.5. Test Time

The device must be efficient, so test time and ease of use are important to its design. Test time should also be minimal for purposes of lowering the cost of the device in terms of the EPA's time and to allow for maximum repeatability in a given time period.

3.1.6. Ease of Use

In order to encourage proper use of the device we have been asked to create a system with minimal steps and to avoid any complex or cumbersome tasks.

3.1.7. Hydraulic Fluid Sample Size

The sample size of hydraulic fluid must be small in order to avoid compiling large amounts of fluid waste and to allow for multiple tests from the same accumulator, as well as ease of measurement. Large sample sizes may negatively affect the performance of the hybrid hydraulic system, which is unacceptable.

3.1.8. Justifiable Cost

We have been assigned a budget of $1,500 by Dr. Moskalik. However, if we can increase accuracy or usability substantially and justify a larger expense, it would be acceptable to go over budget, but discussion with the sponsor would be necessary.

3.1.9. Reasonable Size and Light Weight

To make the device easier to use, size requirements have been recommended but they are flexible. The footprint of the device must be small in order to conserve laboratory space. The weight should be minimal, to provide for ease of transportation of the device, so that it may be moved between multiple laboratory setups or, if implemented commercially, so that it may be delivered easily.

3.1.10. In-Line Testing

If possible, an in-line system that would allow measurements to be taken while the truck is in use would be an added benefit to the EPA, but is not required.

Demanded Quality	Characteristics of Quality
Safety	The device must be safe to all who come into contact with it.
Accuracy of Measurement	Measured value must be as close to the actual value as possible.
Precision of Measurement	Measured value must be repeatedly found.
Quantifiable Output	The device must have an output that gives a numeric value of the amount of nitrogen found in the hydraulic fluid.
Portability	The device should be easily transportable
Test Time	Test time must not be excessive
Ease to Use	Test procedure must be clear and easy to execute
Sample Volume	Sample size should be under 0.5 gallons
Cost	Cost should not exceed $1,500 unless warranted
Size	Footprint should be manageable
Weight	The device should be light weight
In-Line Testing	If possible an in-line system would be desired

Table 3.1: Customer demanded qualities and coordinating characteristics

3.2. Engineering Specifications

Upon evaluation of the customer requirements and from conversations with Dr. Moskalik, the engineering specifications were created. Table 3.2 on page 13 lists the specifications and their associated target values. The specifications were created based on those of current analytical tools as well as customer demands, and the description of each is given below.

Engineering Specification	Value	Unit
Fitting and Seal Ratings	≥ 300	psi
Level of Accuracy	± 2 or better	% by concentration (Moles/ml)
Test Time	<10	min
Steps in the Process	≤5	steps
Hydraulic Fluid Sample Size	<0.5	gal
Cost	<1500	USD
Footprint to Device	<1	ft^3
Weight	<20	lbs

Table 3.2 Engineering specifications with values and units

3.2.1. Fitting and Seal Ratings

Dr. Moskalik emphasized that safety be a top priority for our project. The highest possibility of failure is in our seals and fittings. For this reason Dr. Moskalik said that we should have them rated to 300 psi; he believes that 1.5 times the pressure is the maximum necessary to ensure safety. Anything built to handle more pressure will not be any safer and will likely be more costly making it less desirable.

3.2.2. Level of Accuracy

After talking with Dr. Moskalik, an accuracy value of ± 2% by molar concentration (Moles/ml) or better is needed to ensure the device is useful to the EPA, so this will be our ceiling target value. This number is based on current market models' accuracy and the EPA's need to be able to see accurate changes in dissolved gas levels.

3.2.3. Test Time

To make this test useful for the EPA we have been asked to make the test time no more than ten minutes. Dr. Moskalik does not want the test time longer than ten minutes because he wants to be able to collect data often and a long test will reduce the number of tests possible. Due to the science behind our measurement procedure, this specification will prove challenging to our design.

3.2.4. Steps in Process

Dr. Moskalik recommended we keep the number of steps low to ensure that they are followed during every test. He stated that we could have anywhere between three and seven steps and that three steps is not a major improvement over five. However, he wants us to aim for five or less steps as our specification and if more steps are needed, the specification could be adjusted later. The number of steps is to be kept low to ensure that the procedure is properly followed; the EPA likes concise directions and few steps per process.

3.2.5. Sample Size

Dr. Moskalik has outlined that the sample size be less than half a gallon to avoid having to withdraw and waste an excess amount of hydraulic fluid. Half a gallon is roughly 1% of the total fluid volume in the hydraulic system, and removing more than this would be a waste and would make the likelihood of a repeat test from the same accumulator low. As stated in the customer demands section, large sample sizes may negatively affect the performance of the hybrid hydraulic system, which is unacceptable.

3.2.6. Cost
The cost of our project should be less than $1,500. However, we must be able to justify the cost. Dr. Moskalik wishes for us to aim for at or below the $400 ME450 budget, but realizes that our project is very likely to go over that number. Therefore, he has given us $1500 as our absolute ceiling on the project cost.

3.2.7. Footprint of Device
Our sponsor stated that the device should have a reasonable size and be able to sit on a lab table. Thus, it must have footprint of approximately one cubic foot. The lab table and shelf space available at the EPA limit the footprint. Also, the portability of our device depends on minimizing its size.

3.2.8. Weight
To make the device portable, the weight should be less than twenty pounds. This specification translates to the device being easily handled by one person. The EPA has standards which they must follow to ensure a safe work environment, if a device is over twenty pounds two people will be required to use it, thus wasting time and money.

3.3. QFD
Combining the customer requirements and engineering specifications, a QFD was created. It shows the relationships between the requirements and specifications as well as the relationship between multiple specifications. It can be found in Appendix D.

The QFD shows that the device needs to be easy to use and accurate. Accuracy and precision, when related to sample size and time of testing, is an important correlation to consider in our design. This is a trade off we will constantly be considering during the design process. The QFD also shows a positive correlation between size and weight. This is useful for us because we wish to minimize both of those characteristics. Weight also has a strong correlation with sample size. The cross correlation of specifications will help to determine the importance of design aspects. Positive correlations between specifications are mutually beneficial whereas negative correlations show design tradeoffs. These tradeoffs will have to be weighed when making our design. The factors that will weigh the decision are customer demands and cost. The negative correlations are between cost and accuracy, sample size and accuracy, and test time and steps in the process, cost and steps in process, and cost and sample size.

4. LITERATURE REVIEW AND CORRESPONDING FUNDAMENTALS

4.1. General
As previously discussed, cavitation is a major issue when dealing with hydraulic pumps and is one of the driving factors of our project. It can be caused by gas being present in the hydraulic fluid and occurs when the local static pressure of the fluid lowers below the fluid's vapor pressure at that particular temperature. According to the Bernoulli equation, cavitation can occur when the fluid accelerates in a control volume. Damage due to cavitation occurs when the vapor collapses after evaporation, when the velocity of the fluid is decreased and the pressure is increased, which results in small hot air bubbles (or a foam-like appearance). Cavitation bubble collapse results in highly-localized, large-amplitude shock waves and microjets. This can lead to transient surface stresses on the hydraulic accumulators. Typical damage caused by cavitation

can be seen in Figure 4.1 below [6]. Cavitation can be avoided by distancing the local static pressure of the fluid from the vapor pressure. In the EPA's hydraulic hybrid system, dissolved nitrogen gas that has permeated through the rubber bladders in the accumulators can lower the local static pressure of the hydraulic fluid, thus increasing chances of cavitations [7].

Figure 4.1: Damage on a mixed flow pump blade caused by cavitation [6]

An important property pertaining to the amount of dissolved gas in a liquid is Henry's Law, which states: At a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid. Or, the solubility of gas in a liquid at a particular temperature is proportional to the pressure of that gas above the liquid. However, Henry's Law only applies for sufficiently dilute solutions, as well as solutions where the solvent does not react chemically with the gas being dissolved [8]. Since nitrogen does not easily react with anything, it is reasonable to assume it will not react with hydraulic fluid.

An important factor in our project when measuring the amount of gas present in a liquid is that the gas is in two forms: dissolved and free gas. Dissolved gas is completely mixed in and dispersed throughout the liquid, whereas free gas takes the form of bubbles in the liquid. While it is not initially clear which type has more of a negative impact on the hydraulic system, it is important that the final device we design has the ability to measure both. This will ensure that we are reporting an accurate measurement of total gas in the hydraulic fluid [9].

In determining whether to test our hydraulic fluid sample while pressurized or after exposure to atmospheric conditions, we had to understand the properties of gas coming out of liquid, or diffusivity. Adolf Fick developed the most widespread equations for determining the diffusivity of gas within a liquid, and Fick's First Law states that the diffusive flux of a material is proportional to the concentration of that material in the mixture, as shown below [10].

$$J = -D\frac{d\varphi}{dx}$$

Since our project goal is to determine this concentration (φ) of gas within a fluid, we have no way of accurately determining the diffusive flux (J), even if we knew the proper diffusion coefficient (D).

Also, Fick's findings only apply to "Fickian" fluids, and the overall validity of his findings have been disputed [11]. Therefore, it will be more useful to approximate the behavior of fluid in our system using Henry's Law than Fickian approximations.

4.2. Partial Pressures

From the literature search, one method for determining the concentrations of gases in a liquid involves measuring their partial pressures, and there were three separate ways found to accomplish this.

4.2.1. Measuring Dissolved CO2, O2, and N2 Concentrations in Soda

This method was found from a patent assigned by the Coca-Cola Company for measuring the concentrations of CO_2, O_2, and N_2 dissolved in soft drinks. To do this, gas was first extracted from the liquid and the concentrations of CO_2 and O_2 were measured using an infrared detector and photomultiplier respectively. Together with the temperature of the gas sample, the partial pressures of CO_2 and O_2 could be determined. These pressures were then subtracted from the total pressure of the gas sample, which gave the partial pressure of N_2. These partial pressures and overall gas temperature were converted into concentrations of dissolved CO_2, O_2, and N_2 using standard solubility tables [12].

Although the concentration measurement methods in this patent were specific to CO_2 and O_2, a similar approach could be used for testing the level of dissolved gases in a variety of liquids, including hydraulic oil. A major advantage to this device is that it measures the total amount of gas in the liquid, both dissolved and free gas since it removes all gas from the liquid. However, the accuracy of this approach was not discussed, and the system's overall complexity and expense would make it difficult to adapt into a solution to our problem.

4.2.2. Total Dissolved Gas Pressure (TGP) Probe

The use of a TGP probe in measuring the concentrations of dissolved gases in liquids was discussed in a journal regarding ground water studies. For this application, a probe consisting of a pressure transducer inside a headspace volume was surrounded by a silicon membrane, which allowed only gas to permeate through the membrane as shown in Figure 4.2 on page 17.

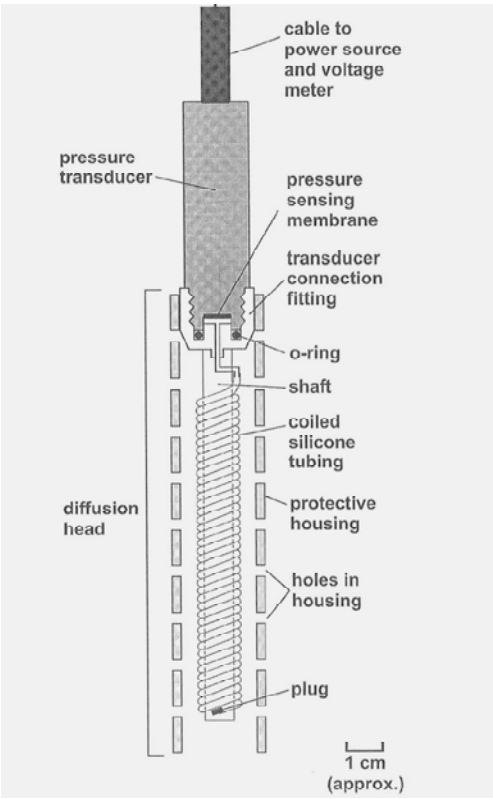


Figure 4.2: TGP probe [13]

The probe was then completely submerged in a ground water well and a gas exchange between the air in the headspace volume and the dissolved gases would continue until equilibrium was reached. Once this occurred the probe would measure the total dissolved gas pressure, $P_T = \sum p_i$, where p_i is the partial pressure of the each dissolved gas. These are given by Henry's law:

$$p_i = \frac{C_i}{H_i(T,S)}$$

where C_i is the dissolved gas concentration of gas i, and H_i is the Henry's law proportionality constant for gas i, which is a function of temperature, T, and salinity, S [13]. In order to apply Henry's law to our specific system it will be necessary to obtain a value of the Henry's law proportionality constant for the solubility of nitrogen in hydraulic fluid, which has yet to be determined. To this point, we have been unable to find a value for this specific constant. We plan to use a constant for nitrogen gas in a similar fluid. Constants from oils with similar densities are applicable for our purposes [9].

Since the primary gas concentration in ground water consists of N_2, O_2, and water vapor, the probe was used in conjunction with a dissolved oxygen meter and thermometer, from which the partial pressures of O_2 and water vapor could be measured and subtracted from the total pressure to give the partial pressure of N_2. Then using the above equation, the concentration of dissolved O_2 and N_2 could be found.

This method seems to be an attractive alternative to the previously discussed partial pressure approach since it does not require the initial removal of gas from the liquid and could potentially be adapted to an in-line measurement on a hydraulic system. A major problem for our design would be determining the effects and accuracy of installing such a device in a 100-200 psi system. In this article, the probe was tested at a depth range of 1-9 m and was accurate to ±0.005 atm, which when compared to the values given in the article corresponds to a lowest accuracy of 0.75% [13]. Also, this device only measures the amount of dissolved gas and not free gas since large bubbles would not be able to permeate the silicon membrane.

4.2.3. Apparatus for Removing Gas from a Liquid and Measuring Concentration

The last method for using partial pressures to calculate the concentration of gas in a liquid came from a patent that sought to improve on a historically known device called a Van Slyke Apparatus. The Van Slyke Apparatus employed a sample chamber along with a mercury manometer and a mercury reservoir which was used to produce a vacuum to draw out gas from the liquid. The device described in this patent uses a piston/cylinder arrangement as shown in Figure 4.3 below, and does not require the use of liquid mercury, which has been found to be very toxic.

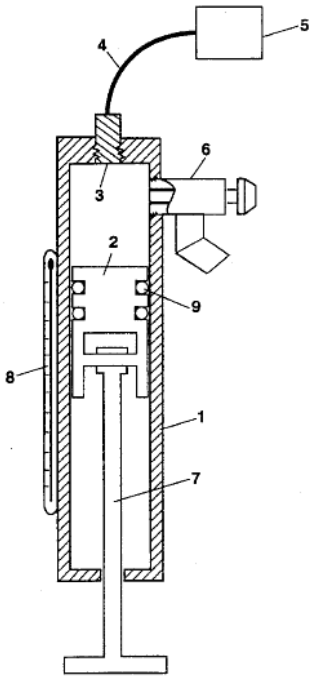


Figure 4.3: Plunger/cylinder apparatus for determining gas concentration in liquid [14]

In reference to Figure 4.3 above, the plunger (7) is initially compressed vertically with the valve (6) open so that all air in the cylinder is removed. The valve is then placed into the liquid and the plunger is withdrawn to a predetermined position, allowing liquid to enter the cylinder. With the valve closed the plunger is further withdrawn so that a vacuum is created and all gas entrained in the liquid is allowed to outgas. The plunger is then compressed again to a predetermined position and the resulting pressure is recorded by a pressure transducer (3). The concentration of gas in liquid is then given by the ideal gas law in the equation shown on page 19:

$$n = \frac{(P - P_V)V_{gas}}{RTV_{liq}}$$

where n is the gram-moles of gas dissolved in the liquid, P is the pressure reading from the transducer, P_V is the vapor pressure of the liquid at sample temperature, V_{gas} is the gas volume in the cylinder, R is the universal gas constant, T is the absolute temperature of the gas, and V_{liq} is the volume of the liquid [14].

This patent did not provide any testing results of the device or corresponding accuracy, however, the accuracy of the Van Slyke apparatus was given as 0.5% [15]. However, because we have no other way of gauging the accuracy of this device, we will assume that such a method would have at least the level of accuracy as the original for the purposes of comparison. Because this system provides a relatively straight forward way to remove gas from a liquid and to measure the total gas concentration, it appears to be a valid and worthwhile approach to accomplishing the objective of our project.

4.3. Chemiluminescense

Chemiluminescence is light emitted during a chemical reaction. This light comes from a photon and can be measured with specific sensors. To detect nitrogen, a machine is built with the following process sequence: A liquid sample is injected into the machine through an automatic syringe pump, allowing precision in sample size. The injection speed is regulated to ensure complete combustion of the sample. The sample is mixed with oxygen to ensure complete combustion and to encourage NO to form. After combustion the NO stream is mixed with oxygen in the form of ozone (O_3) making NO_2 and O_2. NO_2 is in an excited electron state at this point and will emit a photon when it returns to ground state. The light intensity of this photon is detected by a photomultiplier tube (PMT) sensor and through calibration the mass or percent nitrogen can be output [16].

This process has the advantage of being accurate. Some companies advertise up to 0.01 parts per million (ppm) measurement range [16]. This accuracy makes it a very complex device and is above what is necessary for our application. The disadvantages of this device come from its complexity, its cost (the machine is very expensive with a base model around $5000), and the danger associated. This machine also destroys the original sample making it impossible to create an in line system with this science. Despite its high level of accuracy, chemiluminescense will not be a worthwhile option to pursue due to these disadvantages.

4.4. Mass Spectrometry

In mass spectrometry, a sample is loaded into a machine, and then the components are charged by one of a variety of methods (electron beam impact, etc.) with the use of an ion source. This results in the formation of charged particles. The ions are then directed in an electric and/or magnetic field, after which they are sorted by their masses using a mass analyzer. The mass-to-charge ratio of the particles is computed based on their motion as they move through the electromagnetic field. Finally, a detector is used to calculate the abundances of each ion present [17].

Since nitrogen is a difficult element to detect through any method, mass spectrometers often use the "nitrogen rule" when applicable. This states that any organic compound containing exclusively hydrogen, carbon, nitrogen, oxygen, silicon, phosphorus, sulfur, and the halogens will have either: (1) An odd nominal mass, and therefore an odd number of nitrogen atoms presents or (2) an even nominal mass, and therefore an even number of nitrogen atoms [18].

Therefore, this process is extremely accurate in its measurements of other elements, but mass spectrometers are large, expensive machines whose measurements of nitrogen are usually indirect.

Firms including LECO Corporation and Thermo Fisher Scientific use these methods in their mass spectrometers.

4.5. Permittivity

Permittivity is a substance characteristic, describing the ability of a substance to transmit or 'allow' an electric field [19]. The permittivity of a substance can be measured using sensors. It is this method that Chemical ElectroPhysics Corp used to develop their in-line Proceptor® system [20]. Hydraulic Fluid has a base permittivity value between 8-9 farad meter^{-1} (F m^{-1}) while air has a permittivity of 1 F m^{-1}. The Proceptor® reads the change in the permittivity value of the fluid. In the case of hydraulic fluid with dissolved N_2 gas it is able to calculate the volumetric percentage of the gas in the liquid. While the Proceptor® is designed to measure the air content in hydraulic fluid, N_2 is inert, as is air, and it has a permittivity of 1 F m^{-1} and therefore the Proceptor® is capable of measuring the N_2 content.

While the Proceptor® unit offers a great solution to our assignment, the major drawback is the price of the system. Quoted at well over $50,000 this unit is well outside out budget range and therefore is unsuitable for our use. Also, despite this high price, the accuracy of such a system is only 2%, which is larger than less complex and expensive methods [21]. In addition, a large majority of the unit price comes from sensors and probes, so building a device on our own may be outside our price range.

4.6. Gas Chromatography

Exeter Analytical has developed a system that uses gas chromatography to detect the concentration of certain gases in organic and inorganic compounds [22,23]. A small sample of the compound, usually less than 5 mg, is combusted in a pure oxygen environment. Helium is used to carry the combustion products through the analytical system. Helium is used for this because it is inert and has a high thermal conductivity. The combustion products are first passed over reagents to assure complete oxidation and to remove unwanted contaminants. After the water and carbon dioxide are removed from the system, thus giving the concentrations of carbon and hydrogen in the original compound, all that remains is helium and nitrogen. This mixture is passed through a thermal conductivity cell and the resulting reading is compared to a reference cell to determine the concentration of nitrogen in the original compound.

The accuracy of this method was given by an article that specifically sought to measure its quantitative accuracy, and was given as ±0.001 g/ml, which when compared to the values in the article corresponds to a lowest accuracy of 0.65% [24]. While this accuracy is fairly high in

relation to the other methods discussed, it is not without its disadvantages. The system requires the destruction of the sample, which is not ideal, and costs over $30,000.

4.7. Future Research Areas

Future research areas include the effect of initial air quantities on N_2 readings and the speed with which N_2 will leave solution upon exposure to atmospheric pressures. Many of our options for reading N_2 concentrations assume that the readings being made are for air concentrations and not strictly N_2. If the effect of initial air concentrations throw off our measurements too much, certain options may become unacceptable.

For solutions that do not involve in-line systems, the sample must be transported to the testing station. Upon exposure to atmospheric pressures any dissolved or free gas N_2 in the hydraulic liquid would begin out-gassing and if this takes place very rapidly, it could affect readings for certain solutions we are investigating.

5. CONCEPT GENERATION/SELECTION

We used a funnel technique to decide on our alpha design. First, we decided on a testing method to use. We began by creating two forms of a functional decomposition to help us better understand the steps needed to make a successful device. Using the functional decomposition, we then created a tree of all the possible test methods and the cases in which they would be applicable. After eliminating the infeasible concepts from this tree, we were left with our final candidates for our test method of choice. We utilized a Pugh chart to decide on our best method of choice.

Next, we decided on what functions and components to use with our design. This came after choosing the method because the particular functions and components needed for our final design were largely driven by the method we chose. Again, we brainstormed possible solutions to each function and component needed for the design, and used a Pugh chart to decide between them.

Finally, we generated alpha design concepts based on our rankings from the previous Pugh charts. We generated six concepts and made one final Pugh chart to weigh them against each other. While the final Pugh chart was not the only deciding factor on our alpha design, we considered its recommendation heavily when choosing which concept to pursue further.

5.1. Functional Decomposition

To understand the intended functionality of our design we created a functional decomposition. To make sure we understood our process, we used two methods: the first is in list form; the second is a diagram, both of which are in Appendix E. Our overall function is a device for measuring gas concentration in hydraulic fluid. We established six sub functions: calibrate device, transfer hydraulic fluid into device, contain hydraulic fluid sample, analyze gas concentration, convert measurements to useable form, and dispose of fluid safely. The sub functions were further broken down into functional components.

The list decomposition allowed us to see how each sub function broke down into components, and what order of processes would be the most logical. Applying our function and sub functions in a diagram forced us to understand how our process would work and what an ideal system would look like. From our better understanding of the function of our device we realized that we had multiple options, and it was necessary to organize these in a way for us to logically select the best suited test methods for our purposes.

5.2. Choosing the Method

The concept generation process began with researching methods that could be used to measure the concentration of gas. Identifying which method to use was our first priority. We made a tree diagram of all the potential methods for testing and for which methods could be used in certain cases. The levels of the tree, from top to bottom, were: test location, test pressure condition, test containment apparatus, test method, step before elimination, elimination standard, and final step in test. The diagram can be seen in Appendix F. Upon completion of the diagram, we identified fourteen different paths of implementing the five different test methods previously discussed. At this point, some of the paths were deemed infeasible. Next, we eliminated those paths that were infeasible in order to leave a final set of test methods that could then be ranked against each other in a Pugh chart.

5.2.1. Eliminating Paths

We eliminated paths from the concept tree that we deemed infeasible. The following is a list of the concepts we eliminated with reasons provided.

5.2.1.1. Path A: In-Line TGP Probe

This path was eliminated because TGP probes can only measure the dissolved gas in a sample. Since there will be free gas (bubbles) in the low pressure accumulator where we want to obtain our sample, this flaw is not acceptable. Another issue was the unknown effect of using the probe above atmospheric pressure and in a fluid more corrosive than water.

5.2.1.2. Path C: TGP Probe in an Open Container, Withdrawal by Pouring

This path was eliminated because gas would leave solution during transportation and testing. In addition, any bubbles in solution would not be measured by the TGP probe.

5.2.1.3. Path D: Permittivity in an Open Container

This path was eliminated because gas would leave solution during transportation and testing. Test results would give a concentration less than the actual value.

5.2.1.4. Path E: Gas Chromatography at Atmospheric Pressure, Withdrawal with Piston/Cylinder/Syringe

This path was eliminated because gas would leave solution during testing. Test results would give a concentration less than the actual value.

5.2.1.5. Path F: TGP in an Open Container, Withdrawal with Piston/Cylinder/Syringe

This path was eliminated because gas would leave solution during testing. Test results would give a concentration less than the actual value.

5.2.1.6. Path G: Mass Spectrometry at Atmospheric Pressure, Withdrawal with Piston/Cylinder/Syringe

This path was eliminated because our sponsor does not have a mass spectrometry machine available to them and purchasing one would be well over budget limits. Gas leaving solution during testing was also a concern.

5.2.1.7. Path N: Mass Spectrometry at System Pressure

This path was eliminated because our sponsor does not have a mass spectrometry machine available to them and purchasing would exceed budget limits.

5.2.2. The Feasible Paths

The remaining paths were deemed feasible and moved onto the next stage of our decision process: rankings by a Pugh chart, which can be found in Appendix G and Table 5.1 below. The following is a brief description of each path that made it into this initial Pugh chart, and a brief overview of the pros and cons associated with each path. Note that the pros and cons listed here were initial thoughts on each path and were not taken into account when the Pugh chart was made.

		Concepts of Gas Measurement Techniques						
Path		**B**	**H**	**M**	**J**	**K**	**L**	**I**
Selection Criteria	**Weight**	Rating	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	-	-	0	0	0	+	+
Accuracy of Measurement	3	-	-	0	0	0	+	0
Precision of Measurement	4	+	+	+	+	+	+	0
Speed	2	+	+	+	0	0	-	0
Ease of Use	2	+	+	+	+	+	+	+
Cost	2	-	-	+	0	0	-	+
Size	1	+	+	0	+	+	-	+
Weight	1	+	+	+	+	+	-	+
Small Sample Volume	2	+	+	+	+	+	+	+
In-Line	1	+	-	-	-	-	-	-
Quantifiable Output	3	+	+	+	+	+	+	+
Power Input	4	+	+	+	+	+	-	-
Total Score		11	9	19	16	16	7	10
Rank		4	6	1	2	2	7	5

Table 5.1: Measurement techniques Pugh chart

5.2.2.1. Path B: In-Line Permittivity

This path would measure the concentration of gas in the hydraulic fluid by measuring the change in permittivity of the fluid as the concentration changed. Theoretically, as the concentration increased the permittivity would decrease. The biggest pro of this concept was it can be incorporated as an in-line system, therefore allowing for testing as the vehicle was in operation. There were, however, initial concerns over the accuracy of this measurement technique. There was also some uncertainty of the effect a strong fluid flow rate would have on this technique.

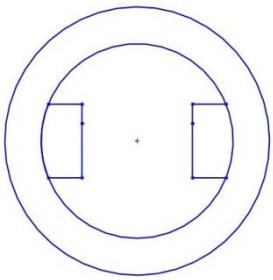


Figure 5.1: In-line permittivity

5.2.2.2. Path H: Permittivity in a Pressure Vessel

This path would also measure the concentration of gas in the hydraulic fluid by measuring the change in permittivity of the fluid as the concentration changes. This method eliminated the concerns of strong fluid flow rates, as seen in Path B, but loses the added benefit of an in-line system. As with Path B, there were again initial concerns over the accuracy of this technique.

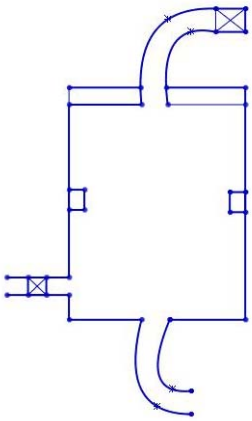


Figure 5.2: Permittivity in a pressure vessel

5.2.2.3. Path I: Partial Pressures in a Pressure Vessel

This method would measure the concentration via Henry's Law and pressure changes as gas leaves solution. The concept is to create a vacuum on a pressure vessel, and then drop a known volume of fluid--which would be much less than the pressure vessel volume--into the pressure vessel. The decrease in pressure and increase in volume would cause gas to leave solution. Using Henry's Law and the pressure measured in the container, the number of moles of gas in the container could be calculated. Assuming the remaining fluid was at its saturation limit, the number of moles of gas still in solution could be found as well. This system is appealing because it would be simple to build and use. There were no initial concerns with this system.

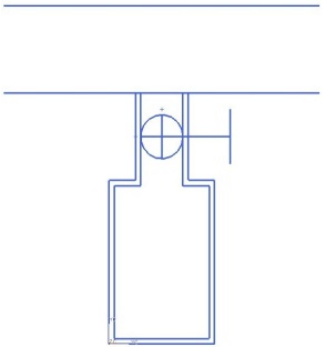


Figure 5.3: Partial pressures in a pressure vessel

5.2.2.4. Path J: TGP Probe in a Pressure Vessel

This path involved measuring the concentration by installing a TGP probe in a pressurized vessel. Using a pressure vessel at the system pressure would allow testing without gas leaving solution. This system would be relatively easy to construct and simple to use. Pressure losses during transportation were an initial concern.

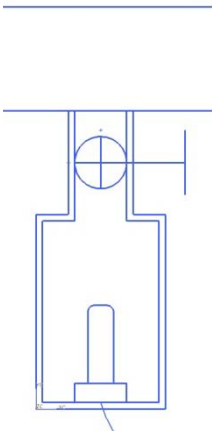


Figure 5.4: TGP probe in a pressure vessel

5.2.2.5. Path K: Partial Pressure/TGP Probe in a Pressure Vessel

This method involved measuring the concentration using both partial pressures and a TGP probe. Hydraulic fluid would be drawn into a vacuum pressure vessel with a volume much larger than the volume of fluid. The drop in pressure would cause gas to leave solution. A measurement of the gas pressure in the cylinder would allow for a measurement of the free gas using Henry's Law. These two values would give the total concentration of gas in the hydraulic fluid. This method was appealing because it allowed for accurate determination of both the free and dissolved gas in the fluid. There was some concern over the added complexity of having two different techniques in one device.

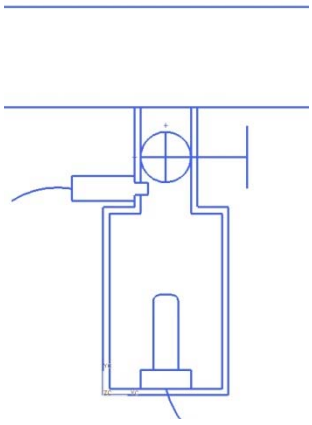


Figure 5.5: Partial pressure/TGP probe in a pressure vessel

5.2.2.6. Path L: Gas Chromatography at System Pressure, Withdrawal with Piston/Cylinder/Syringe

This path would use the gas chromatography method at system pressure to find the concentration. Fluid would be withdrawn with a piston/cylinder/syringe, in order to maintain system pressure, and injected into a combustion chamber. The hydraulic fluid would be combusted in a pure oxygen environment and the products would be collected and put into the gas chromatograph. The gas chromatograph would then be able to give the concentrations of various gases in the fluid. This technique initially seemed appealing because our sponsor owns a GC unit. There were no major problems when considering this path for the next stage in our selection process.

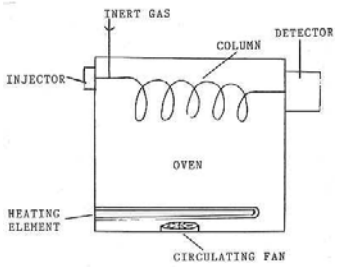


Figure 5.6: Gas Chromatography at system pressure, withdrawal with piston/cylinder/syringe

5.2.2.7. Path M: Partial Pressures in a Piston/Cylinder

This method was very similar to Path L, except no TGP probe would be used. Fluid would be drawn into the piston/cylinder and then gas would be allowed to leave solution via increasing the volume in the system. The piston would then be used to recompress the gas to a volume larger than the initial fluid volume, and a pressure reading would be taken. Using Henry's Law, the concentration could be found. This technique is based on existing devices, so it was initially very appealing.

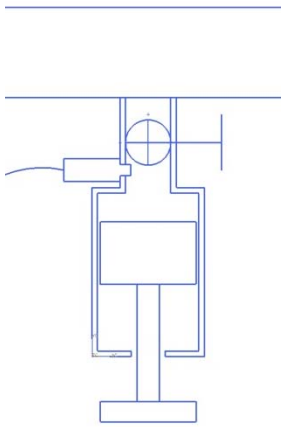


Figure 5.7: Partial pressures in a piston/cylinder

5.2.3. Comparing the Feasible Methods

The next step in our process was to decide on which method to use. The easiest way to do this was to create a Pugh chart, based on our customer demands, and rank each method against each other. This Pugh chart can be seen in Appendix D. Based on talks with our sponsor, we concluded that safety, accuracy of measurement, precision of measurement and quantifiable output were the most important selection criteria for our chart. This is reflected in the high weights those criteria received. On a 1-4 scale, with 4 being the most important, safety, and precision of measurement received a weight of 4. Accuracy of measurement and quantifiable output both received a weight of 3. After the first version of the Pugh chart was made, our sponsor expressed his desire for the device to not require an external power supply, in order to make the device portable. The Pugh chart provided has been updated to include this criterion, which was given a weight of 4.

Other selection criteria included speed, ease of use, cost and small sample size, all with weight of 2, as well as size, weight and in-line testing capabilities, which all received a weight of 1. Each method was given a +/0/- rating, which correspond to values of 1/0/-1 respectively, for each selection criteria. The total score for each method was the sum of the product of the weight of each criterion, multiplied by the value of the rating it received. For example, a '+' for the safety criterion would add 4 points to that concept's score.

Upon completion of the Pugh chart, we found that the partial pressures method in a piston/cylinder was the top choice. This method won due to strong scores in the precision of measurement, quantifiable output and power input criteria. The TGP probe in a pressure vessel and the combination partial pressure/TGP probe in a pressure vessel finished tied for second, only a few points behind. Ultimately, we decided on the partial pressures method in a

piston/cylinder because the last step of compressing the gas/fluid mixture before taking the pressure reading decreases the error in the final concentration by increasing the difference between the pressure reading and the vapor pressure in the fluid.

5.3. Choosing Functions and Components

The next step in our process was deciding on what functions and components to use with the piston cylinder. The functions and components we looked at were depressurization method, temperature measurement, pressure measurement, and piston shaft actuation method. We chose what to use for each function and component by brainstorming ways of accomplishing each one, and then ranking them against one another in a Pugh chart. This chart can be seen in Appendix H and in Table 5.2 below. We used the same selection criteria as in the Pugh chart used to choose which method we would use, but we removed small sample size and in-line capabilities because they did not apply to the functions and components.

		Concepts for Piston/Cylinder Functions										
		Depressurization				Temperature Measurement		Pressure Measurement		Piston Shaft Actuation Method		
Description		Open valve	Increase Volume	Expansion Valve	Pipe/hose system	Thermometer	Thermocouple	Gauge	Transducer	Screw	Gear	Spring
Selection Criteria	Weight	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	+	+	+	+	+	+	+	+	+	0	0
Accuracy of Measurement	3	0	0	0	0	-	+	-	+	+	+	0
Precision of Measurement	4	0	0	0	0	0	+	0	+	+	+	0
Speed	2	+	+	+	+	0	+	+	+	-	+	+
Ease of Use	2	+	+	+	+	+	+	+	+	+	+	+
Cost	2	+	+	-	-	+	-	+	-	0	-	+
Size	1	-	0	-	-	0	0	0	0	0	0	0
Weight	1	-	0	0	0	0	0	0	0	0	-	0
Quantifiable Output	3	0	0	0	0	+	+	+	+	0	0	0
Power Input	4	+	+	+	+	+	0	+	0	0	0	0
Total Score		12	14	9	9	12	16	14	16	11	8	6
Rank		2	1	4	4	2	1	2	1	1	2	3

Table 5.2: Functions and components Pugh chart

5.3.1. Depressurization Method

We came up with four possible ways to depressurize the system upon completion of testing. They were: opening a valve, increasing the volume in the cylinder, using an expansion valve, and a pip/hose system. Increasing the volume was the best choice according to the Pugh chart. This method won on the strength of good scores in safety, ease of use and cost. Opening a valve came in second, also receiving strong scores in safety, ease of use and cost. Ultimately, we decided in favor of increasing the volume as our function because it would require no extra components to be installed on the device.

5.3.2. Temperature Measurement

The two components we came up with that could accomplish measuring the temperature were a thermometer and a thermocouple. We decided to use a thermocouple not only because it won in our Pugh chart rankings, but also our sponsor has thermocouples available for our use.

5.3.3. Pressure Measurement

We were able to come up with two methods to measure the pressure; a pressure gage and a pressure transducer. From our Pugh chart we found that a pressure transducer best met our needs. In addition, our sponsor was able to provide us with a pressure transducer, further strengthening that as our choice for measuring the pressure.

5.3.4. Piston Shaft Actuation Method

One challenge we anticipate was finding a way for the piston to resist the force caused by the pressurized hydraulic fluid while still having the ability to actuate freely. We came up with three ways to accomplish this task: a screw shaft, a geared shaft, and a spring-loaded shaft. Our Pugh chart ranked the screw shaft highest. However, we did still generate alpha design concepts with the other options in mind in order to see how they compared once everything was put together. Ultimately, though, we did decide on a screw shaft as the best choice for our alpha design.

5.3.5. Connection Method

Initially, the connection method was included in our Pugh chart and our group brainstormed several techniques of connection. Since then, our sponsor has provided us with the necessary equipment to connect our device to the hydraulic fluid line. Since this is being provided by our sponsor, we have removed it from the Pugh chart. The connection method provided is a screw-on hose where the free end can easily be screwed onto our device.

5.4. Choosing an Alpha Design

The next step in the process was to generate concepts that took into account the method, functions and components we had chosen. These concepts are all feasible alpha designs, and we again used a Pugh chart to weigh them against each other. This chart can be seen in Appendix I in Table 5.3 below. We used the same selection criteria and weights as used in the methods Pugh chart, with the addition of manufacturability. Manufacturability, given a weight of 3, allowed us to take into account our ability to actually produce the concept with the time and skill our group possesses.

		Concepts of Piston/Cylinder System Actuation					
Description		Manual Screw	Automatic Screw	Manual Spring	Automatic Gear	Hand Drill Attachment	Gun
Selection Criteria	**Weight**	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	+	+	+	+	-	+
Accuracy of Measurement	3	0	+	0	+	0	+
Precision of Measurement	4	0	+	-	+	0	+
Speed	2	-	+	0	+	+	+
Ease of Use	2	-	+	-	+	0	-
Cost	2	+	-	+	-	+	-
Size	1	+	+	+	-	+	-
Weight	1	+	0	+	-	0	0
Small Sample Volume	2	0	0	0	0	0	0
In-Line	1	0	0	0	0	0	0
Quantifiable Output	3	+	+	+	+	+	+
Power Input	4	+	-	+	-	0	+
Manufacturability	3	+	-	+	-	-	-
Total Score		14	10	12	7	1	12
Rank		1	4	2	5	6	2

Table 5.3: Alpha design concepts Pugh chart

The following is a list of the concepts generated by our group with a description of each concept. Each concept is based off the partial pressures in a piston/cylinder apparatus.

5.4.1. Concept A: Manual Screw

This concept used a screw shaft as the method of actuating the piston and resisting the force from the pressurized hydraulic fluid. A bolted-on cap on the end of the cylinder would have threads for the shaft to rotate about. This means the cap would carry the load from the pressurized hydraulic fluid pushing down on the piston. A hex on the end of the shaft would allow the user to attach a wrench and move the piston up or down, despite the large forces (up to 500 N) that would be pressing against the piston.

Advantages of this system include the low cost to manufacture, little to no need for an external power supply and a size and weight that fall within target values. The main disadvantage is the ease of use is decreased because the piston must be actuated by hand. There are also concerns that actuating the piston by hand may lead to inaccuracies from inconsistent volumes in the cylinder.

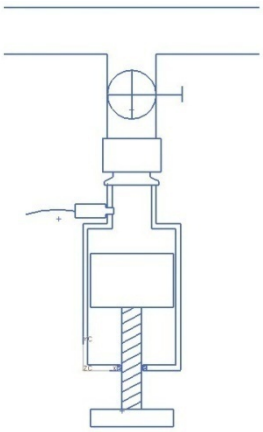


Figure 5.8: Concept A- Manual Screw

5.4.2. Concept B: Automatic Screw

This concept is similar to Concept A, with the difference being that a motor would be used to turn the screw shaft instead of the user.

Advantages of this system include a size or and weight that fall within target values, as well as ease of use as the piston is actuated by a motor. The main disadvantage in this design is a motor would likely require an external power source, which decreases the portability of the device.

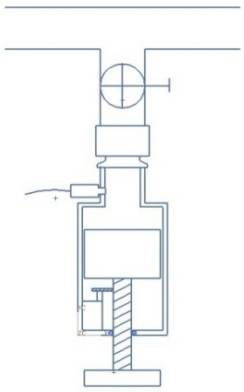


Figure 5.9: Concept B – Automatic Screw

5.4.3. Concept C: Manual Spring

This concept would use springs to resist the force from the pressurized fluid. Dampers would also be used to insure the piston didn't have any sudden movements, which could alter the volume or make the device unsafe. The piston would be moved via the user pushing or pulling it.

Advantages of this system include a low cost and no need for an external power supply. Disadvantages include inaccurate results and the user having to actuate the piston by hand, which would include working against the force in the spring at times.

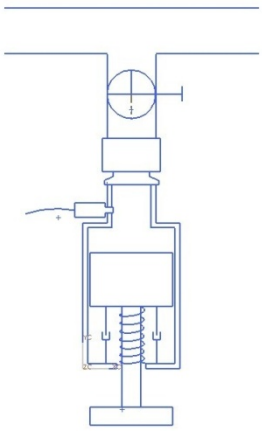


Figure 5.10: Concept C – Manual Spring

5.4.4. Concept D: Automatic Gear

This concept is similar to Concept B, differing in that gears would be used to obtain a high mechanical advantage. A motor would be used to turn the gears.

Advantages of this system include high precision and accuracy, as well of ease of use because the piston will be actuated by a gear attached to a motor. Disadvantages include a need for an external power supply and complexity.

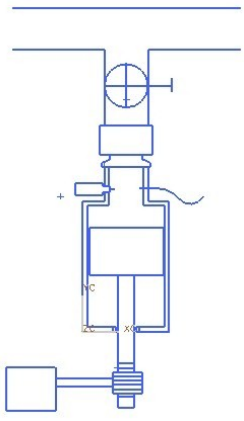


Figure 5.11: Concept D – Automatic Gear

5.4.5. Concept E: Hand Drill Attachment

This concept would use the shaft of the piston as a hand drill attachment. The end of the shaft would be in a hand drill and when the drill was on threads in the end cap on the cylinder would force the shaft up or down. This concept came about because a hand drill is available to us via our sponsor.

Advantages of this system include a low cost of manufacturing and no need for an external power supply. The main disadvantage is in safety; a slip up while using the power drill could lead to damage, or even failure of the device.

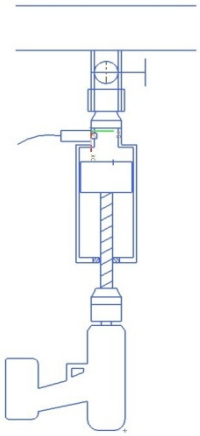


Figure 5.12: Concept E –Hand Drill Attachment

5.4.6. Concept F: Gun

This concept would use a lever mechanism to control the actuation of the piston. The lever would give the user enough mechanical advantage to withstand the force of the pressurized fluid.

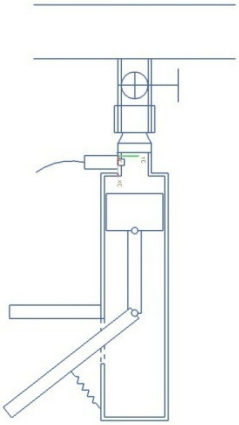


Figure 5.13: Concept F - Gun

The main advantages of this system are that there is no need for an external power supply, and it is an acceptable size and weight. The disadvantages include issues with ease of use and the ease of manufacturability.

5.5. The Chosen Concept

When we first ranked these six concepts against each other in the Pugh chart (Appendix F), the automatic screw concept was the highest rated. However, after this first ranking we added power input as a selection criterion after speaking with our sponsor. This dropped the automatic screw to fourth. The manual screw became the highest rated, followed by the manual spring and the gun tied for second.

We ultimately decided on the manual screw as our alpha design. This design best meets our customer demands and will allow us to meet a majority, if not all, of our engineering specifications. There are few moving parts and, since we will be designing each component to be rated for at least 300 psi, there are no glaring safety issues associated with this design. Since this design is based off of existing patents, we are confident that we will be able to obtain accurate and precise measurements with this device. Our initial calculations on the accuracy and precision agree with this assessment. The low cost associated with this design is also a large plus, since we will be able to use many components provided by our sponsor.

This design also meets the customer demands of quantifiable output and small sample volume. The pressure and temperature that will be recorded during testing easily lead to an output we can use. We don't expect to require anything more than a 100 ml sample size for testing. This design also helps us meet the portability demand our sponsor has stressed in recent meetings. In addition, it should be small enough and light enough for one user to hold in their hand during testing. Finally, there should be no external power sources required to operate the device, which further increases the device's portability.

6. ALPHA DESIGN

After applying the concept generation and selection methods previously discussed, the design chosen as the initial alpha design is a manually operated piston-cylinder. The purpose of this section is to present the components and corresponding functions of the alpha design, which are shown in Figure 6.1 on page 34.

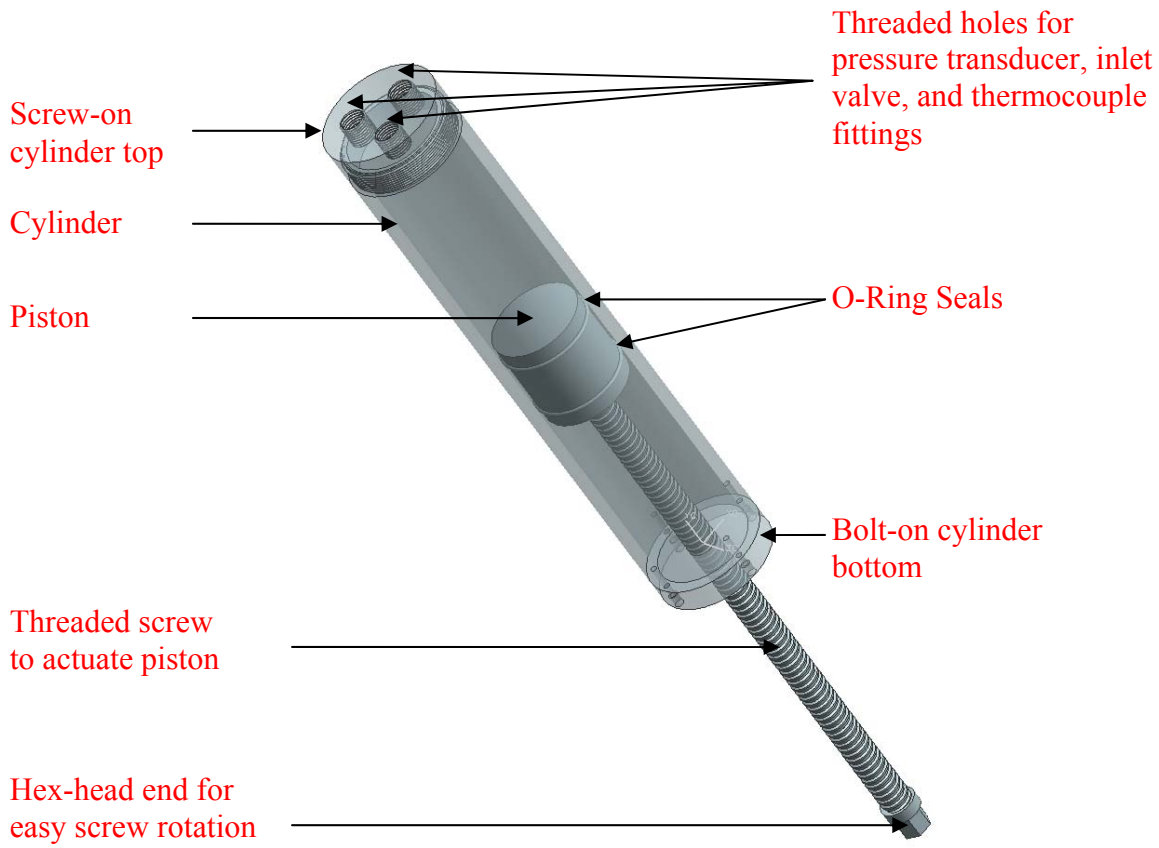


Figure 6.1: Initial piston-cylinder alpha design with main components

6.1. Main Components and Functions

In developing this design it was necessary to keep in mind several factors, which included customer requirements, engineering specifications, and manufacturability. There are two main assemblies with this device, the cylinder assembly and moving piston assembly, and the components comprising both were designed to address these factors while still achieving their individual desired functions.

6.1.1. Cylinder Assembly

To aid in manufacturability as well as assembly and disassembly of the device, the cylinder is composed of three components, the thin-walled cylinder and a top and bottom disk, which are shown respectively in Figure 6.2 and Figure 6.3 on page 35 and Figure 6.4 on page 36.

6.1.1.1. Thin-Walled Cylinder

The thin-walled cylinder is the main component of the entire design since it not only provides the outer surface for the piston to slide against, but is the supporting structure that all of the other components of the device will mount to. As shown in Figure 6.2 on page 35, the top of the cylinder will have male threads on it that the top cylinder disk will screw onto. This connection will need to be able to safely withstand the stresses from the 200 psi present when withdrawing fluid from the vehicle as well as the stresses from the vacuum pressure when the piston is lowered, and have a tight, sealed fitting to ensure there is no leakage. At the bottom of the cylinder there are four threaded holes that will be used to bolt the bottom disk to the cylinder.

Figure 6.2: Thin-walled cylinder

6.1.1.2. Top Disk

The top disk of the cylinder is shown in Figure 6.3 below. The three threaded holes at the top of the disk will be used to screw in fittings for the pressure transducer, thermocouple, and inlet valve. Placing all of these components on the top of the cylinder will allow us to actuate the piston all the way to Top Dead Center (TDC) without damaging them. Having this ability is important because it prevents us from having to bleed the system of air before attaching it to the vehicle and withdrawing fluid. On the underside of the disk, there are female threads that will screw into the top of the cylinder as previously discussed.

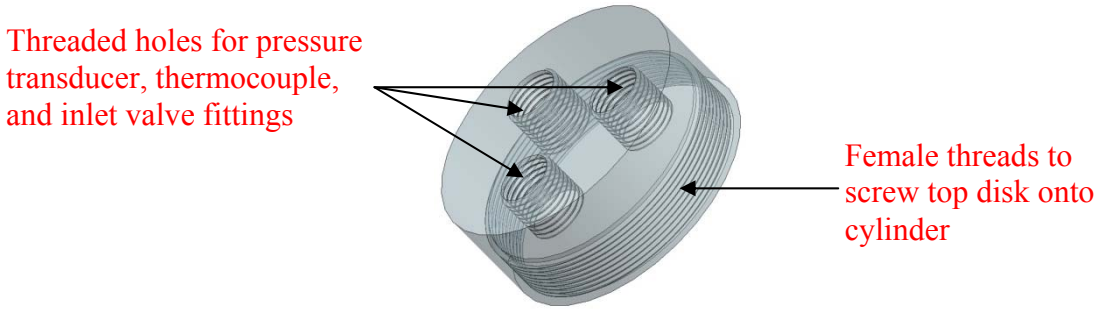


Figure 6.3: Top disk of cylinder

6.1.1.3. Bottom Disk

The bottom disk of the cylinder is shown in Figure 6.4 on page 36. The disk will bolt to the cylinder through four counterbored holes, and these bolts will need to withstand not only the force applied by the system pressure of 200 psi, but also resist any torque put on the disk by rotating the piston shaft. The piston shaft will screw through the threaded center hole of the bottom disk, allowing the piston to move linearly inside the cylinder.

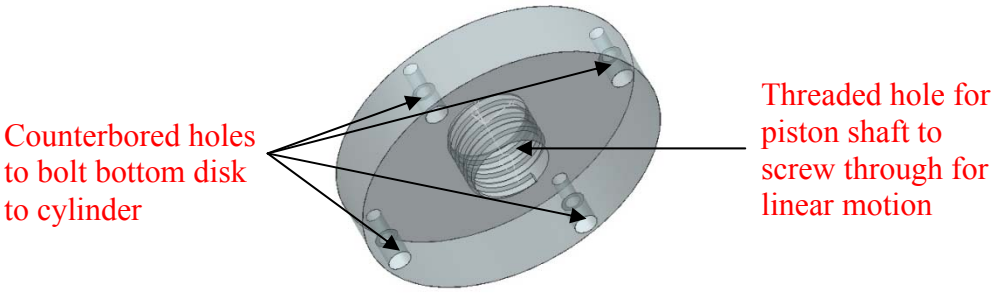


Figure 6.4: Bottom disk of cylinder

6.2. Piston Assembly

The main components of the piston assembly include the piston itself as well as the threaded shaft that will be used to actuate it, which are shown respectively in Figures 6.5 below and Figure 6.6 on page 37.

6.2.1.1. Piston

The piston in our design will use o-ring seals to prevent liquid and gas from exiting the controlled chamber of the cylinder, as shown in Figure 6.5 below, and to ensure that no unwanted pressure or fluid loss takes place. The bottom of the piston has a threaded hole for the piston shaft to screw into, and set screws will be used to prevent the shaft from loosening from the piston as it is rotated through the bottom disk.

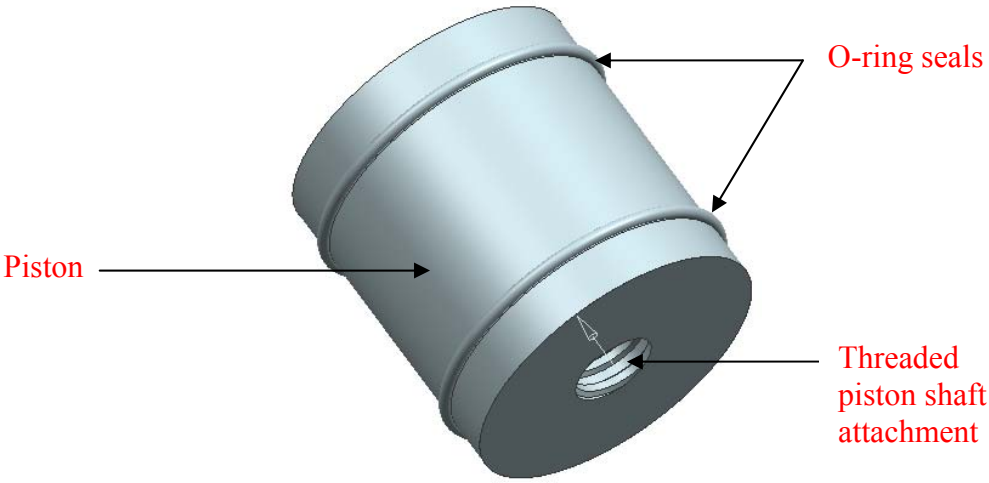


Figure 6.5: Piston and O-ring assembly

6.2.1.2. Piston Shaft

As shown in Figure 6.6 on page 37, the shaft of the piston will be threaded, and turning it will move the piston linearly inside the cylinder. The end of the threaded shaft will have a standard hex-head end so that a wrench or socket can be easily attached for convenient rotation of the screw.

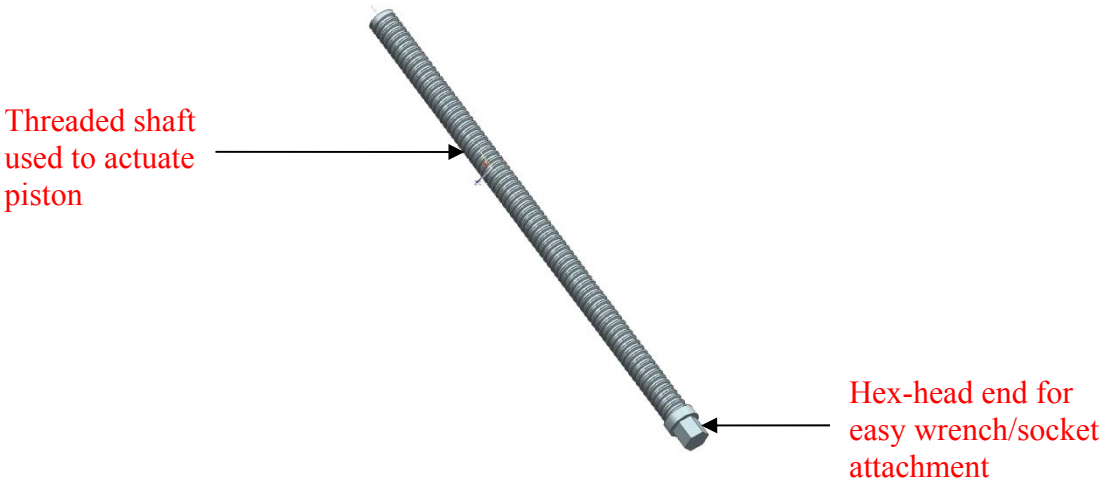


Figure 6.6: Piston shaft

6.3. Overall Function of Alpha Device and Testing Procedure

One of the driving factors in creating this alpha design was ensuring that hydraulic fluid was removed from the system at pressure so that no gas present in the hydraulic fluid could escape, as well as preventing any outside air from entering the device. Referring to Figure 6.7 on page 38, the steps below outline how each component will interact with one another to accomplish this and achieve the ultimate goal of determining the amount of gas present in hydraulic fluid.

Step 1: Prior to beginning a test, any remaining hydraulic fluid will need to be expelled from the cylinder by moving the piston to TDC with one end of the quick-connect hose attached to the cylinder, and the other directed into the hydraulic oil recycling bin at the EPA. The quick-connect attachment method was provided to us by the EPA and was previously discussed in Section 5.3.5. With the piston still at TDC, the device will then be connected to the low-pressure side of the hydraulic system (max 200 psi).

Step 2: A pre-determined amount of volume will then be extracted by rotating the shaft will with either a wrench or socket to a prescribed position. It will be very important to ensure that each prescribed position is reached with minimal variation between tests so that the volumes necessary for calculating the final concentration are consistent and repeatable.

Step 3: Once the desired amount of hydraulic fluid is entered into the device, it will be disconnected from the vehicle via the quick-connect, the piston will be further retracted, again to a pre-determined position. This will be close to Bottom Dead Center (BDC) so as to create the maximum amount of vacuum possible above the hydraulic fluid, thus promoting the maximum amount of gas to expel from the oil.

Step 4: After the pressure gauge has stopped fluctuating with the piston at BDC, it can be assumed that all gas able to come out of the solution at the given temperature

and pressure has come out, and the piston will then be quickly compressed to the final pre-determined volume. It will be necessary to compress the gas to a volume that will provide a large pressure reading compared to the vapor pressure of the fluid, so that the error in this reading can be minimized. Also, compressing it quickly will ensure that no gas other than hydraulic vapor has entered back into the fluid. Once the gas is compressed to this final volume, the pressure and temperature will be recorded, either manually or digitally depending on which final output method is chosen, and the molar concentration of the gas can be determined using the Ideal Gas Law and Henry's Law.

Figure 6.7: General testing procedure for Alpha design

Test Proceedure: 1) Device attached to system with piston in top dead center position.
2) Hydraulic fluid drawn into device by moving piston back to pre-determined location.
3) Piston extended the rest of the way to create vacuum on top of hydraulic fluid to promote expulsion of gas from the fluid.
4) Piston recompressed to pre-determined location, pressure and temperature readings taken and applied to Ideal Gas Law to attain mole concentration.

7. DESIGN EVOLUTION

Since the development of the alpha design, we have made several changes in order to best overcome previous challenges and accommodate industrial standards for this type of device. The design of our device has evolved from multiple concepts into a final apparatus. The evolution

was driven by customer requirements, engineering specifications and industry standards. Our design went through three major stages (alpha, beta, final), and the various design changes are outlined in this section. They include changes in cap design, cylinder material, actuation methods, pressure measurement devices and bearings.

7.1. End Caps

The end caps are used to contain pressure in the cylinder and assist in actuation of the shaft. They are made out of 6061 aluminum, making them easy to machine but able to withstand the forces applied to them.

7.1.1. From Threaded to Bolted

The alpha design involved screw-on caps. The threads created multiple barriers to prevent pressure leakage. With the use of a compression O-ring at the bottom of the thread, we would have been able to completely seal the system. The alpha design can be seen in Figure 7.1 below. The largest complication associated with using a threaded system came from the actuation rod in the bottom cap. The force from rotating the actuation screw through the bottom cap could have forcibly tightened the bottom cap, causing the threads to shear. When the actuation screw was driven the opposite direction, the cap could loosen and come off. This flaw and further investigation into pressure vessel standards and vacuum chambers led to a tie-rod bolt cap system for our design. It is the vacuum chamber industry standard to use two square caps with O-rings grooved into them, and four bolted tie-rods to tighten the lids together, forming a compression seal on the cylinder.

Figure 7.1 Alpha design threaded top cap

7.1.2. Sealing

The O-rings used in our design are 3/16” O-rings with a Shore A hardness of 50. They are located in grooves milled in each cap, and the cylinder is able to slide into the cap. When the bolts are tightened the cylinder compresses the ring, making a tight seal. The seals are rated to 1000 psi, and our design has been created based on industry and seal specifications, giving us confidence in the robustness of our sealing. We have ensured that air will not leak in or out of our system, but we were posed with the design challenge of removing air already trapped in the device.

7.1.3. Bleed Valve

When it became apparent that the alpha design would have trapped air within it, we installed a bleed valve. The trapped air was in the fittings for our measurement devices and for the fluid inlet channel. A bleed valve must be at the highest point in the system. In order for us to succeed in meeting this requirement the bleed valve was located on the side of the device which would be on at the highest point when the device was laid on its side for bleeding. Having the bleed valve

on the side created design problems as it began to interfere with the seal gland and with the O-ring itself. This beta design can be seen in Figure 7.2.

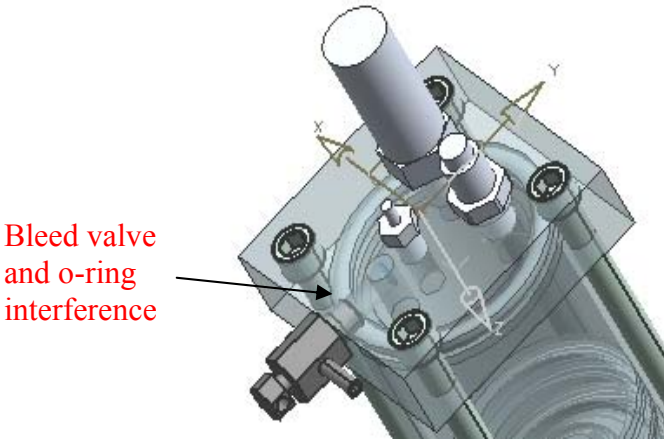


Figure 7.2 Beta design bolted top cap with bleed valve

Using a bleed valve increased the complexity of both our design and of the process, making it desirable to design away from. To eliminate the use of a bleed valve the inside of the top cap was designed such that the piston would be flush with the inner surface. The fittings for the thermocouple, pressure gauge and fluid inlet will sit flush on bottom face of the top plate as shown in the final top plate design in Figure 7.3 below. The two sources of trapped air are minor gaps and the inlet fluid line. The air that could be trapped in the minor cracks between the cylinder and the cap is minimal, and after the initial use a thin film of oil will provide filler for these areas; it is believed the air will become negligible. Testing will allow us to ensure that this conclusion is true. If not, further design evolution and calibration will be necessary. The inlet tube provides a possible source of air, but using the EPA technique of semi attaching the end of the line to the device and allowing the air and a small sample of hydraulic fluid to bleed into a rag will ensure that the line is charged and that only fluid is delivered to the device when the fitting is fully tightened. To ensure the safety of the person performing this task, it is recommended that safety glasses and a smock be worn. If hydraulic fluid makes contact with skin, wash with soapy water to prevent adverse reactions.

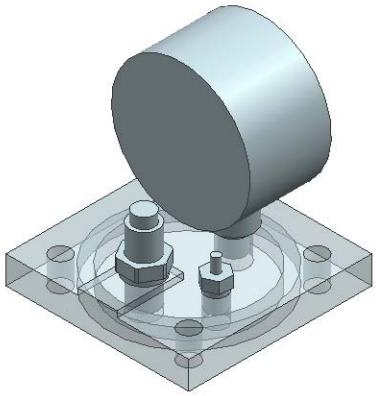


Figure 7.3 Final design of bolted top plate

7.1.4. Bottom Cap

The bottom cap evolved from the alpha screw design to the bolt design, and the method for attaching the ACME threaded rod has changed. In the alpha design we had planned to just tap the aluminum cap with the correct ACME size threads, however, the machine shop we will be manufacturing in does not have ACME taps and purchasing one proved to be far too expensive (~$200). Instead we decided to purchase a bronze ACME threaded mounting nut that has standard threading on its outer diameter, for which we can easily tap the aluminum cap and screw the nut onto. The bolt system for maintaining sealing will also provide stability to the caps, ensuring they do not spin with the applied torque.

7.2. Cylinder

The cylinder is the containment system for our device; it needs to withstand pressure differences, actuation and compressive forces. The cylinder material has gone through three material changes.

7.2.1. Alpha - Aluminum Cylinder

An aluminum cylinder was the obvious choice for our alpha design, given that it provides the toughness and strength necessary to ensure a safe device. Aluminum is a light material and the cylinder could be thin and lightweight while providing a large factor of safety. The chemical resistance of aluminum makes it a desirable material, but as our design evolved we found that creating an inexpensive and effective means of measuring linear actuation would be difficult without being able to see through the cylinder. This made the choice of aluminum less desirable and led to the first design change to acrylic.

7.2.2. Beta - Acrylic Cylinder

Acrylic is a clear, chemically resistant material that provided desirable strength and toughness properties. The wall thickness increased with acrylic but the transparent walls allowed us to create a simple linear actuation measurement system that increases the ease of use, and provides added accuracy and precision in that the user can visually measure the exact position of the piston by looking through the cylinder, and using an engineering scale. The fracture toughness of acrylic is just enough for it to not crack under the stresses our system runs under. Machining acrylic is very tough, as it has a tendency to chip unevenly and crack under the stress of drilling. This created design issues because acrylic tubing is sold by the foot, while our device calls for a ten inch cylinder. The lack of robustness that acrylic material provided made us look into other clear materials. Given some advice from our peers and further research, we were led to polycarbonate.

7.2.3. Final - Polycarbonate Cylinder

Polycarbonate is clear, chemically resistant to hydraulic fluid and has high fracture toughness. This increased fracture toughness allowed our walls to be thinner, making the cylinder lighter, and provided a higher safety factor on our leak before rupture condition. The increase in fracture toughness also makes polycarbonate easier to machine, as it is much less likely to crack than acrylic. Polycarbonate is not as chemically resistant as acrylic but under our usage it will not have any negative effect on the physical properties of the material.

A comparison of the physical properties of aluminum, acrylic, and polycarbonate is shown in Table 7.1 below. Further calculations regarding our specific system can be found in the Parameter Analysis portion of the report, Section 8.

Material	Yield Strength (ksi)	Fracture Toughness (ksi)	Transparent
Aluminum	42.1	21.8	No
Acrylic	7.8	1.46	Yes
Polycarbonate	8.56	4.19	Yes

Table 7.1: Physical properties of cylinder materials [27]

7.3. Actuation and Bearings

To actuate the piston, the design uses an ACME screw that moves through a ACME threaded nut mounted on the bottom cap. The method and design of actuating the ACME threaded rod has gone through several design changes and its evolution is described in the subsections below.

7.3.1. Alpha Manual Actuation

The manual actuation of the piston came from attaching a wrench or socket to the hex end of the rod and turning the handle. The lever arm created a low torque ensuring the process would not be tedious on the user. The ACME screw used to move the piston is rigidly attached to the piston base in the alpha design. The piston would rotate as it moves linearly up and down. Initially, having the piston rotate with the rod was not a concern because we felt that due to the relatively slow operation this would not impact sealing. However, after consulting piston seal experts at Parker Engineering, it became apparent that the seals we plan on using are rated only for linear motion and rotation could severely degrade their performance [28].

7.3.2. Beta Automated Actuation with a Ball Joint Swivel Bearing

To make our device easy to use, automated actuation was incorporated. We thought that if we made the device fully automated, then the operator could simply push a button and the process would occur. Automation would allow the actuation to be controlled within thousands of an inch and could increase the precision by eliminating human error. To fully automate this device a mechatronic system involving a DAQ, motor, amplifier and gear system would be used. These devices rely on electricity and are costly; this was the ultimate reason for our final design being manual. We reviewed our design after the second review and while making sure that it satisfied all customer demands and specifications, we realized that the design would not be portable enough for our customer nor would it be within the desired budget. From these constraints we developed our final actuation design.

Automating our device made us focus on constraining the rotation of the piston. Using a ball joint swivel bearing provides stability in the shaft, and accounts for misalignment up to 23° while still allowing the shaft to spin but keep the piston stable. Upon receiving the joint it was determined that the torque necessary for the bearing to rotate was beyond the scope of our device and a change would have to be made.

7.3.3. Final Manual Actuation with Tapered and Thrust Roller Bearings

To simplify our device and meet the portability and budgetary customer specifications a manually actuated tapered and thrust roller bearing system was created. The manual actuation is the same as in our alpha design: the ACME screw will be spun through the mounting nut using a

wrench or socket. The tapered bearing allows the screw to spin but keeps the piston from rotating, while being able to withstand a sufficient dynamic axial load. It can withstand the force of the linear actuation and still allow for free spinning of the screw.

7.4. Pressure Measurement

Measuring the pressure inside of our device is imperative to our design. From these pressure readings we will know when the system has reached equilibrium at vacuum and be able to determine the concentration of gas in the fluid.

7.4.1. Alpha Pressure Transducer

Pressure transducers can be very accurate measuring devices but they provide outputs in voltage or amperage, meaning they require electricity to operate. Our alpha and beta designs incorporated pressure transducers that would output to a voltmeter or LCD screen, respectively. The accuracy and precision ratings make them desirable but the need for an excitation voltage at 12 to 24 volt energy requirement makes them hard to incorporate into a portable device, which lead us away from this type of measurement system.

7.4 Omega pressure transducer [29]

7.4.2. Final Digital Pressure Gauge

The digital pressure gauge incorporated in our final device has an accuracy of 0.25% and runs off of an incorporated battery. The gauge allows our device to be fully portable but provides enough accuracy to satisfy our needs.

7.5 APG digital pressure gauge [30]

8. PARAMETER ANALYSIS

We performed rigorous parameter analysis in order to ensure that we would not need to substitute parts (or worse, design ideas) once we had already begun manufacturing. Additionally, a weak analysis could increase cost, as we may need to purchase new parts. We feel as though the following analysis ensures that our prototype will be robust, and able to accommodate any changes that must be made after manufacturing, assembly, and testing.

In order to finalize our design there were several main parameters that needed to be taken into account and determined. These include the sizing of the cylinder, end cap attachment and piston actuation method, each of which is described in further detail below.

8.1. Cylinder Sizing

The steps taken to properly size the cylinder, select a material, and validate its design are described in the subsequent sections.

8.1.1. Amount of Nitrogen in Hydraulic Fluid

The first step in sizing the cylinder was to estimate the amount of nitrogen we could expect to draw out of the hydraulic fluid, which is directly dependent on the pressure of the fluid at a given temperature, and is given by Henry's Law [8]:

$$k_h P_g = C$$

where k_H is the Henry's Law constant [moles/pressure-volume], P_g is the partial pressure of the gas, and C is the concentration [moles/volume]. The process of actually estimating the amount of nitrogen dissolved in hydraulic fluid proved to be very involved, which can be directly attributed to our inability to find a value for the Henry's Law constant of nitrogen dissolved in hydraulic fluid. Despite an exhaustive literature search performed throughout the duration of this project, we were unable to locate this constant. After consultation with a professor knowledgeable in hydraulic fluid applications, he recommended that another acceptable method would be to apply the parameters of an oil of similar density to that of our fluid and proceed with the analysis [9]. After further research we chose to use olive oil, which has a density of 0.895 g/ml, compared to that of hydraulic oil at 0.85 g/ml, because the molecular properties of its main constituent of oleic acid were readily available [30]. These properties were necessary to determine the Henry's Law constant of olive oil, given by the equation below [31]:

$$k_h = \frac{\rho_l y}{P_g M_l}$$

where ρ_l is the density of the liquid, y is the mol fraction of the gas dissolved in the liquid (y for nitrogen dissolved in olive oil is $2.82 \cdot 10^{-3}$ at STP), and M_l is the molar weight of the liquid (282.46 g/mol for oleic acid) [30]. With this constant, the above equation could then be used to determine the concentration of nitrogen in hydraulic fluid at the system pressure of 200 psi, which would give us the maximum amount of nitrogen we could expect to remove from the fluid. Multiplying the concentration by the volume of liquid withdrawn from the system then gives the moles of gas, n_g, as shown in the equation below.

$$n_g = C V_{liq}$$

8.1.2. Initial Fluid Volume

Once a relationship between the estimated concentration of nitrogen in hydraulic fluid at the system pressure of 200 psi and liquid volume was established, it was necessary to determine the initial volume of liquid we needed to enter into the system in order to achieve our final engineering specification of an accuracy of 2% by molar concentration.

Since our final molar concentration will be determined using the ideal gas law, we needed to relate the volume of gas to the volume of liquid. This was required to determine two gas volumes: the volume created by retracting the piston to produce a vacuum over the liquid head, which is necessary to outgas the nitrogen from the fluid, and the volume of the gas above the liquid after the piston is moved back towards TDC, which is necessary to compress the gas for the final pressure and temperature readings. Each of these volumes is based exclusively on the expected concentration of nitrogen in hydraulic fluid, which is in turn based on the assumed Henry's Law constant of oleic acid. The scaling factor, *x*, relates these gas volumes to the liquid volume as per the following equation:

$$V_g = xV_{liq}$$

By substituting this into the ideal gas law the following relationship can be established as shown below [32]:

$$PV_g = n_g RT$$

$$n_g = \frac{PxV_{liq}}{RT}$$

Where P is the gas pressure, R is the gas constant for nitrogen, and T is the temperature of the gas. To then find the initial liquid volume required to achieve our final accuracy specification of 2% molar concentration, we applied the partial derivative error analysis method to account for the error in each of our measuring devices, which is shown in the equation below [32]:

$$e_n^2 = \left(e_P \frac{\partial n}{\partial P}\right)^2 + \left(e_V \frac{\partial n}{\partial V}\right)^2 + \left(e_T \frac{\partial n}{\partial T}\right)^2 + \left(e_x \frac{\partial n}{\partial x}\right)^2$$

where the mole error is $e_n = e_{n\%} \cdot n_g$, pressure error is $e_P = e_{P\%} \cdot P$, volume error is e_V, temperature error is $e_T = e_{T\%} \cdot T$, and scaling factor error is e_x. For our device, our goal of molar concentration accuracy is $e_{n\%} = 2\%$, the digital pressure gauge has an accuracy of $e_{P\%} = .25\%$, and the thermocouple has an accuracy of $e_{T\%} = 1\%$. We chose a volume error of e_V=0.5 ml as the minimum volume change we could create based on the manual actuation of the lead screw, and took the scaling factor error to be zero since it was not possible to quantify. Substituting the specific error equations into the overall equation listed above and applying them to the concentration equation, we were able to solve for the liquid volume. The combination can be seen in the equation listed below, yielding a result of 30 ml sample size.

$$V_{liq} = \sqrt{\frac{e_V^2}{e_{n\%}^2 - e_{P\%}^2 - e_{T\%}^2}} = 30mL$$

8.1.3. Vacuum and Compressed Gas Volume

As discussed in the previous section, the vacuum gas volume and compressed gas volume were determined based on a scaling factor relating the gas volume to the liquid volume. These volumes are exclusively dependent on the Henry's Law constant, which indicates the amount of nitrogen that can be dissolved in hydraulic fluid at the system pressure. Again, since we were

unable to find this specific constant for our application we applied the properties of olive oil which has a similar density to that of hydraulic fluid, and based the volume sizing off of those results. By multiplying the concentration, which was found from this Henry's Law constant, with the initial liquid volume of 30 ml, the particular scaling factors could be determined for a range of pressures using the ideal gas law. Based on the 30 ml initial volume, the plot of the vacuum scaling factor and compressed scaling factor against the corresponding pressure are shown below in Figures 8.1 and 8.2 respectively.

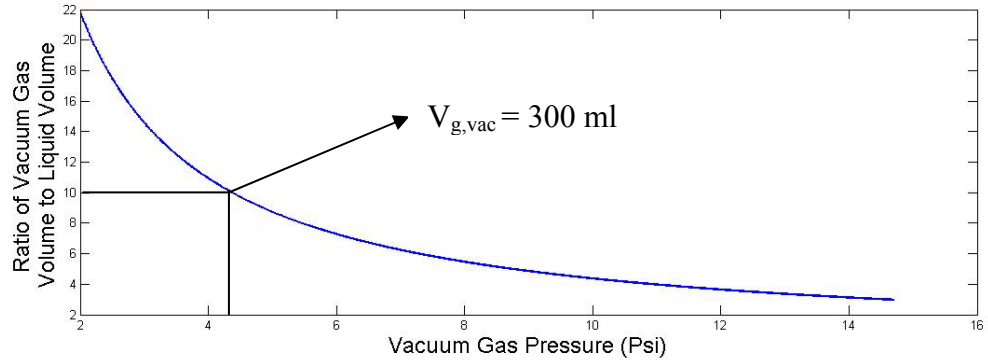


Figure 8.1: Vacuum gas scaling factor and corresponding vacuum pressure

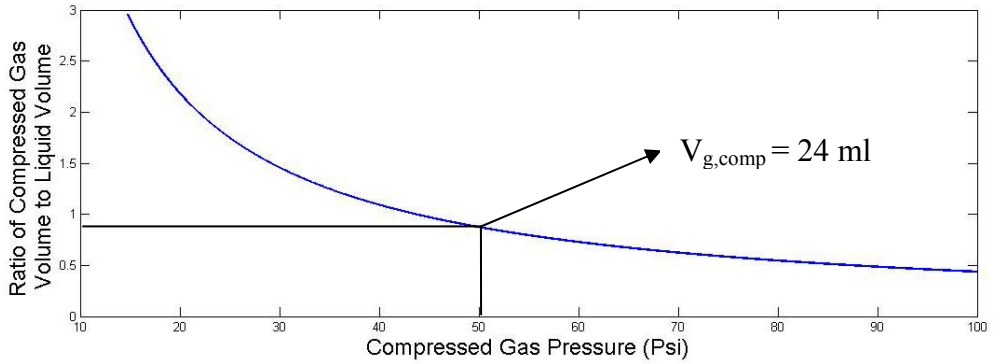


Figure 8.2: Compressed gas scaling factor and corresponding compressed gas pressure

As shown in Figure 8.1 above, selecting a ratio of vacuum gas volume to liquid volume of 10:1 gives a vacuum gas pressure of around 4.3 psi, and a vacuum gas volume of 300 ml. The ratio of 10 times the liquid volume was based on a patent of a similar device which used a 10:1 expansion ratio [14]. Similarly, selecting a compressed gas pressure of 50 psi as a reasonable final measurement pressure gave a ratio of compressed gas volume to liquid volume of 0.8:1, corresponding to a compressed gas volume of 24 ml.

It is important to note again that the determination of these values was based on the Henry's Law constant for nitrogen dissolved in olive oil, which is a major assumption. As a result, we chose to re-calculate the vacuum and compressed gas volumes after both doubling and halving the Henry's Law constant for nitrogen in olive oil to ensure we covered the maximum possible range. These results are summarized in Table 8.1 on page 47 and correspond to the volumes needed to achieve the same vacuum pressure of around 4 psi and compressed gas pressure of 50 psi.

	$2 \cdot k_H$	k_H	$0.5 \cdot k_H$
Vacuum Volume (ml)	690	300	120
Compressed Volume (ml)	60	24	10

Table 8.1: Volume sizing results based on changes of Henry's Law Constant, k_H

The main concern was sizing the cylinder based on a concentration assumption that was too low, which would give us an insufficient amount of dissolved nitrogen to remove from the fluid, and consequently a low, inaccurate reading. Therefore, it was necessary to size the cylinder so that if the concentration was indeed small, we could take in more fluid to achieve the same concentration. If the concentration is half of what was originally assumed, it would be necessary to double the volume from 30 ml to 60ml, which is given in Table 8.1 as $2 \cdot k_H$, and has a maximum volume of 690 ml. Adding the vacuum volume along with initial liquid volume gives 750 ml, which is the target for the cylinder size.

8.1.4. Radius Size

The sizing of the cylinder radius was dependent on the maximum force we wanted to allow the piston to experience, as well as the overall size of the device for portability. After initial research of the load capabilities of our system, we decided to require the load the piston must resist at the maximum system pressure of 200 psi to be less than 1,500 lbs. We then applied the equation below to find the corresponding radius [25]:

$$F = PA$$

where F is the maximum 1,500 lbs of force, P is the system pressure of 200 psi, and A is the area of the piston. Given the equation for the area of a circle, this gave us a maximum radius of 1.545", so we chose a radius of 1.3125" or 1-5/16". With an inner diameter then of 2-5/8" the cylinder is easily handled with one hand and will remain portable.

8.1.5. Cylinder Thickness

The cylinder material evolved from aluminum, to acrylic, and finally to polycarbonate based on each material's ability to meet our criterion regarding yield strength, fracture toughness, and transparency. With the material decided upon, it was necessary to size the thickness of the cylinder based on the material properties of polycarbonate, namely yield strenth, σ_y = 8,560 psi, and critical fracture toughness, K_{IC} = 4,190 psi$\cdot\sqrt{in}$ [27]. First, we applied a safety factor of 4 on yield and applied the resultant yield stress of 2,140 psi to the axial and hoop stress equations for a thin walled pressure vessel, given below in first and second equation respectively [25].

$$\sigma_{zz} = \frac{Pr}{2t}$$
$$\sigma_{\theta\theta} = \frac{Pr}{t}$$

At a maximum system pressure of 200 psi and the radius of 1-5/16", the worst case thickness came from hoop stress and was 0.12". Since the actual thickness must be greater than this, we chose a thickness of 0.1875" or 3/16".

Next, we needed to ensure that the leak before rupture condition was satisfied, which is an important safety criterion for any pressure vessel. This condition is met if the critical crack length, C_C, is greater than the thickness. The critical crack length was determined from the following equation [25].

$$C_C = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_{\theta\theta}}\right)^2$$

Substituting the critical fracture toughness for polycarbonate as well as the hoop stress from the chosen thickness at system pressure into the above equation produced a critical crack length of 2.85", which is much greater than the 0.1875" thickness and therefore satisfies the leak before rupture criterion.

The actual safety factor on yield, X_y, is 6 and was found using the equation below [25].

$$X_y = \frac{\sigma_y}{\sigma_{\theta\theta}}$$

To find the actual safety factor on leak before rupture, X_K, the actual fracture toughness, K_I, first needed to be determined using former equation, and then substituted into the latter equation listed below [25].

$$K_I = \sigma\sqrt{\pi t}$$
$$X_K = \frac{K_{IC}}{K_I}$$

The actual safety factor on leak before rupture is 4, and both safety factors are more than sufficient to ensure the safety of our device under its range of operating conditions.

8.2. End Cap Attachment

As previously discussed, the end cap design has changed from the alpha design of screw on caps, to the final design of bolting together the top and bottom caps. This design change was driven by talking with various engineers in industry who indicated that this type of design is the industry standard since it is rated for high pressure applications and O-rings provide a good seal with hydraulic fluid [3]. The end cap material between the alpha and final designs has remained the same, 6061 aluminum. However, with the new design it was necessary to determine the minimum bolt thickness required.

Similar to the cylinder wall thickness, the bolt thickness was determined based on the yield strength of the steel bolts we will use, σ_y = 60 ksi, and applying a safety factor of 4. The actual minimum bolt diameter was then calculated using the equation below [25].

$$\sigma = \frac{F}{A_{bolt} \cdot 4_{bolts}}$$

where F is the maximum force on the piston, which at 200 psi and a radius of 1.3125" is 1,082 lbs. This gave a minimum diameter of 0.15", so we chose to use 0.375" or 3/8" diameter bolts. The safety factor on yield of these bolts is 27, which is more than enough to safely sustain the

loadings our device will experience as well as allow enough room for preloading them to ensure a tight seal between the end caps and the cylinder. The specific torque for this preload has not been specified – the engineers we spoke with regarding similar systems indicated the torque to hand tight, plus a quarter turn, and we will follow a similar approach.

The necessary length of engagement of the brass ACME threaded nut to the aluminum bottom plate to carry the load was calculated to be 0.269 inches; the actual length of engagement is 0.5 inches which provides a safety factor of almost two. The necessary length of engagement was calculated using the following equations where D is the screw diameter and p is pitch. The last two equations were used to account for the differences in thread material. Here Q is the length of engagement between two different materials, A_s is the shear area of the external thread (screw) and A_n is the shear area of the internal thread (hole).

$$A_t = \frac{pi}{4}(D - 0.938194p)\text{^}2$$

$$L_e = \frac{2 * At}{Pi * K_n max(\frac{1}{2} + 0.57735n(E_s min - K_n max))}$$

$$J = \frac{As * Tensile\ strength\ of\ external\ thread\ material}{An * Tensile\ strength\ of\ internal\ thread\ material}$$

$$Q = J * Le$$

8.3. Piston Actuation

In order to verify that the piston actuation method and assembly could withstand the loads our device will experience, namely the force on the piston due to system pressure, it was necessary to assess both the ACME lead screw assembly as well as the piston/bearing/ACME rod assembly.

8.3.1. ACME Lead Screw Assembly

The ACME lead screw assembly consists of a 1018 steel ACME threaded rod, as well as a bronze ACME threaded nut that the rod will rotate through. Both of these components have been purchased from Roton, and the assembly comes rated as able to withstand 5,000 lbs dynamic load and 16,000 lbs static load. Since the maximum force on the piston due to a system pressure of 200 psi is 1,082 lbs, this assembly will be more than able to safely withstand such a force.

To determine the torque required to actuate the piston, we applied the torque equations for forward drive and back drive, which are respectively shown below [35].

$$T_f = \frac{LF}{2\pi e_f}$$
$$T_b = \frac{LFe_b}{2\pi}$$

where L is the lead in inches/rev, F is the load, e_f is the forward drive efficiency of 35%, and e_b is the back drive efficiency of 20%. We chose a lead of 0.1 inches/rev as the best compromise between resolution accuracy of changing the piston location and keeping the device as least

cumbersome as possible. The forward drive torque was based on a max force due to a compressed gas pressure of 50 psi, which is the target measurement pressure as described in Section 8.1.3, and was calculated to be 12.3 in-lb. The back drive torque was based on a max force due to the system pressure of 200 psi and was calculated to be 3.4 in-lb. Each of these torques are very low, and can be easily achieved by a user turning the screw by hand with a wrench or socket.

Also, an initial concern of this assembly was whether or not the threaded rod would back drive under system pressure, which would be both unsafe and contribute unwanted error in the process. However, this is no longer a concern since ACME threads have an inherently low lead angle which prevents them from back driving under an axial load alone.

8.3.2. Piston/Bearing/ACME Rod Assembly

The piston/bearing/ACME rod assembly is shown in Figure 8.3 below. As previously discussed, the piston and ACME threaded rod attachment method has evolved from a rigid connection, to a ball swivel bearing, to the final design of a tapered and thrust bearing.

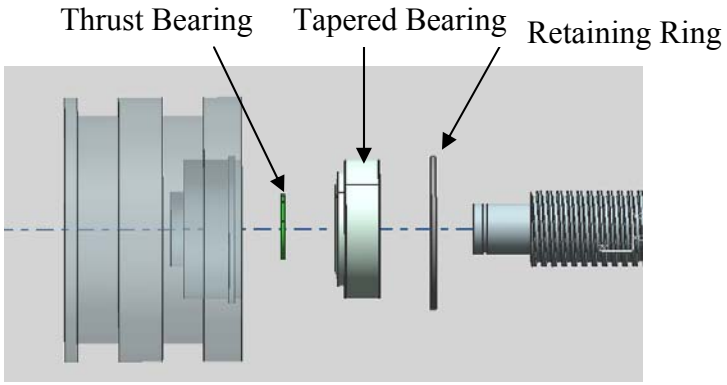


Figure 8.3: Piston/bearing/ACME rod assembly

As shown in Figure 8.3 above, the steel tapered bearing will be press fit onto the threaded rod, held in place with the force between the piston and a thrust bearing, then press fit into the piston, where it will also be held in place with a stainless steel retaining ring.

To ensure this assembly could withstand the loadings our device will experience, both the tapered and thrust bearings were selected because they can support 2,000 lbs axial load. Since this rating is close to our max loading of 1,082 lbs at a max system pressure of 200 psi we verified with the bearing manufacturer that we could design to this rated load, which is acceptable since their ratings have safety factors built into them.

8.4. Parameter Analysis Summary

Table 8.2 on page 51 provides a summary of all the safety factors, with the associated failure condition, for each part of our assembly. The only safety factor that raises some concern is in the bearing assembly in the piston. This assembly holds the piston and shaft together, and allows for smooth actuation of the piston. Due to the size of our shaft, and the limited availability of bearings suitable for our purpose, we were only able to achieve a safety factor of two against yielding. To minimize the impact of failure in the bearing assembly, a retaining ring has been

installed to keep the shaft in the piston. Therefore, if failure were to occur there would be no safety hazard for the user and the impact of the failure would be limited to loss of functionality, in that the piston would be unmovable inside the cylinder or part replacement would be required.

All other parts have safety factors at or above acceptable industry values for all modes of failure associated with the particular part.

Component	Material	Strength (ksi) [4]	Fracture Toughness ($ksi \cdot in^{1/2}$) [4]	Maximum Expected Load	Rating	Failure Condition	Safety Factor
Cylinder	Polycarbonate	8.65 (Yield)	4.19	200 psi	-	Yield	6
Cylinder	Polycarbonate	8.650 (Yield)	4.190	200 psi	-	Leak Before Rupture	4
End Plates	6061 Aluminum	47 (Yield)	21.8	1,000 lbs	-	Yield	250
Piston	6061 Aluminum	47 (Yield)	21.8	1,000 lbs	-	Yield	250
Bearing Assembly	Steel	57.3 (Yield)	74.6	1,000 lbs	2,000 lbs	Grinding/ Functional Failure	2
ACME Rod Assembly	Brass Nut Steel Rod	Steel: 57.3 (Yield) Brass: 79.8 (Tensile)	Steel: 74.6 Brass: 54.6	1,000 lbs	5,000 lbs dynamic; 16,000 lbs static	Shearing Deformation	5
Bottom Plate ACME Assembly	Brass Nut Aluminum Plate	Brass: 79.8 (Tensile) Aluminum: 52.9 (Tensile)	Brass: 54.6 Aluminum: 21.8	1,000 lbs	-	Thread Shearing	7
Tie Rod Bolts	Steel	60 ksi (Tensile)	$74.6\ ksi * in^{1/2}$	1,000 lbs	-	Yield	27

Table 8.2: Summary of materials, material properties and safety factors

8.5. Material and Manufacturing Process Selection

Out team utilized CES Software to assist in our material selection for our cylinder wall and end plates. A detailed summary of the work done with CES can be found in Appendix K. From this software, we were able to decrease the potential field of material candidates for each part. For the end cap, were we able to set minimum boundaries on the yield strength our material so shearing would not occur between the plate and the threaded nut used to actuate the piston. This helped limit our choices. Using material indices as well, we were able to come up with a final list of materials that met our requirements. We then compared this list to materials that could be easily obtained, mostly from McMaster, and from that decided on Aluminum 6061 because it was easily machinable, inexpensive and resistant to corrosion from oils.

Where CES was especially helpful was in selecting the cylinder wall material. While it was not a mandatory requirement, we wanted our cylinder wall to be transparent in order to making

measuring the piston actuation easier. With CES were we able to find which materials were transparent and still able to carry the loads we required. Initially, our search lead us to select acrylic for you cylinder wall. After a fellow student suggested polycarbonate as a possibility, we were able to check the yield strength's and fracture toughness's of the two materials and found that polycarbonate offered better safety factors against both yield and leak before rupture, while still being resistant to corrosion by oils. This, along with the availability of a polycarbonate cylinder in the size we required, led us to choose polycarbonate as our material.

8.6. Design for Environmental Safety

Our team utilized SimaPro software in order to quantify the environmental impact of the difference materials we chose for our device. We also compared the materials we chose to other materials we were considering from our CES aided material selection process. The work done in SimaPro can be found in full in Appendix C. The biggest thing we took away from SimaPro was the realization that emissions from making a material come from many unexpected places. There were over 100 sources of waste for every material we investigated using SimaPro.

For the cylinder we compared polycarbonate, the material we made the device from, to polypropylene. In terms of total emissions, polypropylene has the larger environmental impact. However, polycarbonate has a larger impact on human health and a higher EcoScore. In the end we decided we would stick with polycarbonate because of the higher safety factors against both yield and leak before rupture the material offers, as well as the longer expected life cycle of the part.

For the end cap, we compared Al 6060, which we assumed to be similar to the Al 6061 used in our device, to ABS. Aluminum by far leads to more total emissions. It was interesting to see that manufacturing ABS is a very low emission process, and this is reflected in its low EcoScore. However, in terms of EcoScore Al 6060 also scores very low and the decrease in emissions would not be worth the decrease in safety factors, especially when looking at the safety factor on shearing in the threads between the plate and the ACME nut.

8.7. Safety Report

The safety report allowed our team to understand the vulnerabilities in our project and to better understand our manufacturing plan. The safety report makes you put thought into what you are working with and how best to make your base materials into a final product. Making this report made us more aware of how our product would work and any flaws that could occur in our design before we had manufactured anything; this made us cautious and had us redesign certain areas to make the design more robust.

9. FINAL DESIGN

After conducting all necessary parameter analysis, the final design was easily derived. A CAD model of the final design is shown in Figure 9.1 on page 53.

Figure 9.1: Final design CAD model

9.1. Fabricated Components

As shown in the model and previously discussed, the final design consists of a 2-5/8” inner diameter, 3/16” thick, 10” long polycarbonate cylinder, which is compressed by two 6061 aluminum end plates (3.5” x 3.5” x 0.75”), which are held together using steel 3/8” diameter tie rod bolts, as per National Fluid Power Association standards for pressure-rated cylinders. The piston is also comprised of 6061 aluminum, and is actuated by an ACME threaded 1018 steel rod. The piston has an outermost diameter of 2.622”, and is 1.75” thick. The threaded rod has a total length of 14” and an outermost radius of 0.75”. We will be fabricating each of these parts from raw materials in order to best meet our needs, and their fully detailed drawings can be found in Section 10.

9.2. Purchased Components

In addition to the fabricated parts, we have several purchased components vital to the success of our design. We have purchased a digital pressure gauge which will be attached to the top plate and used to read the final compressed gas pressure, from which the concentration of gas within fluid is calculated. A Stauff line attachment has been purchased in order to properly connect our device to the EPA’s hydraulic accumulators. We have purchased several O-ring seals, which will be used for two specific purposes: first, they will form a seal between the cylinder and end plates; second, they will provide the seal between the piston and cylinder. The seals we have chosen are rated to handle high pressure, and contact with hydraulic fluid is not only safe for them, but it provides a lubricant for the seal, which is advantageous. Finally, we have purchased a tapered and thrust roller bearing to prevent rotation of the piston. The bearing is capable of handling several times the dynamic load we expect it to experience during use of the device. Additionally, it will allow the shaft to rotate freely while preventing any rotation of the piston. Though it should be able to form press fits with both the rod and the piston, we have added grooves for retaining rings to prevent both the shaft removal from the bearing, and bearing removal from the piston. Rotation of the piston is to be avoided to reduce wear and leakage in the seals.

9.3. Pressure Relief Valve

Upon the request of our advisors we have added a pressure relief valve to our design. The top plate design does not have room for another hole to be drilled into it so a pipe T adapter has been added to the hole that was originally tapped for the Stauff line attachment. The T allows the line attachment and the pressure relief valves to be in the same location without hindering the operability of the device. The pressure relief valve we have chosen to use is a brass adjustable relief valve designed for use with hydraulic fluid. It is set bleed fluid into a hose if the pressure is above 200 psi.

9.4. Prototype Description

The prototype will closely model the final design. While we do not expect to see any major deviations, it would be reasonable to assume that they may arise from the small tolerances featured in our engineering drawings, which mandate that the fabrication process be extremely accurate. Fortunately, each of our fabricated components was relatively inexpensive and had a short lead time. In the case we are forced to re-order and re-machine them, we would have ample time and resources to do so. In addition to this, our team has brainstormed possible failure modes for components. They are listed in our contingency plan, Table 9.1 below.

Part	Failure Mode	Impact	Contingency Plan
Piston Seals	Loosening or breaking	Leak of gas or hydraulic fluid	Disassemble the top and bottom plates from the cylinder. Replace faulty seals with higher rated seals or higher diameter seals within groove fittings of the piston. Re-assemble the device.
Face Seals	Loosening or breaking	Leak of gas or hydraulic fluid	Disassemble the top and bottom plates from the cylinder. Replace faulty seals with higher rated seals or higher diameter seals within groove fittings of the piston. Re-assemble the device.
Top/Bottom Plates (Threaded Holes)	Expansion due to wear or fatigue	Leak of gas or hydraulic fluid	Remove device(s) where leakage occurs. Re-apply Teflon tape to male threaded attachment on the device. Replace the device. Place epoxy on the edges of the hole if leakage still occurs.
Cylinder	Crack due to fatigue	Leak of gas or hydraulic fluid	Disassemble the device. Replace the faulty cylinder with a new 3/16” thick polycarbonate cylinder. Re-assemble the device.
Cylinder	Rupture or fast crack growth	Leak of gas or hydraulic fluid, flying debris	Disassemble the device. Replace the faulty cylinder with a 3/16” thick 6061 aluminum cylinder. Re-assemble the device. Attach an engineering scale on the bottom to measure actuation and use specified alternate measurements for standard tests.
Mount Nut	Threads stripped	Limited or no actuation of the piston	Disassemble the device. Replace the nut with a new one of the same parameters. Re-assemble the device.

Table 9.1: Contingency plan

We believe that through rigorous parameter analysis, interviews with professors and industrial professionals, and progressive design changes, we have produced the best possible design. We also believe that it will be easily fabricated and assembled, and these tasks will be completed in such a way that minimizes risk. We have assessed most, if not all, methods of failure or

possibilities for necessary adjustment, and designed accordingly. For these reasons, we are very confident in our final design and its translation into a physical prototype.

9.4.1. Prototype Procedure for Usage

The procedure for using our prototype will involve five steps, as per our engineering specification. The first step is to bleed the system of all air. This is performed using the EPA's method (previously outlined in section 5.3.4). Second, the piston will be backed down to a specified volume marking, and fluid will be entered into the device. Third, the piston will be backed down to a second specified volume marking, creating a vacuum and drawing all dissolved gas out of the hydraulic fluid sample. Once pressure has reached equilibrium (seen via the digital pressure gauge), the user will proceed to step four: actuating the piston forward to a third marked volume measurement, compressing the gas volume so that it is more accurately read by the gauge. Again, the user should wait for pressure to reach an equilibrium point, and the pressure should be read and recorded, as the final calculation is dependent on this reading. The concentration of nitrogen gas present in the sample can be calculated using the final pressure reading, temperature reading, and gas volume. Finally, the user will flush the system of all fluid, according to the EPA's disposal and recycling standards.

10. MANUFACTURING PLAN

The manufacturing process lists the steps to take our design from raw material to a final device. Each part has a specific plan including machine choice, cutting speeds, and feed rates. We will be using a band saw, lathe, vertical linear table mill, and vertical rotary table mill. From these plans, the parts can be fabricated to meet our needs. We have assessed all risks associated with our manufacturing plan.

10.1. Top End Cap

The top end cap will be manufactured to the drawings shown in Section 4 by manual machining on the mill. The drawings will be used to determine the proper drill size and depth. The material will be 6061 Aluminum. Because aluminum is easily machined, we will be using high-speed steels bits for the machining operations. The Machining Handbook dictates that the cutting speeds not exceed 375 surface feet per minute. These speeds are then converted to rotations per minute (rpm) by using the equation below:

$$RPM = \frac{12 * V}{\pi * d}$$

where V is the velocity in surface feet per minute and d is the diameter of the drill bit. The bit sizes, cutting speeds, feed rates and taps required for each operation are summarized in Table 10.1 on page 56, and correspond to the features shown in Figure 10.1 on page 56. Due to constraints with the machines available to us, we will not exceed 2500 rpm for any machining operation.

Step	Hole/Cut	Drill/Mill Size	Cutting Speed (rpm)	Feed Rate (in./min)	Tap (If applicable)
1	Band Saw	N/A	500 (fpm)	N/A	N/A
2	Fixture part in vertical linear table mill				
3	Facing	1” End Mill	2500	10	N/A
4	A,D	7/16” Drill	2500	12.5	1/4” NPT
5	B	R (11/32”) Drill	2500	10	1/8” NPT
6	C	13/32” Drill	2500	12.5	N/A
7	Flip part, re-fixture in vertical linear table mill				
8	Facing	1” End Mill	2500	10	N/A
9	Fixture in vertical rotary table mill				
10	Flip part, re-fixture in vertical rotary table mill				
11	Cylinder Groove	1/8” End Mill	2500	10	N/A
12	Hand tap holes A and B				

Table 10.1: Manufacturing operations for Top End Cap

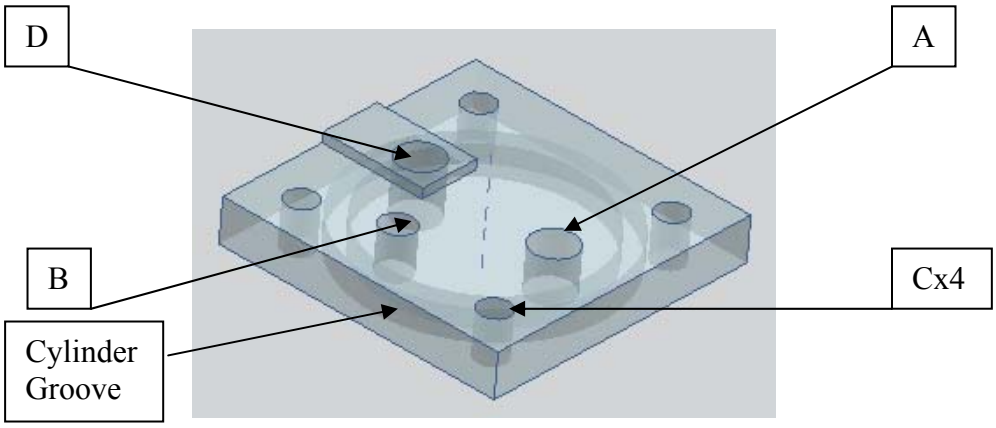


Figure 10.1: Top End Cap features

Since we will purchase the 6061 aluminum in a 3.5” x 3.5” x 3.5” block from McMaster, the first step will be to cut it into three blocks of thickness 1”, so that there is excess material for the mill fixture to clamp onto, allowing the top and sides to be faced to the appropriate dimensional tolerances. This also gives us an extra block in case we make a mistake during machining.

Next, we will fixture the block in a vertical linear table mill, face the top and sides and drill holes A, B,C and D. To make the system easy to bleed the line attachment needs to be the highest point on the plate. To easily manage this, the top of the plate will be milled with a rectangle over hole D that is three millimeters higher. The part will then be flipped and the bottom surface will be face milled to the appropriate tolerances. To machine the cylinder grove on the bottom it will be necessary to use a vertical rotary table mill, and to flip and re-fixture the part in between steps. Finally, holes A and B will be tapped by hand using the appropriate taps listed in Table 10.1.

10.2. Bottom End Cap

The basic procedure for manufacturing the bottom end cap is the same as described above for the top end cap. Table 10.2 lists the bit sizes, cutting speeds, feed rates and taps required for each operation, and the corresponding features are shown in Figure 10.2 below.

Step	Hole/Cut	Drill/Mill Size	Cutting Speed (rpm)	Feed Rate (in./min)	Tap (If applicable)
1	Fixture part in vertical linear table mill				
2	Facing	1" End Mill	2500	10	N/A
3	C	13/32" Drill	2500	12.5	N/A
4	G	1/4" Drill	2500	12.5	N/A
5	Re-fixture part in vertical linear table mill				
6	E	#25 Drill	2500	12.5	10-24 UNC
7	Fixture in vertical rotary table mill				
8	F	3/4" End Mill	2500	10	1-18 UNS
9	Cylinder Groove	1/8" End Mill	2500	10	N/A

Table 10.2: Manufacturing operations for Bottom End Cap

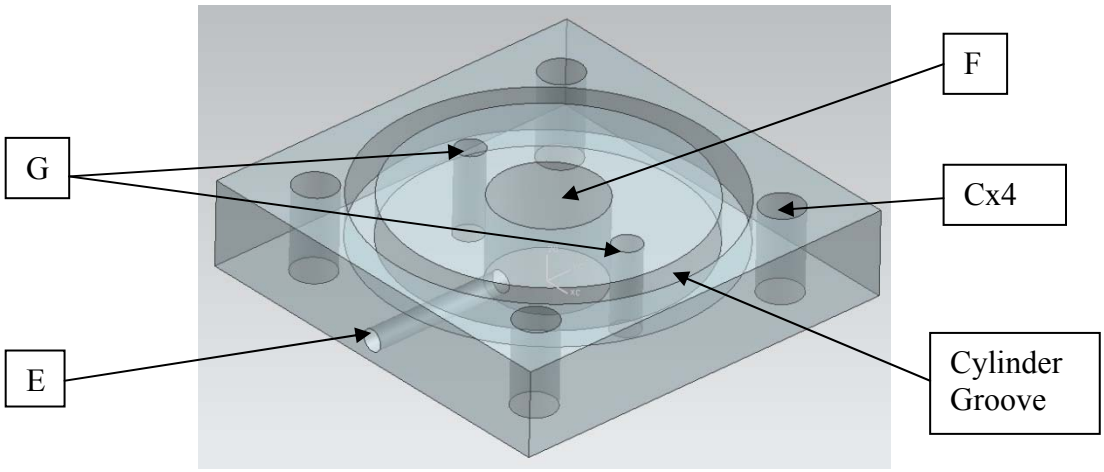


Figure 10.2: Bottom End Cap features

First, the other half of the 3.5" x 3.5" x 3.5" 6061 aluminum block from McMaster will be fixtured into the vertical linear table mill and the top and sides will be faced to the appropriate dimensional tolerances. Holes C and G will then be drilled. Next, the part will be re-fixtured on its side so that hole F can be drilled. To machine hole F and the cylinder groove it will be necessary to use a vertical rotary table mill. Hole E will be cut using a mill, ensuring that it is even and straight. Finally, hole E and F will be tapped by hand using the appropriate tap listed in Table 10.2.

10.3. ACME Threaded Lead Screw

The ACME Threaded Lead Screw will be ordered from Roton with a diameter of 3/4", length of 14", and made of 1018 mild steel. To machine this part it will be necessary to use both the lathe

and mill. Table 10.3 lists the bit sizes, cutting speeds, feed rates and taps required for each operation, and the corresponding features are shown in Figure 10.3.

Step	Hole/Cut	Machine	Tool Type	Cutting Speed (rpm)	Feed Rate (in./min)
1	Fixture part in increment table mill				
2	Hex	Mill	3/4" End Mill	1000	10
3	Fixture part in lathe				
4	Press Fit Edge	Lathe	Turning Tool	150	1.5
5	Retaining Ring Groove	Lathe	Parting/Groove Tool	150	1.5

Table 10.3: Manufacturing operations for Bottom End Cap

First, the hex attachment will be machined. This will be done on a mill, using the tool, speed and rate listed in the table above. This part will be milled using an increment device to rotate it 60° after every cut, thus insuring a good fit for a hex wrench.

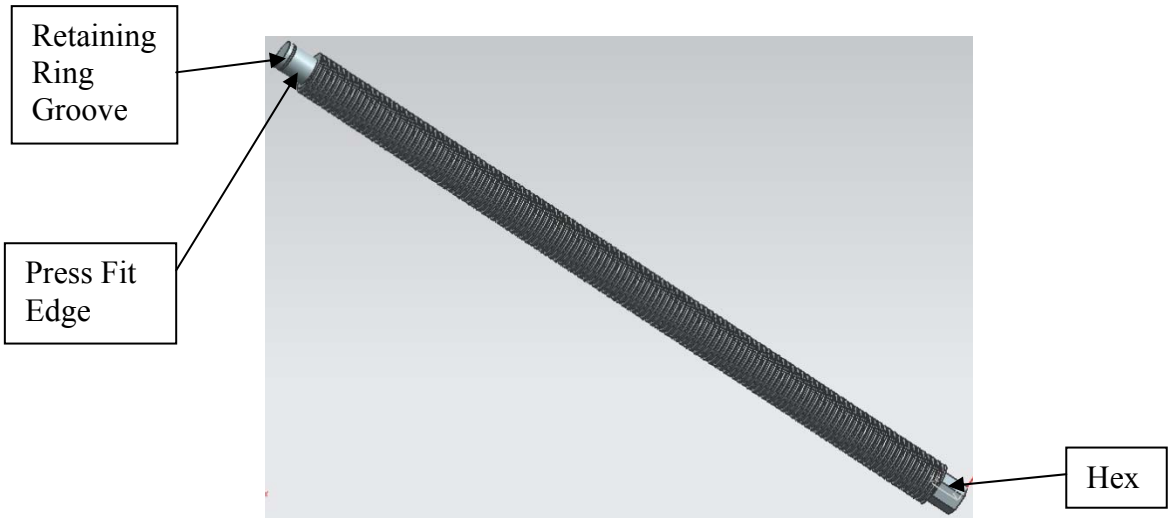


Figure 10.3: ACME Lead Screw features

Next, the lead screw will be fixture into a lathe and a turning tool will be used to bring the outside diameter of the rod down to proper size required for press fitting the tapered bearing onto it. This will also take off all the threads on that portion of the rod. A parting/grove tool will then be used to create the groove, which will hold the rod in the bearing by use of a retaining ring.

10.4. Piston Head

The material for the piston head is 6061 aluminum and will be ordered from McMaster as a 12" long, 2.75" diameter cylinder. All machining for this part will be done on the lathe. Table 10.4 on page 57 lists the bit sizes, cutting speeds, feed rates and taps required for each operation, and the corresponding features are shown in Figure 10.4 on page 59.

Step	Hole/Cut	Machine	Tool Type	Cutting Speed (rpm)	Feed Rate (in./min)
1	Cut cylinder	Band Saw	N/A	500 (fpm)	N/A
2	Fixture part in lathe				
3	Turn down to correct diameter	Lathe	Turning Tool	400	8
4	Seal Grooves	Lathe	Parting/Groove Tool	400	8
5	Bearing Space	Lathe	Boring Tool	400	8
6	Rod Clearance Space	Lathe	Boring Tool	400	8
7	Retaining Ring Groove	Lathe	Parting/Groove Tool	400	8
8	Flip part, re-fixture in lathe				
9	Cut off extra material	Lathe	Turning Tool	400	8

Table 10.4: Manufacturing operations for Piston

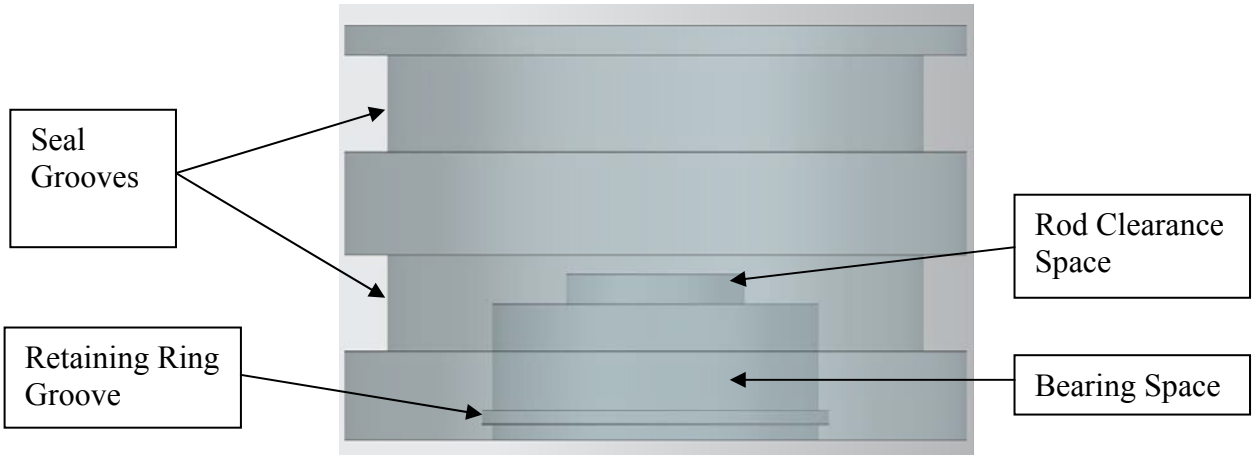


Figure 10.4: Piston features

First, the material will be cut down using a band saw. About 2.5" of extra material will be left to allow the lathe to grip the material. Next, the cylinder will be fixed in the lathe and outside turned down to the proper size. Grooves for the seals will then be added using a parting/turning tool.

Next, the openings for the rod and bearing must be made. A boring tool will be used to cut out the openings needed inside the piston. Special care will be given to these cuts because the tolerances must be good to insure a proper press fit with the bearing and rod. Next, the groove for the retaining ring will be cut using a parting/groove tool. Finally, the part will be flipped and re-fixed so all excess material on the top of the piston can be removed with a turning tool.

10.5. Polycarbonate Cylinder

The polycarbonate cylinder to be used for the cylinder walls will be ordered from McMaster as a 12” long cylinder with an inner diameter of 2-5/8” and outer diameter of 3”. This will be band sawed down to 10”, and then wet sanded to insure a proper finish and a good fit in the end caps.

11. ASSEMBLY

The design is a combination of manufactured and purchased parts. When manufacturing is complete the parts will be assembled using the following directions.

11.1. Bottom End Cap Sub-Assembly

The bottom end cap consists of the aluminum bottom plate, the nut that the ACME threaded screw will rotate through, and a set screw to prevent the nut from loosening. Figure 11.1 shows an exploded and complete CAD model view of the bottom plate sub-assembly.

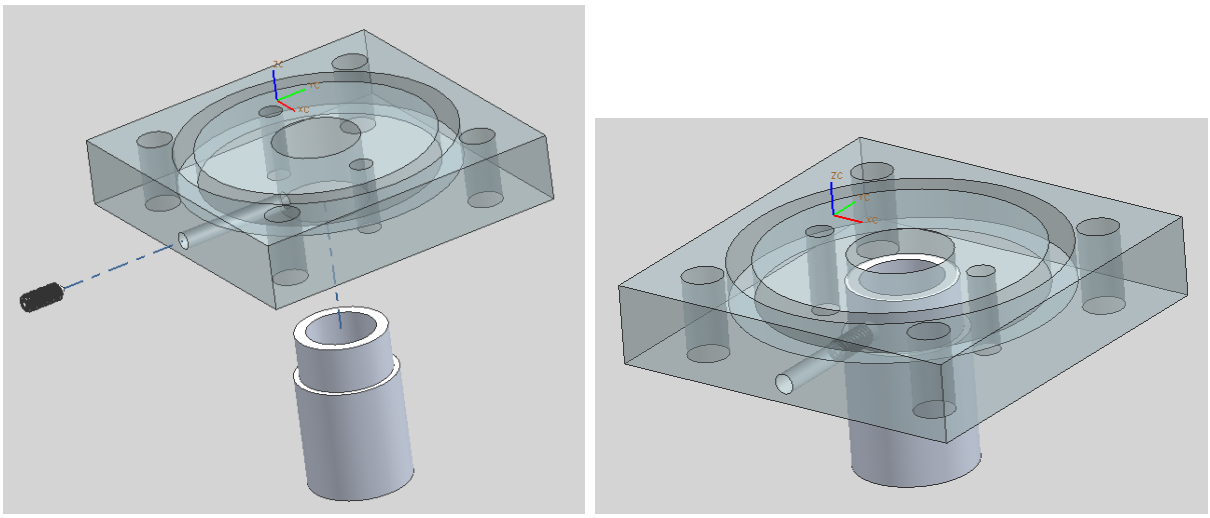


Figure 11.1: Bottom end cap sub-assembly, exploded view (left), assembled (right)

This sub assembly will be put together using the following procedure:

1. Connect the 3/4”-10 right-hand ACME threaded mount nut. This nut requires 1-18 UNS threading, which was added to the bottom end cap during machining. This will help to ensure a tight fit between the nut and the cap. Caution should be taken to avoid overturning the screws and causing damage to the threading on the aluminum block.
2. Install the set screw for the mount nut. A hole has been added to the side of the end cap for the set screw. Caution should be taken to avoid penetrating the inner diameter of the mounting nut, because this could interfere with the rod during use of the device.

11.2. Piston/Shaft Sub-Assembly

This sub assembly consists of the ACME threaded lead screw, the piston head, the roller bearing holding, and two retaining rings. Figure 11.2 on page 61 shows a CAD model of the finished piston/shaft sub-assembly.

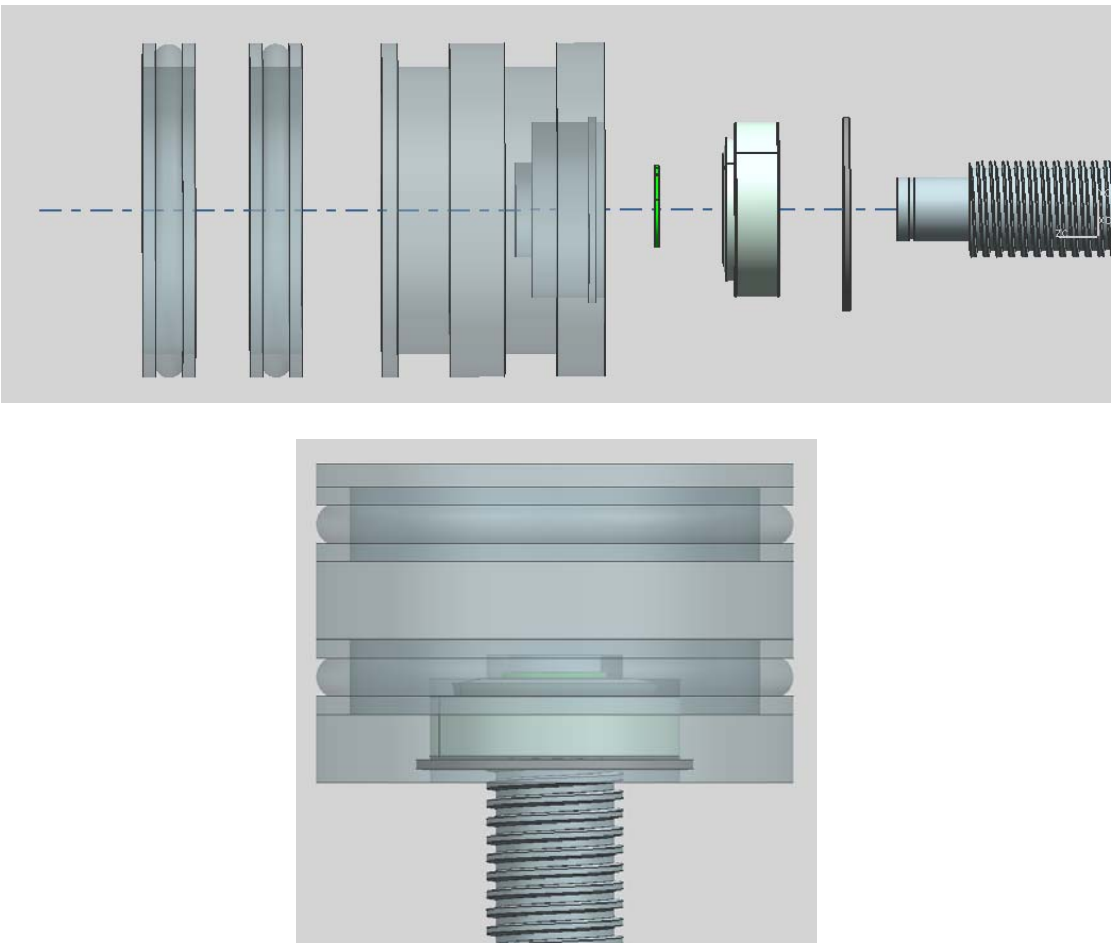


Figure 11.2: Piston/shaft sub-assembly, exploded view (top), assembled (bottom)

This sub assembly will be put together using the following procedure:

1. Install the roller bearing on the rod. This will be accomplished using a bench press. The rod has been designed to have very tight tolerances so that a press fit with the bearing is possible. After the bearing is attached to the rod, a washer and thrust bearing assembly is added to the remaining section of shaft.
2. Attach the rod to the piston head. This was accomplished using a bench press. The piston head has been designed to have very tight tolerances so that a press fit with the outside of the bearing is possible. After the rod and bearing have been pressed into the piston head, a 1-3/8" retaining ring will be installed to hold the entire sub-assembly together.
3. Install the seals on the piston head. Slip the seals over the outside diameter of the piston head and insert them into the grooves machined into the piston head.

11.3. Device Assembly

After the above sub assemblies have been made, the next step is to assemble the main device. Figure 11.3 on page 62 shows a CAD model of the main device assembly.

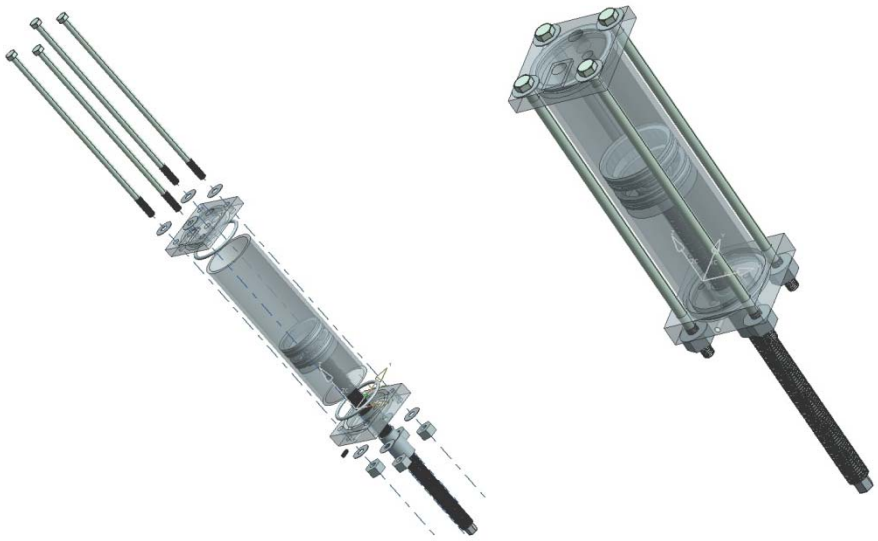


Figure 11.3: Main device assembly, exploded view (left), assembled (right)

The device assembly will be put together using the following procedure:

1. Install the polycarbonate cylinder on the piston head. Take caution to avoid scratching the polycarbonate during installation.
2. Install the 3/16” O-Rings in the bottom and top end caps. There are machined grooves in the caps for these rings. A screwdriver will be used to firmly press the O-Rings down into the grooves.
3. Install the piston/shaft sub-assembly in the bottom end cap sub-assembly. The bottom of the piston/shaft sub assembly will be screwed into the mounting nut installed in the bottom end cap.
4. With the piston head inside the cylinder, slide the cylinder down and insert the end in the O-ring groove on the bottom end cap.
5. Install the top end cap on the opposite end of the cylinder from the bottom end cap. Insert the edge of the cylinder in the O-ring groove in the top end cap.
6. Install the 12” long, 3/8” diameter bolts in the holes in the corners of the top end cap. Slide them down and through the corresponding holes on the bottom end cap. Install corresponding washers and nuts to keep the bolts in place. The nuts will be hand torqued until tight, plus a quarter turn to ensure a tight seal on the cylinder.

11.4. Final Device Assembly

The last process in assembling the final device includes installing the pressure gauge, compression fitting for the thermocouple, and the line attachment to take in and withdraw fluid from the system. Figure 11.4 on page 63 shows a CAD model of the final device assembly.

Figure 11.4: Final assembly, exploded view (left), assembled (right)

This sub assembly will be put together using the following procedure:

1. Connect the digital pressure gauge to the top plate. This is done using one of the ¼" NPT Female holes made during the machining process. The male threading on the pressure gauge should be covered with Teflon tape to ensure a tight fit. Next, the gauge should be screwed into the hole. A wrench should be used to ensure a tight fit. Caution should be taken to avoid overturning the screws and causing damage to the cut threading on the aluminum block. This could lead to leaks in the seal.
2. Connect the line attachment to the top plate. The line attachment is threaded with ¼" Male NPT, which corresponds with the remaining ¼" Female NPT hole made during machining. The male threading on the line attachment should be covered with Teflon tape to ensure a tight fit. After this, the gauge should be screwed into the hole. A wrench should be used to ensure a tight fit. Caution should be taken to avoid overturning the screws and causing damage to the threading on the aluminum block. This could lead to leaks in the seal.
3. Insert the compression fitting into the top plate. The compression fitting has 1/8" Male NPT, and a corresponding hole was made during machining. The male threading on the compression fitting should be covered with Teflon tape to ensure a tight fit. After this, the gauge should be screwed into the hole. A wrench should be used to ensure a tight fit. Caution should be taken to avoid overturning the screws and causing damage to the cut threading on the aluminum block. This could lead to leaks in the seal.
4. Insert the thermocouple into the compression fitting. This should be done while the top end plate rests on a flat surface because the thermocouple must be flush with the plate to avoid contact with the piston. After insertion, the hex nut on the compression fitting should be tightened using a wrench, locking the thermocouple in place.

11.5. Final Device – Actual, Completed Assembly

The final device was manufactured and assembled according to the respective plans listed in the previous sections, and the final, completed device is shown in Figure 11.5 on page 64.

Figure 11.5: Fully completed and assembled device

12. VALIDATION AND RESULTS

Before evaluating how well our final device satisfied the required engineering specifications we had designed to, it was necessary to perform a rigorous validation. The validation of our device progressed through several stages which included safety and structural testing, initial validation using olive oil, and final validation using hydraulic fluid. Each of these is described in further detail in the subsections below. During all testing our team wore nitrile gloves and safety glasses for proper protection.

12.1. Safety and Structural Validation Testing

Since safety was at the forefront of our customer requirements from the initial design stages, the first step in validating our device was to prove that it was safe. Prior to doing any actual testing, the device was placed in a safety box fabricated with aluminum supports and acrylic walls that was created by a previous ME 450 team, which is shown in Figure 12.1 on page 65.

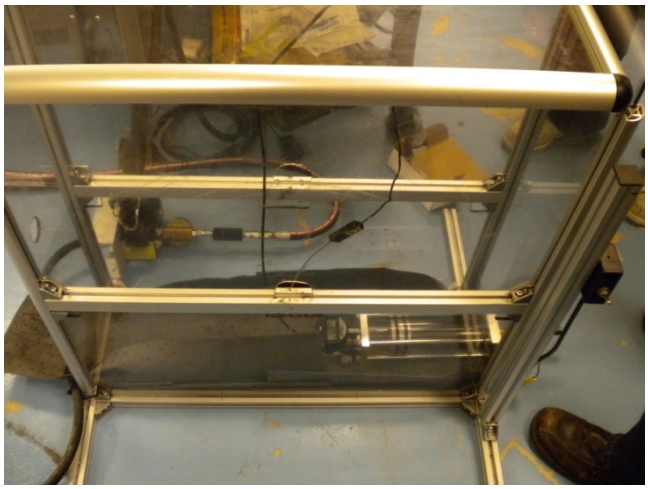


Figure 12.1: Safety box used for safety testing

Once inside the box, the first safety test was completed by drawing in air and compressing it by raising the piston, in increments of 20 psi. Each incremental level was held for 5 minutes, and the max test pressure of 220 psi was held for one hour. Upon compression at each test there would be some initial fluctuation in the pressure gauge, but the reading would level off after about one minute. All stages of this test passed – there was no loss of pressure and no visual or audible damage could be detected. Similarly, the same test procedure was used next for water, followed by olive oil, and finally with actual hydraulic fluid. Again, all stages of these tests passed – there was no loss of pressure and no visual or audible damage could be detected. Based on these results and with the addition of a pressure relief valve which we have set to 200 psi, our device is deemed safe and can be used for its intended purpose.

12.2. Initial Validation Using Olive Oil

As previously discussed, in order to properly size our device it was necessary to apply Henry's Law, the relationship which gives the amount of gas that can be dissolved within a particular fluid depending on the pressure of the fluid. Since we were unable to find the Henry's Law Constant for nitrogen dissolved in hydraulic fluid, we chose to use the constant for nitrogen dissolved in olive oil because it is similar in density to hydraulic fluid, and the properties required to calculate it were readily available, as discussed in Section 8. Therefore, the first step in validating our device was to determine whether or not we sized it properly by comparing the measured Henry's Law Constant for nitrogen dissolved in olive oil to the calculated value.
The initial testing procedure we used was the same as given previously in Section 9.4.1, which included drawing a sample of fluid into the device, lowering the piston to create a vacuum, allowing the liquid to degas, and then raising the piston to compress the extracted gas so the final pressure and temperature could be measured. The amount of extracted gas (moles) could then be calculated using the ideal gas law as per the equation below, where P is pressure, V is the gas volume, R is the gas constant, T is the temperature , and n is the number of moles [32].

$$n = \frac{PV}{RT}$$

The gas volume was taken as the difference between the final volume and initial liquid volume, which gives the volume of gas extracted from the fluid. By taking the difference between these volumes we were able to eliminate the added volume in each fitting hole due to the fittings not sitting flush against the top plate. Since we were using air for our tests and not pure nitrogen, it was necessary to determine the partial pressure of nitrogen. This was done by applying the equations listed below, where P_{Tot} is the measured pressure, P_{Air} is the air pressure, $P_{v,Water}$ is the pressure of the water vapor present in the air (found using steam tables for water at the measured temperature), $P_{v,Oil}$ is the vapor pressure of the oil (approximately zero and therefore negligible), y_{N2} is the concentration of nitrogen in air (78.1%), and P_{N2} is the partial pressure of the nitrogen used in our calculations [32].

$$P_{Tot} = P_{Air} + P_{v,Water} + P_{v,Oil}$$
$$P_{N_2=} y_{N_2} P_{Air}$$

For this initial round of testing we performed tests on store bought olive oil samples at two different initial pressures: atmospheric (14.7 psi) and 100 psi. The purpose of testing oil with an initial pressure of 100 psi was to try and replicate the hydraulic hybrid's system pressure that can range between 60 and 200 psi. For this test we entered olive oil into our device and before sealing it, lowered the piston to draw in a large amount of air. The device was then sealed and the piston was compressed until a pressure of 100 psi was reached. To ensure that the oil reached its saturation limit at this pressure we left it overnight and since there was a slight pressure drop of 5 psi, we were confident we had saturated the oil. The results of these tests are shown in Figures 12.2 below and 12.3 on page 67.

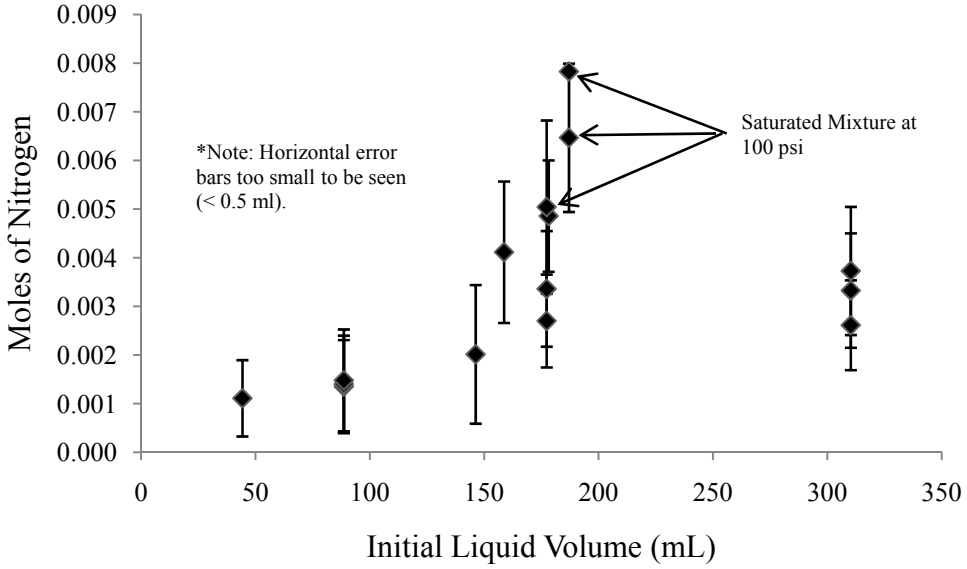


Figure 12.2: Moles of nitrogen dissolved in olive oil increases with liquid volume size and mixture pressure

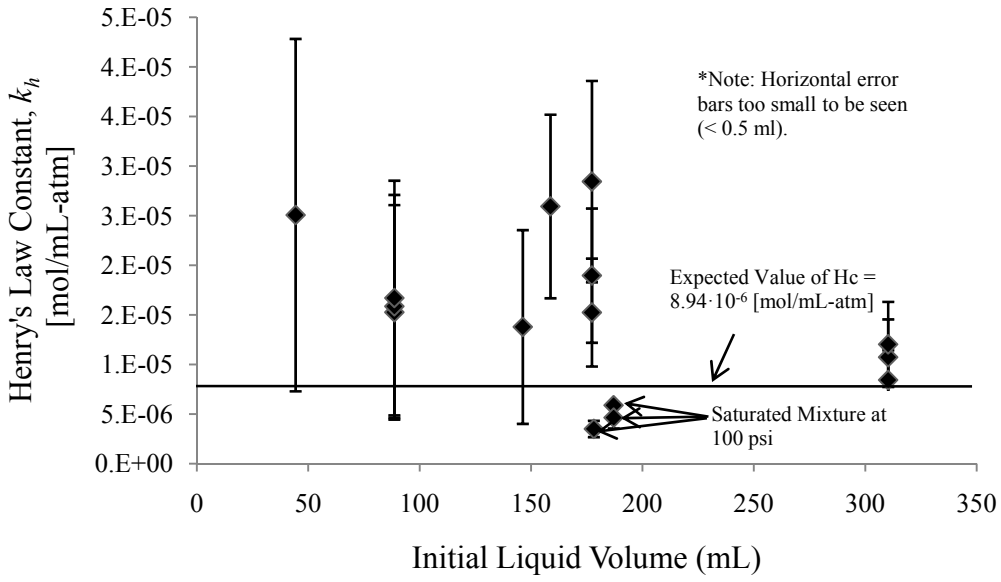


Figure 12.3: Henry's Law Constant, k_h, at 24°C for nitrogen dissolved in hydraulic oil based on initial test procedure

From this initial round of testing there were several important outcomes. The first is that although the measured values for Henry's Law Constant had a large amount of variation, they were on the same order of magnitude and relatively close to the expected value of $8.94 \cdot 10^{-6}$ mol/ml-atm, which is shown in Figure 12.3. Secondly, as shown in Figure 12.2 on page 64, the amount of nitrogen dissolved in olive oil increased with both increasing initial liquid volume size and initial mixture pressure, as was expected.

However, the actual amount of gas we were extracting from the fluid was significantly lower than what we had originally anticipated. After re-assessing our initial analysis we discovered that the direct cause of this was an error in our original calculation of the Henry's Law Constant, k_h, for nitrogen dissolved in olive oil, as well as the expected concentration, C, given by the equations below.

$$k_h = \frac{\rho_l y}{P_g M_l}$$
$$k_h P_g = C$$

When calculating k_h we had to convert the density of the fluid, ρ_l, from g/ml into kg/ml, and instead of multiplying by a factor of 1000 we had divided. When calculating the expected concentration we used the system pressure, P_g, of 200 psi because for all of our other calculations it was necessary to use that pressure for safety concerns. From a measurement device standpoint, 200 psi represents the greatest amount of dissolved nitrogen we could expect to withdraw from the fluid. Instead, we should have used atmospheric pressure of 14.7 psi, which would correspond to the lowest concentration. That way, if we were able to accurately measure the amount of gas dissolved in a solution at atmospheric pressure, we would be able to measure the increased concentration at system pressure.

Both of these errors significantly reduced the amount of gas we had originally expected to withdraw from the fluid, and were the reasons the uncertainty in the values shown in Figures 12.2 and 12.3 was so large. Since we were extracting much less gas than we had expected, when we went to take the final pressure and temperature readings we had to raise the piston to almost the same final volume as the initial volume to record a positive pressure, which was very low and ranged from 10-20 psi. Then when taking the difference between final and initial volumes, the gas volume would be around 2 ml. The resolution on the engineering scale we were using to measure the location of the piston and to calculate volume was 0.01", which for our cylinder corresponded to about 1 ml. Measuring this 2 ml gas volume with a device that has a resolution of 1 ml resulted in a final error in molar concentration of between 35-70%, which is much higher than our engineering specification of 2%.

12.3. Final Validation Using Hydraulic Fluid

In an effort to improve the accuracy of our existing device without completely re-designing and building a new one, we developed a new procedure that produced significantly better results. After much trial and error throughout the initial validation testing, we realized that even though there was not as much gas present in the fluid as we had originally calculated, our initial procedure was not removing all possible gas from the fluid.

The new procedure was focused on agitating the fluid while under vacuum to help promote degassing, and is given below with the revisions to the old procedure in bold. Refer Figure 12.4 on page 70 for pictures showing the device at each step of the procedure.

1. With system cleared of all hydraulic fluid from previous test and the line attachment disconnected (1a), lower piston to desired height measured with a scale from the base of the top plate to the top edge of the piston (1b).
2. Hold the device upright and pour hydraulic fluid into the line attachment hole until it is full and leaks out (2a). Screw on the line attachment fitting, turn the device upside down to allow any air that was initially trapped in the system to rise towards the piston (2b). Slowly return the device to its upright vertical position such that the air bubble travels to the line attachment hole. Unscrew and remove the line attachment, pour more fluid into the hole until it is full and leaks out, and re-screw the line attachment fitting. Tighten with an 11/16" wrench. The system will now be slightly pressurized since screwing on the line attachment fitting compressed the fluid. Lay the device flat on a table with the end of the lead screw hanging off the table edge and pressure gauge facing you (2c).
3. Lower piston to the height that achieves the maximum vacuum (usually about an inch further that the initial height will achieve the max vacuum of about -14 psig).
4. **Grasp the lead screw and with the device still flat on the table push/pull it rapidly to shake the mixture. Proceed until the pressure stops rising (about 20 seconds). Allow the majority of bubbles to rise to the surface and disperse.**
5. **Lower piston halfway between its current position and BDC and repeat Step 4.**
6. **Lower piston to BDC and repeat Step 4.**
7. Raise the piston to the initial height plus 0.1".
8. Record pressure measurement.
9. Turn device upright so that the air bubble is under the thermocouple sensor hole and record temperature measurement.
10. Lower the piston so that the pressure gauge reads zero psig (10a). Hold the device upright, unscrew the line attachment fitting and pour into appropriate container (10b). Raise the piston to TDC to force all remaining fluid out of the system (10c).

Step 1a

Step 1b

Step 2a

Step 2b

Step 2c

Step 3

Step 4

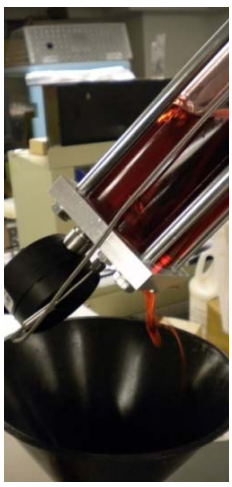
Step 5

Step 6

Step 7 and 8

Step 9

Step 10a



Step 10b

Step 10c

Figure 12.4: Pictures showing final test procedure

This procedure was performed with standard hydraulic fluid initially at atmospheric pressure and at six different initial liquid volumes, the results of which are shown in Figures 12.5 and 12.6 below.

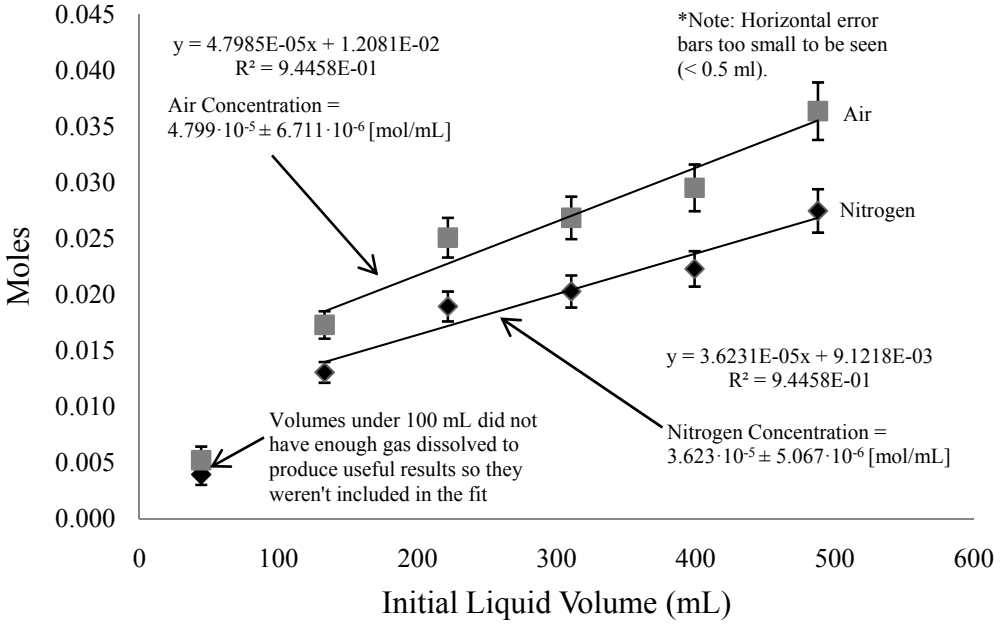


Figure 12.5: Moles of gas dissolved in hydraulic fluid at atmospheric pressure based on final test procedure

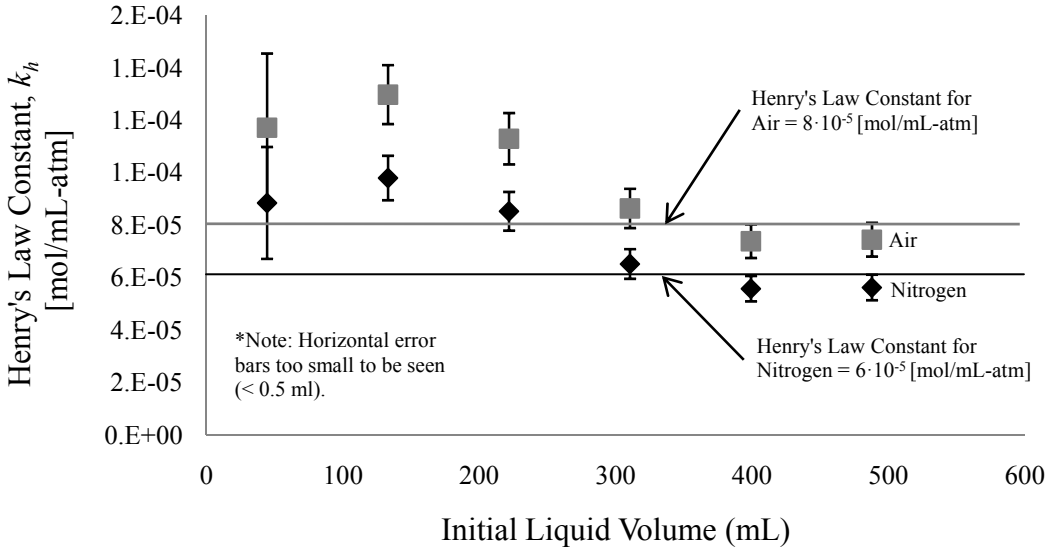
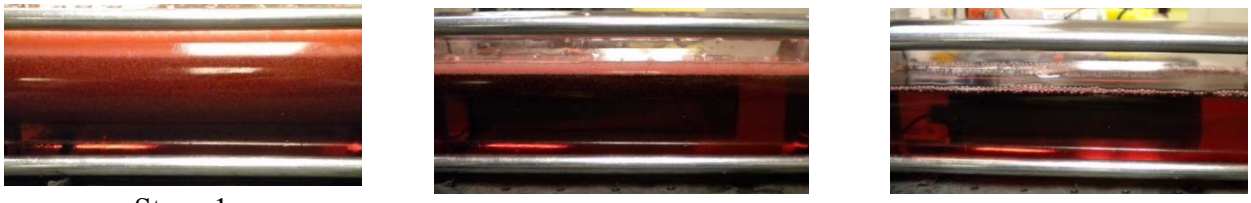


Figure 12.6: Henry's Law Constant, k_h, at 24°C for air and nitrogen dissolved in hydraulic fluid at atmospheric pressure based on final test procedure

The consistency of these tests and overall accuracy on all data points were significantly improved with the new procedure versus the old one. By rapidly agitating the fluid at three

different stages it was clear when all the gas had been removed. This was quantitatively apparent by watching the pressure gauge while shaking the fluid – as gas continued to expel the pressure would slightly increase and then level off. Visually it was apparent because you could see when all bubbles had dispersed. Referring to Figure 12.7 below, after agitation at the first vacuum degassing stage there would be a very large amount of bubble formation coming out of solution. By the third stage, when the fluid was agitated hardly any bubble formation would occur and the solution would remain clear and much darker, also indicating the complete removal of gas. Compared to the initial testing, the calculated gas volume increased by a factor of 4.5 from 2 ml to 9 ml. Similarly, the measured pressure readings were much higher than the previous test method, increasing from 10-20 psi to 20-40 psi.



Stage 1 Stage 2 Stage 3

Figure 12.7: Vacuum degassing stages showing complete removal of air from fluid

As shown in Figure 12.5 on page 71, volumes below 100 ml did not have enough gas dissolved in them to produce useful results, and these data points were therefore disregarded when determining the gas concentrations. The concentration of nitrogen in hydraulic fluid at atmospheric pressure was found to be $3.623 \cdot 10^{-5} \pm 5.067 \cdot 10^{-6}$ mol/ml, while air was $4.799 \cdot 10^{-5} \pm 6.711 \cdot 10^{-6}$ mol/ml. Again it should be noted that the test was done with air, so all nitrogen values are scaled appropriately based on air being composed of 78.1% nitrogen. The uncertainty in the air and nitrogen concentration is 14%, which is still higher than our engineering specification of 2%, but much better than the initial 35-75%.

As previously discussed and shown in Figure 12.3 on page 67, our measured values of k_h correlated well to the predicted k_h for nitrogen in olive oil for the initial test results. However, the value of k_h was an order of magnitude larger for the final test performed on actual hydraulic fluid. Our measured value of k_h and how it compares to nitrogen dissolved in other fluids is given below in Table 12.1.

Nitrogen Dissolved in	Henry's Law Constant, k_h, (mol/ml-atm)
Water	6.10×10^{-7}
Olive Oil	8.94×10^{-6}
Hydraulic Fluid	6.00×10^{-5}

Table 12.1: Henry's Law Constant for nitrogen dissolved in various fluids at 25°C

According to the value we obtained for k_h, hydraulic fluid would actually have the highest concentration of nitrogen dissolved in it when compared to olive oil or water at a given pressure and liquid volume. As shown in Figure 12.6 on page 71, the Henry's Law Constant we are reporting is based on the last three data points corresponding to larger liquid volumes. Since

more gas was dissolved in the fluid at larger liquid volumes, the confidence level of these values was much larger than that of smaller liquid volumes, as shown in the size of the error bars.

Although we could have repeated this final test procedure using olive oil to better validate the results from the initial test procedure, we deemed it unnecessary. Olive oil was used only to compare the predicted Henry's Law Constant, k_h, for nitrogen in olive oil to our measured value so we could determine whether we had sized our cylinder appropriately. Despite the constants correlating well from the initial test, it revealed the two errors we had made during our original analysis, which lead to the realization that we were not removing the originally anticipated amount of gas. Regardless of those calculations being wrong, we correctly chose to oversize the cylinder design, and although the accuracy level of 14% does not meet the original specification of 2%, we feel that the device can still be used for its intended purpose. In that sense, the first test served its purpose and since the EPA will be using this device for hydraulic fluid we felt it was only necessary to perform the final procedure using hydraulic fluid.

While we are reporting the value of Henry's Law Constant we obtained, it needs to be understood that this is an approximation. To establish an actual value of k_h for nitrogen dissolved in hydraulic fluid it would be necessary to continue testing at various initial fluid pressures. We chose to only test hydraulic fluid initially at atmospheric pressure for several reasons. The major reason was based on time constraints of our project – by the time the device was built and new test procedure created, we did not have time to go back and perform further testing at replicated system pressures. Also, the EPA's actual hybrid hydraulic system is not currently pressurized, which would be the single best way of obtaining this data.

As previously discussed, the worst case (lowest) amount of nitrogen dissolved in hydraulic fluid would be from a stock bottle at atmospheric pressure. If we could detect this level we would be able to detect the level at system pressure. Not only does the solubility of gas in a liquid increase with pressure, but we designed our device to be able to attach directly to the EPA's hydraulic hybrid vehicle so that no gas would be lost in the transfer process. If more nitrogen leaked through the accumulators than could be dissolved in the hydraulic fluid at that pressure, there would be both dissolved and free gas, and our device would be able to remove and measure the contributions of both. At system pressure there would only be higher levels of gas present in the fluid, which would cause the accuracy of our device to increase. Since we have demonstrated that we can measure the dissolved gas in hydraulic fluid at atmospheric pressure with a confidence level of 14%, and because the EPA's hydraulic hybrid vehicle is not currently pressurized and will remain so for the duration of the semester, we felt that this concluded our required validation.

13. SPECIFICATION SUMMARY

In this section we have outlined how our design meets the engineering specifications put forth by our sponsor based on the final construction of our device and validation testing. Table 13.1 below summarizes the original engineering specifications, how our final values compared, and whether or not we met them.

Engineering Specification	Target Value	Actual Value	Unit	Specification Met?
Fitting and Seal Ratings	≥300	1000	psi	Yes
Level of Accuracy	± 2 or better	14%	% by Molar Concentration (Moles/ml)	No
Test Time	<10	15-30 min (Dependant on Concentration)	min	No
Steps in Process	<5	10	steps	No
Hydraulic Fluid Sample Size	≤0.5	0.092 – 0.156 (350-600 ml)	gal	Yes
Cost	<1500	817.63	USD	Yes
Footprint of Device	<1	0.2	ft^3	Yes
Weight	<20	7.5	lbs	Yes

Table 13.1: Summary of engineering specifications, how our final values compared, and whether or not our device met them

13.1. Satisfied Specifications

Our design has satisfied five of the eight required engineering specifications, which include fitting and seal ratings, hydraulic fluid sample size, cost, footprint of device, and weight.

13.1.1. Fittings and Seal Ratings

The fittings and seals have all been purchased to be above the 300psi specification, our lowest seal is rated to 1000psi and all of the fittings exceed the 1000psi rating.

13.1.2. Hydraulic Fluid Sample Size

Upon running validation tests, we found that the results of the test are most accurate when at least 350 ml (0.092 gal) of fluid is used. Therefore, we have set a range of 350-600 ml (0.092-0.156 gal) as the sample size to be tested. Despite being larger than originally anticipated, this sample size still falls within the accepted range listed in our engineering specifications. Therefore, the specification is met.

13.1.3. Cost

The current bill of materials is provided in Appendix G and indicates that the cost to create this device was $817.63. This is less than the budget of $1500.

13.1.4. Footprint of Device

The largest possible volumetric footprint of our device was calculated using the largest dimension in every direction. The piston was located at the base of the cylinder making the

actuation shaft as far from the top as possible and the side dimensions were measured as the sides of the top and bottom plates. The calculation below shows our footprint to be approximately one fifth of the allowable footprint.

$$3.5in \cdot 3.5in \cdot 25in = 306.25in^3 = .2ft^3$$

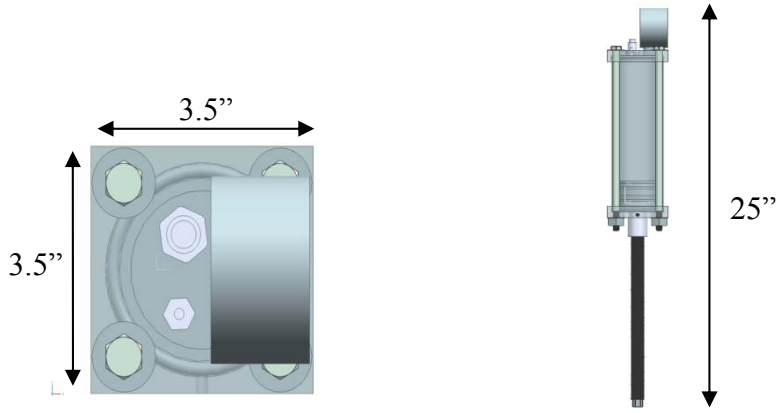


Figure 13.1: Dimensioned drawings showing outer dimensions of device

13.1.5. Weight

We weighed our device once fully constructed and found it to be seven and a half pounds. Even with a fluid sample inside it will not be above 20 lbs. Therefore, we have met the specification requiring our device to be less than 20 lbs.

13.2. Specifications not Satisfied

Our team was unable to meet three of the eight specifications set by our sponsor, which include level of accuracy, test time, and steps in process.

13.2.1. Level of Accuracy

Upon completion of the validation tests, we determined that our device can achieve an accuracy of 14% on the concentration of gas in hydraulic fluid. This does not meet our specification of 2%. The primary reason that this specification was not met was due to the accuracy on the volume measurement, which was previously discussed in Section 12 and will be addressed again in Section 14 and 15.

13.2.2. Test Time

The test time depends on two factors, actuation speed and diffusion rate of air from hydraulic fluid. Upon completion of the validation tests, we determined that our test time ranged from 15-30 min. This time is dependent on the amount of gas in solution in the sample. Originally, our test time was ten minutes; however, we were not able to extract all the gas from solution with this time. Increasing the test time, along with reworking the test procedure, allowed us to remove all gas from solution and increase the accuracy of our device.

13.2.3. Steps in Process

Originally our process involved five steps, therefore meeting the specification provided by Dr. Moskalik. After running the first set of validation tests, we discovered that our process did not completely remove all gas present in the fluid. Therefore, we redesigned the procedure, which not only allowed all possible gas in the fluid to be removed, but greatly improved our overall accuracy. The final procedure, as outlined in Section 12.3, is a ten step process, which does not meet our specification. However, tradeoffs between accuracy and time, complexity and cost have been a primary concern throughout the design process and we believe the increase in steps is not overly detrimental to the usability of our device, and well worth the substantial accuracy improvement.

14. DISCUSSION OF DESIGN

As discussed in the previous section, our design successfully meets five of the eight engineering specifications originally established for our device. The three specifications that we have not met are level of accuracy, test time, and steps in process. Each of these is directly related to one another and if we were given the chance to start this project over knowing what we know now, there are a number of changes we would make to improve the design in these areas. In this section we will discuss the overall critique of our design by outlining the strengths, weaknesses, and improvements we would make if we were given the chance to start this project over.

14.1. Strengths

There are several strengths associated with our final design, which include safety, ease of use, robustness, portability, and accomplishment of intended function. The device will withstand all possibly experienced pressures and forces without damage or leaking as validated by prior safety testing. With the addition of a pressure relief valve set to 200 psi, and the safety factors listed in Table 8.2 on page 50, we can confidently say the device is safe to operate.

Although the steps in the process and test time were both increased in order to achieve higher accuracy, we feel that the device itself, as well as the procedure for testing, contributes to ease of operation. The device weighs less than ten pounds, has digital readouts for pressure and temperature, and the piston takes very little effort to actuate. The procedure is logical and clear, and would not take long for a trained operator to memorize.

From a structural standpoint, the design of our device is very robust. As discussed in the parameter analysis section, each component was sized and built with a safety factor of at least two, which again ensures not only its safety, but also its overall strength.

A major requirement of our sponsor from the outset was that the device be portable and not require an outside power source so the EPA could take it with them when testing and showing the hydraulic hybrid vehicle. The device, thermocouple readout, and hose for the pressure relief valve can all fit within a box that can be easily carried by one person. Since it can directly attach to the vehicle and the pressure and temperature readouts are battery powered, it can be used anywhere without requiring a wall outlet or additional power source.

While the final accuracy did not meet our original engineering specification, we were very satisfied with the ability of our device to accomplish its intended function of removing gas from a fluid and measuring the content. Throughout the design process the sealing of our device was a major concern. If we were unable to seal the piston and fittings properly we would not only risk a safety issue with the leaking of hydraulic fluid, but would also introduce extra error by potentially adding/removing gas to/from the system. From the safety validation tests in which we pressurized the cylinder to 220 psig with both air and fluid and experienced no change in pressure, we are confident that our sealing is satisfactory. Also, being able to achieve a maximum vacuum pressure of -14.2 psig for degassing the fluid was an impressive accomplishment compared to our predicted vacuum pressure of -9.7 psig.

14.2. Weaknesses

Since the overall purpose of this project was to build a device that can accurately detect the level of nitrogen dissolved in hydraulic fluid, the main weakness of our final design is its overall accuracy. While the other two specifications of test time and steps in procedure were also not met, we do not consider these as negatives to our design. Although it would be nice to have a shorter test time and less steps in the procedure, both were increased in order to achieve a higher accuracy, which aside from safety, was the most important specification for our device.

Our weakness in the accuracy specification can be directly attributed to our inability to precisely measure the final gas volume. As discussed in the validation and results section, the large uncertainty in our final measurements was due exclusively to the fact that there was much less gas dissolved in the fluid than originally anticipated. Consequently, when we went to measure the pressure and temperature of the extracted gas, we had to compress the gas to a very small volume in order to obtain a high positive pressure. With our current procedure of calculating the volume based on the piston height, which was measured using an engineering scale of 0.01" resolution, an excess amount of error was introduced. Despite the revised procedure which greatly improved the accuracy from the initial procedure, an uncertainty of 14% does not meet our original specification of 2% molar concentration.

It is worth noting that throughout the design process we were concerned with and acknowledged the importance of being able to accurately measure gas and liquid volumes in our cylinder. This is apparent from the numerous design concepts we created during the concept selection process and the various methods we brainstormed for measuring volume. Again, based on our original calculations (which the initial validation testing proved incorrect) we determined that we needed to be able to accurately measure volume to within 1 ml, which corresponded to about 0.01" in piston height. An engineering scale was then the most logical choice due to its cost effectiveness. Also, we felt that for our purposes and budget constraints, it was most important to prove the validity of our scientific method – that using a piston/cylinder device to remove gas from a fluid was an appropriate method for determining gas concentration, which we accomplished.

We originally set the engineering specification for accuracy at 2% molar concentration based on the accuracy of other much more complicated gas measurement devices. At this point it is still uncertain whether our current method could even produce an accuracy of that degree. However, we feel that it could definitely be further improved from its current rating of 14% by improving

the gas volume measurement. More accurately determining this volume is then the main area we would focus on improving our device.

Another weakness of our device is the shape of the cylinder. The best polycarbonate cylinder we were able to find that suited our purpose had relatively high tolerances on the inner diameter. After testing, we determined that this inner edge may not have been perfectly circular, as play occurred upon actuation of the piston. Again, this factors into the important volume measurement, as the side of the piston where height measurements are taken may have been 0.01" higher or lower than another side.

Finally, our sponsor informed us that hydraulic fluid taken from the EPA's system may be "dirty." We are unsure what type of staining this could lead to on the cylinder. We are also unsure how much prolonged use would lead to staining, nor if our seals would simply erase the stains, given our inability to test directly with the EPA's hydraulic system at the present time. However, we fear that this staining may eventually impact its transparency, thus impairing a user's ability to measure the height of the piston within the cylinder.

14.3. Design Improvements

If we were to start this project over today there would be several changes we would make to the final design, however, the method of removing gas from fluid and measuring the content would remain the same. These improvements include the actuation method of the piston as well as the shape and size of the cylinder.

14.3.1. Actuation Method

If we had a more exacting actuation method then measuring the linear displacement of the piston would be more precise. The inability of our current method to accurately measure gas and fluid volume within the cylinder greatly impacted the overall accuracy of molar concentration. An electric linear actuator would be a much more accurate alternative to the manual lead screw design of our current device. An actuator could be used on a new design, or be implemented as an improvement to the current model and would be able to precisely record the exact position of the piston based on the voltage given to the actuator.

However, implementation of such a system involves tradeoffs from our current design. Not only does an automated system increase complexity of the device (allowing more possibilities for failure due to electrical components and their probable exposure to hydraulic fluid), but the cost of the device increases significantly (by approximately $1,000 minimum), and additional power required to run the device decreases portability. Exclusion of an automated system keeps the device portable and inexpensive, without reducing safety. This is why we chose not to implement the automated system; however, if automation in our system could be achieved on a mass scale to reduce cost, and included a small battery-operated calculator with an LCD output screen which could perform the necessary calculations (without compromising safety), then such a system should be pursued as an advantageous upgrade over the current device.

If the cost of fully automating the system was beyond the needs of the EPA, a compromise could be made by using the current method of manually actuating the piston, but adding an electronic device to measure the exact piston location. While presenting our device at the design expo,

several industry professionals suggested that a linear variable differential transformer (LVDT) could be implemented to increase the accuracy and precision of measuring the height of the piston, and correspondingly, the volume measurement. However, such a device would require an external power source to provide current to the device, and cost is on the order of $100-$600.

14.3.2. Cylinder Shape

Aside from adding electronics to improve the accuracy of the volume measurement, the current design could be used with a modification to the piston and cylinder. By making the cylinder and piston a much smaller diameter, the same volume changes we were experiencing in our tests would correspond to a much larger change in piston height, which would make measuring it with a scale more accurate. However, due to the small amount of air that is dissolved in hydraulic fluid it would be advantageous to have a cylinder that tapers from a large cylinder to a small cylinder where the measurements are made. This reservoir style cylinder would hold a large amount of fluid, ensuring that there is enough dissolved gas to get a good reading, while the smaller cylinder would allow you to get accurate measurement readings. An illustration of this style cylinder can be seen in Figure 14.1 below.

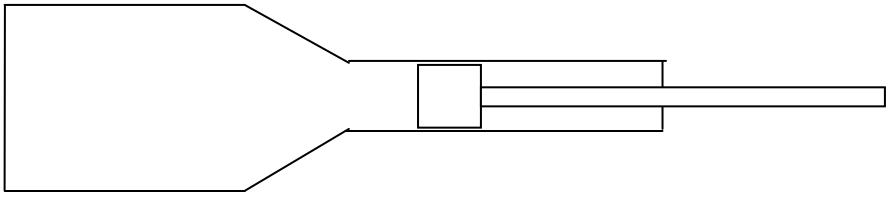


Figure 14.1: Reservoir cylinder design

14.3.3. Additional Improvements

Apart from the possible improvements already listed, there are several minor changes that we would make if we were to re-design our device. The first would be to find a company that could make a much more precisely manufactured polycarbonate cylinder. The one we ordered from McMaster had the best tolerances we could find at ±0.04”, which gave it very poor cylindricity. As a result when the piston is actuated there are several points where it “catches” and “pops”. Although this does not impact the functionality or sealing of our device it would be nice to have a piston that can smoothly move throughout the entire length of the cylinder. Also, we had used a thrust bearing on top of a tapered roller bearing for the connection between the ACME threaded rod and piston. This provided a smoothly rotating connection; however, two tapered roller bearings would have been the preferred method as it is more conventional.

15. RECOMMENDATIONS

Upon completion of our device, validation testing, and design critique, we have compiled several recommendations for both the EPA in using our device as well as anyone that may wish to improve upon it in the future.

15.1. Future steps

As we have only tested our device using hydraulic fluid initially at atmospheric pressure, we recommend that the first step for the EPA is to attach our device directly to their system once it

assembled and repressurized. Once this is accomplished they can refine the test procedure so that it best suits their needs – however, aside from bleeding the system by slightly unscrewing the line attachment until fluid leaks out, no other changes should be required.

With the hydraulic hybrid system functioning, it will be necessary for the EPA to begin using our device incrementally (e.g. every day, week, month, etc) with several tests being performed during each time period. This will enable them to begin establishing a baseline for the amount of nitrogen dissolved in hydraulic fluid and to determine how this changes over time. When damage is seen to have occurred or if efficiency is believe to be lowered, the EPA will be able to test and see how much dissolved gas causes damage. Therefore, they will be able to predict in future cycles when damage would occur, and when the hydraulic fluid used in the system needs to be changed to prevent the onset of damage or losses in efficiency. Also, by performing these tests it will be possible for the EPA to produce an accurate determination of Henry's Law Constant for nitrogen dissolved in hydraulic fluid.

15.2. System and detailed level of discussion

We recommend that the device be kept clean and stored in a clean place at all times when not in use. It is likely that oil will remain on the surface of the cylinder, which is safe for human contact but may lead to it slipping out of a user's hand and breaking. Also, we have seen through testing that minimal oil contact with the electronic attachments does not incur damage to them; however, we recommend that the electronic components of the device be kept as clean as possible, so that they may be used for as long as possible.

During the actual tests we recommend that the EPA withdraw at least 350 ml of fluid from their system and into the device to ensure that they are able to extract enough gas for accurate readings. The exact amount of fluid will vary based on how their results at system pressure differ from our results at atmospheric. While these results should be more accurate and a greater amount of gas should be present in fluid, it will be necessary for them to determine what exact volume provides the best and most repeatable results. From our testing this occurred between 350-600 ml.

When calculating the final concentration of nitrogen dissolved in hydraulic fluid, the EPA will need to account for amount of air initially in fresh oil to determine how much has been added. The results of our validation will be sufficient for these purposes.

15.3. Design changes

It will be up to the EPA to determine whether the current accuracy of 14% molar concentration is acceptable for their purposes. While we expect this accuracy to increase when the device is used at their system pressure, the extent of improvement will be unknown until actual testing takes place. Despite the accuracy of the device not meeting our original specification, we feel that for the EPA's purposes the device will be able to provide them with the information they care about most – detecting an increase in the amount of nitrogen present in hydraulic fluid and determining at what point this excess gas can cause damage to their system.

If the accuracy of the test results at system pressure does not meet the EPA's requirements, we recommend they look into automatic actuation of the piston, so that volume measurements are

far more accurate than those that could be achieved manually using an engineering scale. This would also make the test procedure easier, as an operator would not be required to actuate the piston by turning the shaft. Additionally, the pressure gauge could be replaced with a pressure transducer. This, along with the thermocouple, could be integrated with a data acquisition program and computer to calculate the molar concentration of dissolved gas within the fluid, eliminating the need for hand calculations. Also, the computer could store this data so that the EPA could examine trends and patterns involving pressure, temperature, and molar gas concentration over time via easily produced graphs and charts.

15.4. Areas for improvement

Again, the device could be improved by better measuring volume change through automating the system or applying a LVDT to measure piston displacement. Also, the device could be improved by replacing the present polycarbonate cylinder by one with better inner cylindricity. We believe that polycarbonate is the most suitable material for the cylinder; however, we have found the present one to be somewhat out-of-round on the inner edges, which creates play in the actuation of the cylinder and could also be affecting volume measurements. Since the entire inner edge would not be easily machinable without altering the transparency of the cylinder, replacement with a more precisely shaped polycarbonate cylinder is recommended, as long as the EPA is willing to incur the cost and time needed for replacement.

16. SUMMARY & CONCLUSIONS

As part of a continuing effort to reduce automotive emissions, the U.S. Environmental Protection Agency (EPA) has partnered with UPS to develop a hydraulic hybrid vehicle for their use in delivery trucks. Given the existing 72,000 UPS trucks in the U.S. today and the potential for fuel economy improvement up to 70%, there is great hope for a reduction in emissions in this pursuit. The hydraulic system uses compressed nitrogen gas in a rubber bladder to store and release energy in the vehicle. The rubber bladder provides advantages in capturing and releasing energy in a hydraulic pump, relative to the traditional piston system used in most hydraulics. However, the expansion of the rubber bladder reveals gaps, through which nitrogen gas can escape into the hydraulic fluid.

When gas enters hydraulic fluid, severe damage can occur in the form of cavitation (small air bubbles), which causes physical damage to the actual hydraulic system, as well as pressure alterations that decrease the overall efficiency of the system in the vehicle. Our task is to provide a laboratory measurement device which will accurately measure the gas content of a given small sample of hydraulic fluid. With the help of this device, the EPA will be able to determine how much gas causes damage and loss of efficiency in the hydraulic system, and form methods for preserving the maximum performance of the hydraulic system in their hybrid vehicles.
Our sponsor, Dr. Andrew Moskalik of the EPA, has provided us with many useful requirements for our design. The device must be completely safe and pose no threat to the EPA vehicles, personnel, or environment. It must also be accurate, inexpensive, and easy to use, so that the EPA's resources may be properly allocated towards the overall goal of perfecting the hybrid hydraulic vehicle.

We have researched several methods for measuring dissolved and free gases in solution. These include partial pressure calculation, chemiluminescence, mass spectrometry, permittivity, and gas chromatography. Each method has its advantages and disadvantages. However, we concluded that due to time and budgetary constraints, a partial pressure calculation will be the best course of action for our accurate, inexpensive, small-scale device.

To accomplish this measurement we have presented our final design, which is a manually operated piston/cylinder device. This device can be used to calculate the concentration of gas in a fluid using the Ideal Gas Law. Connections, as well as a temperature measurement method have been given to us by the EPA.

The device will measure concentration through a manipulation of the fluid, by drawing all dissolved gas out of the fluid. Thus, all dissolved and free gas can be included to provide the most accurate measurement possible.

We have concluded fabrication, assembly, and validation of the device. Several adjustments were necessary after the completion of initial validation testing, which were easily achieved due to flexibility in our initial design. Results of our validation testing include being able to detect the amount of air within a given sample of hydraulic fluid accurate to 14% by molar concentration. Although this accuracy level of 14% by molar concentration does not meet the original engineering specification of 2%, we feel that for the EPA's purposes the device can still be used to sufficiently detect an increase in the amount of nitrogen present in hydraulic fluid.

In conclusion, we are confident that we have provided the EPA with a test device capable of helping them achieve their goals of detecting and quantifying at what point excess gas can cause damage within their hydraulic hybrid system, thus advancing their hydraulic hybrid efforts as a whole.

17. ACKNOWLEDGEMENTS

This project would not have been successful without the help of experts, professors, and professionals. We would like to thank:

Dr. Andrew Moskalik of the EPA National Vehicle Fuel Emissions Laboratory. As our sponsor he met with us nearly weekly and helped to hone our ideas into a workable device.

Professor Gordon Krauss of the University of Michigan who met with us every week provided valuable insight and pushed us to see all aspects of our design in a new light. Without his constant input we would have not been successful.

Professor Steven Ceccio who has considerable experience in the area of hydraulic systems, particularly cavitation, provided useful insight into measuring gases in hydraulic oil using partial pressure methods.

Professors Albert Shih and Zoran Filipi have active research programs in the area of hydraulic hybrid propulsion, and loaned us one of their graduate students, Ben Hagan, who is currently

developing a method for removing nitrogen bubbles in a hydraulic system. Ben helped to make our validation possible by providing laboratory setup that incorporated air into hydraulic fluid.

Professor Steven Skerlos and graduate student Dan Johnson for pushing us to make the best design we could and helping us when we got stuck.

The students of section 7 in ME 450, their constant questions pushed us to think on our feet and made us improve our design at every stage of development.

Outside of the university, Andrew Manning of U.S. Geological Survey and Dr. Kip Solomon of the Department of Geology and Geophysics at the University of Utah have provided valuable insight in regards to the total dissolved gas pressure probe discussed in section 4.2.2.

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19. BIOGRAPHIES

19.1. Brian LaFrence

Brian LaFrence is from Plymouth, MN, which is a suburb of Minneapolis. He is interested in Mechanical Engineering because he enjoys learning how things work and thinking of ways to improve them. One of his passions is in energy, which is why he is pursuing a concentration in the field. Over this past summer he worked for the University of Michigan Industrial Assessment Center. In this job he identified areas where companies can save money on energy costs. He will be taking a full time position at the Industrial Assessment Center upon graduation next spring. He hopes to work on research towards his masters while working for the IAC and obtaining a master's within 3 years of graduation.

Some interesting facts about him: He is an absolute football nut, specifically following the Minnesota Vikings and of course the Wolverines. He also is a big fan of college hockey and attends about 75% of the Michigan games each year. In his spare time he likes to play video games or hang out with his girlfriend.

19.2. Matt Feinstein

Matthew Feinstein is a senior hailing from Long Island, New York. He comes from a family of mechanical engineers, and has sought to enter the family industry since his first day of college. He is particularly interested in automation, system analysis, and control. This past summer he was an intern with Lux Research Inc, a research and consulting firm in New York City. Upon graduating in May 2010, he hopes to enter the consulting industry. In his spare time, he enjoys non-fiction sports reading, playing tennis, and watching reality television (specifically, Survivor).

19.3. Kyle Safford

Kyle Safford is a fifth year Mechanical Engineering student at the University of Michigan. Born in Royal Oak, MI, he grew up and went to high school in Novi, MI. Kyle has always enjoyed learning about math and physics, as well as building things and spending weekends working on his father's 1962 Dodge Dart. Combined with this and the fact that his father and older brother are both alumni, the decision to study Mechanical Engineering at U of M was an easy one. So far, Kyle has worked for several different companies as an engineering co-op or intern including GE Aviation, Lockheed Martin Space Systems Company, Toyota, Johnson Controls, and Plastipak Packaging. Upon graduating he plans to continue through at U of M for his masters, also in Mechanical Engineering, and will likely work in either the aviation or aerospace industry. In his free time he loves playing sports, spending time at his family's lake house during the summer, and snowboarding in the winter.

19.4. Casey Timmons

Casey Timmons is a senior from Hartland, Michigan. She pursued the University of Michigan for its academic and athletic prowess. A former chemical engineering student she transferred to the mechanical department to better understand the fundamentals of how the world works. She is hoping to pursue a graduate degree in biomechanics after a summer working in a side impact lab peaked her interest in the subject. Casey competed for the university in rowing, earning four varsity letters and the distinction of team captain. Casey enjoys playing sports, observing people and talking.

20. APPENDIX

A. Bill of Materials

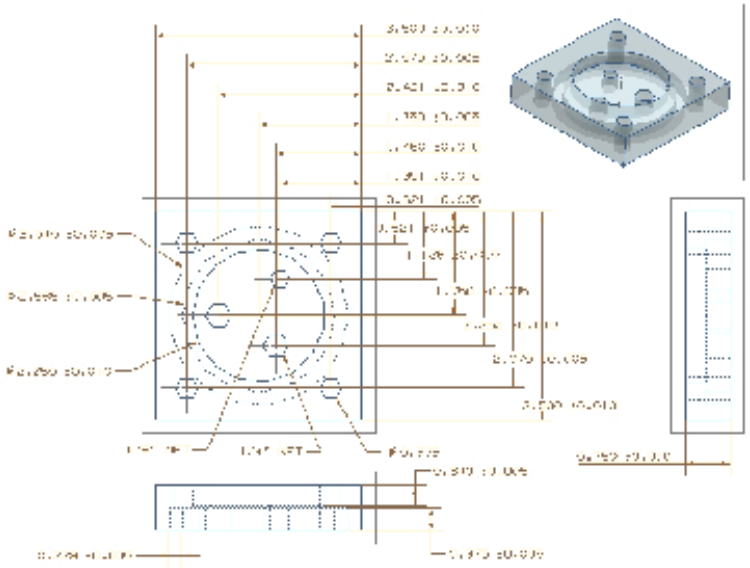
Quantity	Unit of Quantity	Part	Company	Part #	Price/Part	Total
1	Piece	1"-18 UNS Tap	McMaster	2595A472	67.19	67.19
1	Piece	3/4-10 Right Hand Acme Threaded Mount Nut	Roton	90244	28.83	28.83
2	Feet	3/4-10 Right Hand Acme Screw	Roton	60206	9.84	19.68
1	5-Pack	12" 3/8 Diameter Hex Bolts	McMaster	91236A658	7.19	7.19
1	Foot	3/16" Thick, 12" Long Polycarbonate Cylinder	McMaster	8585K67	19.59	19.59
1	Piece	3.5" x 3.5" x 3.5" Aluminum Block (6061 Al)	McMaster	8975K571	26.46	26.46
1	Piece	12" Long 2-3/4" Aluminum Rod (6061 Al)	McMaster	8974K791	26.94	26.94
1	Piece	Line Attachment	Stauff	SMK 20 -1/4 NPT-VD	15.00	15.00
1	Piece	Digital Pressure Transducer Vacuum to 500psi	APG	PG-5	300.00	300.00
1	8-Pack	3/16" O Rings RC-50	McMaster	2418T226	8.33	8.33
1	2-Piece	TP Profile Seals	Parker	TP028-B011N4257	60.01	60.01
1	3-Pieces	Thrust Bearing with two washers	McMaster	5909K31	4.46	4.46
1	Piece	½” Outer Shaft Retaining Ring	McMaster	91590A122	8.94	8.94
1	Piece	Steel Tapered Roller Bearing ½” Shaft Diameter	McMaster	23915T11	27.85	27.85
1	Piece	Steel Tapered Roller Bearing Outer Ring	McMaster	23915T71	12.00	12.00
1	Piece	Brass Pressure Relief Valve with hose	McMaster	4716K53	178.87	178.87
1	Piece	Inch Scale	Carpenter Brothers		6.29	6.29

Grand Total **817.63**

B. Engineering Change Notices

ENGINEERING CHANGE NOTICE

WAS:



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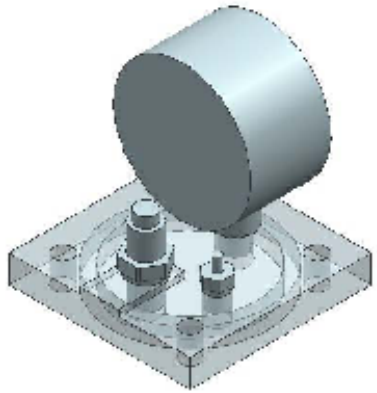
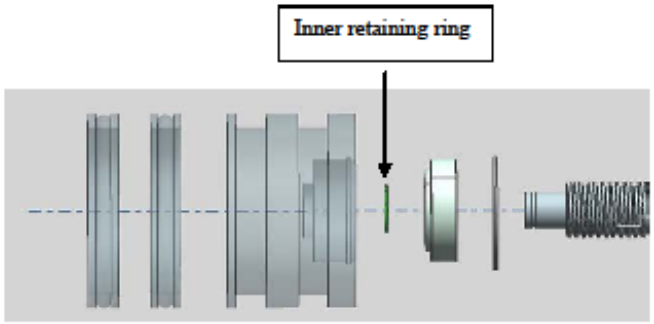


Notes: The top plate was initially ¾" thick throughout. However, in order to properly bleed the system of all air before testing takes place, it is necessary for the line attachment to be located at the highest point in the device when held upright. After fabrication of the top plate was complete, we used an end mill to cut approximately 0.1" off of the plate area surrounding the line attachment, in order to ensure it would be at the highest point.

University of Michigan	
ME 450 Team 23: Hydraulic Fluid Dissolved Gas Tester	
Ref Drawing: Top Plate	
Section Instructor: Prof. G. Krauss	11/23/2009
Sponsor: Dr. Andrew Moskalik	11/23/2009

ENGINEERING CHANGE NOTICE

WAS:



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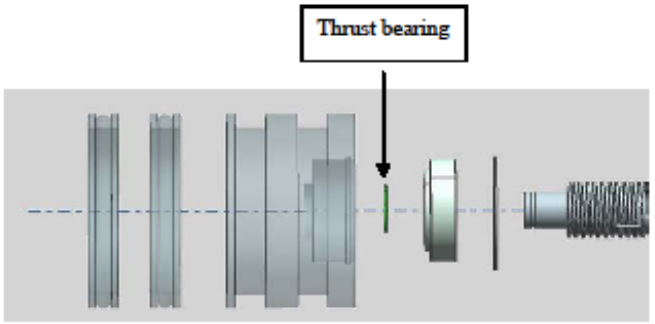


Notes: The initial design included a tapered bearing to prevent rotation of the piston with the rod, and an upper retaining ring to prevent the shaft from falling through the bearing. The final design includes a thrust bearing above the tapered bearing to prevent the top of the shaft from grinding on the piston, with the shaft pressed into the tapered bearing so that there is no need for an upper retaining ring.

University of Michigan	
ME 450 Team 23: Hydraulic Fluid Dissolved Gas Tester	
Ref Drawing: Piston Assembly	
Section Instructor: Prof. G. Krauss	11/23/2009
Sponsor: Dr. Andrew Moskalik	11/23/2009

C. Design Analysis Assignments

C.1. Material Selection - Functionality

Selection for Cylinder

1. The function of the cylinder is to carry the internal pressure or vacuum that our system will see. This includes the ability to go as low as 1 psia and up to 300 psia. Our objective is for the cylinder to have maximum strength while minimizing weight. The EPA has set a total limit of 30 lbs on our device, but would like the device to be less than 20 lbs in order to make transporting it easier. We also wish for the cylinder to meet leak before break criteria. Minimizing cost is also an objective, but it is secondary to those listed previously. The only absolute constraint is that the material chosen for the cylinder must be resistant to wear from contact with hydraulic fluid. It is desired that the material be transparent to make measuring the displacement of the piston easier.
2. Based on the above objectives, we were able to come up with three material indices with which to base our search around. The first is $M = \sigma_Y/\rho$, which maximizes strength while minimizing weight. The second is $M = \sigma_Y/(C_m*\rho)$, which maximizes strength while minimizing cost. The final is $M = K_{IC}^2/\sigma_Y$, which is used to ensure the cylinder meets the leak before break criteria. We set a limit that the material must be transparent in order to minimize the possible choices and so measuring the displacement of the piston will be possible (Ashby*).
3. Based on the results of the CES search, we determined that our top five material choices were acrylic, polycarbonate, PVC; Type 2, Transparent Polyamide and Polypropylene.
4. We decided on polycarbonate because it allowed for a high safety factor against yielding, and it met the leak before break criteria by quite a bit. In addition, this material is relatively cheap and we can purchase a cylinder in the dimensions we desire directly from McMaster Carr. Polycarbonate also has good resistance to corrosion from oils, which is required. While the other options also met our requirement for transparency, polycarbonate gave the best safety factors against leak before rupture and yielding, while also being available in a size that required minimal machining by our group.

Selection for End Plates

1. The function of the end plates is to hold the device together and bear the load from the bolts in order to accomplish this, hold all the attachments to the device, and be able to withstand the pressure differential on the device. Our objective is for the plates to have a maximum strength while minimizing weight. The EPA has set a total limit of 30 lbs on our device, but would like the device to be less than 20 lbs in order to make transporting it easier. We also wish for the cylinder to meet leak before break criteria. Minimizing cost is also an objective, but it is secondary to those listed previously. We also wish for the material to be easily machinable, to make manufacturing simpler. The only absolute constraint on the device is that the material chosen for the cylinder must be resistant to wear from contact with hydraulic fluid.
2. Based on the above objectives, we were able to come up with two material indices to base our search on. The first is $M= \sigma_Y^{1/2}/\rho$, which maximizes strength while minimizing weight. The second is $M= \sigma_Y^{1/2}/(C_m*\rho)$, which maximizes strength while minimizing cost. We also set a limit on the minimum yield strength at 3.33 ksi. This number came

from an analysis on the length of engagement needed between the mount nut and the end plate to prevent yielding in the threads (Ashby*).

3. Based on the results of the CES search, our top five material choices were 6061 Aluminum, 316Ti Stainless Steel, PVC, ABS and polypropylene.
4. We decided on 6061 Aluminum for our material for the end plate. While PVC and ABS are easily machinable materials, 6061 Aluminum gave us better safety factors against yielding. 316Ti Stainless Steel and Polypropylene presented challenges when it came to machining, so they were eliminated. Another positive that lead to 6061 Aluminum being our choice was the availability of the material through McMaster-Carr.

*Ashby. (n.d.). *Material Indices.* Retrieved November 21, 2009, from http://mech.vub.ac.be/teaching/info/Ontwerpmethodologie/Appendix%20les%203%20Materiaal%20Indices.pdf

C.2. Material Selection-Environmental Impact

1. Impact for Cylinder

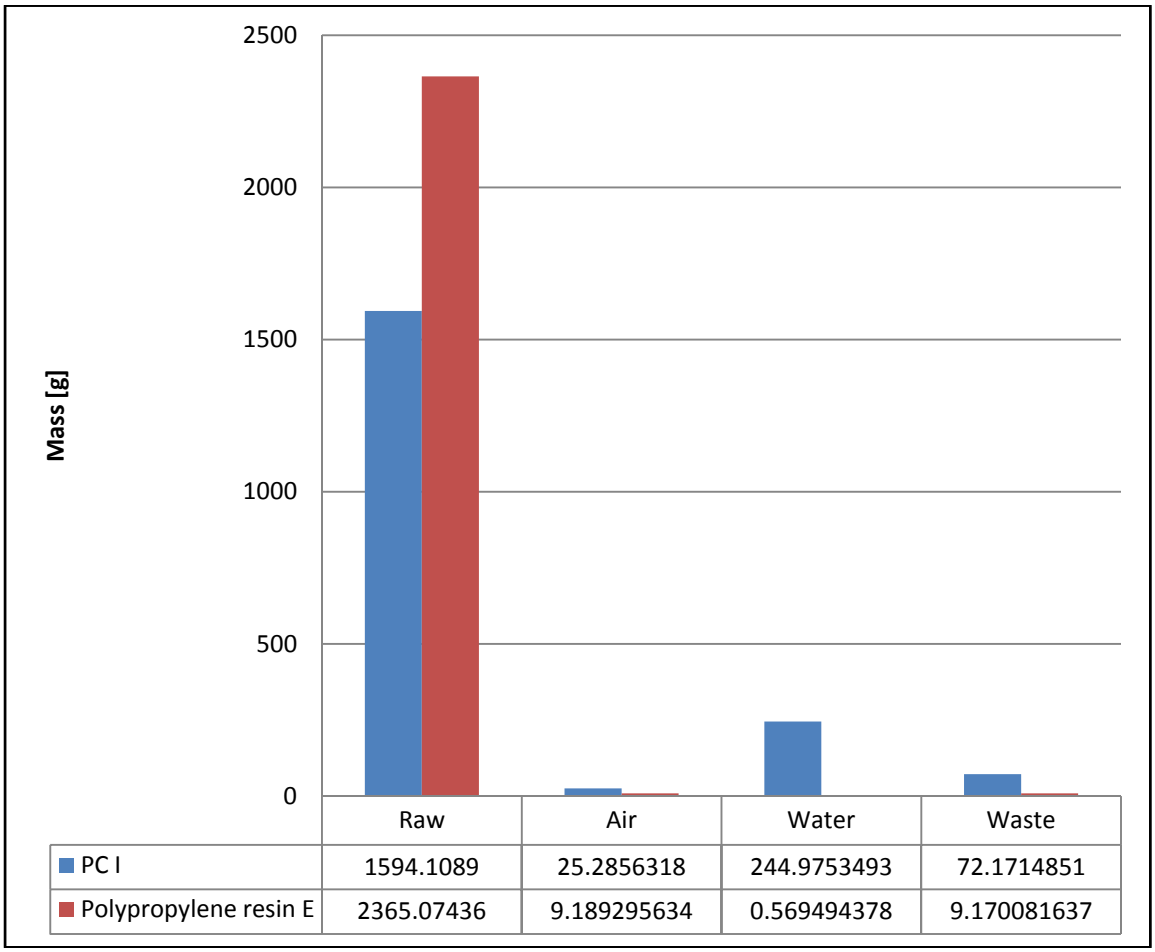


Figure 1.1: Total Emissions for Cylinder on Mass Basis

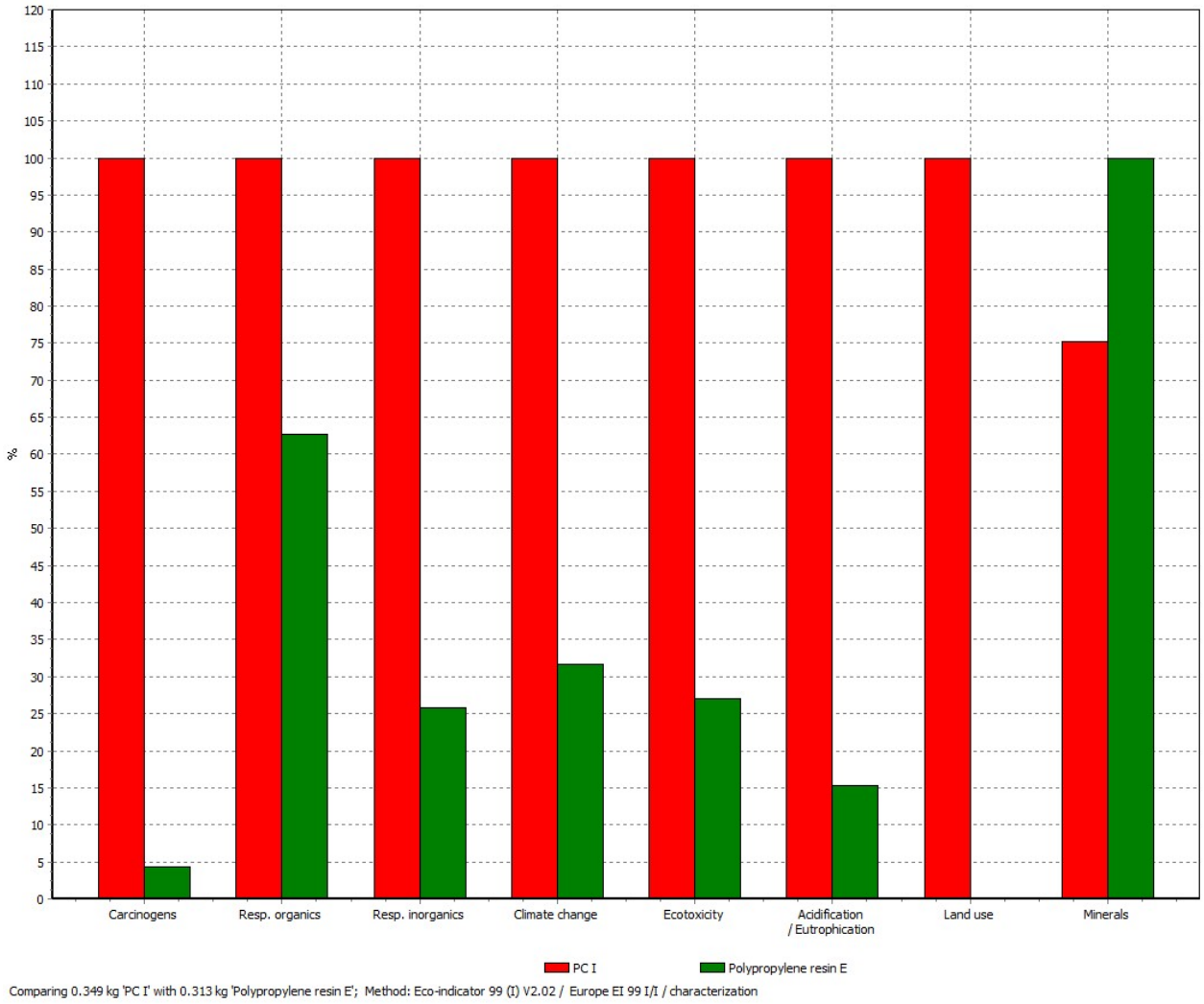


Figure 1.2: Relative Impacts in Disaggregated Damage Categories

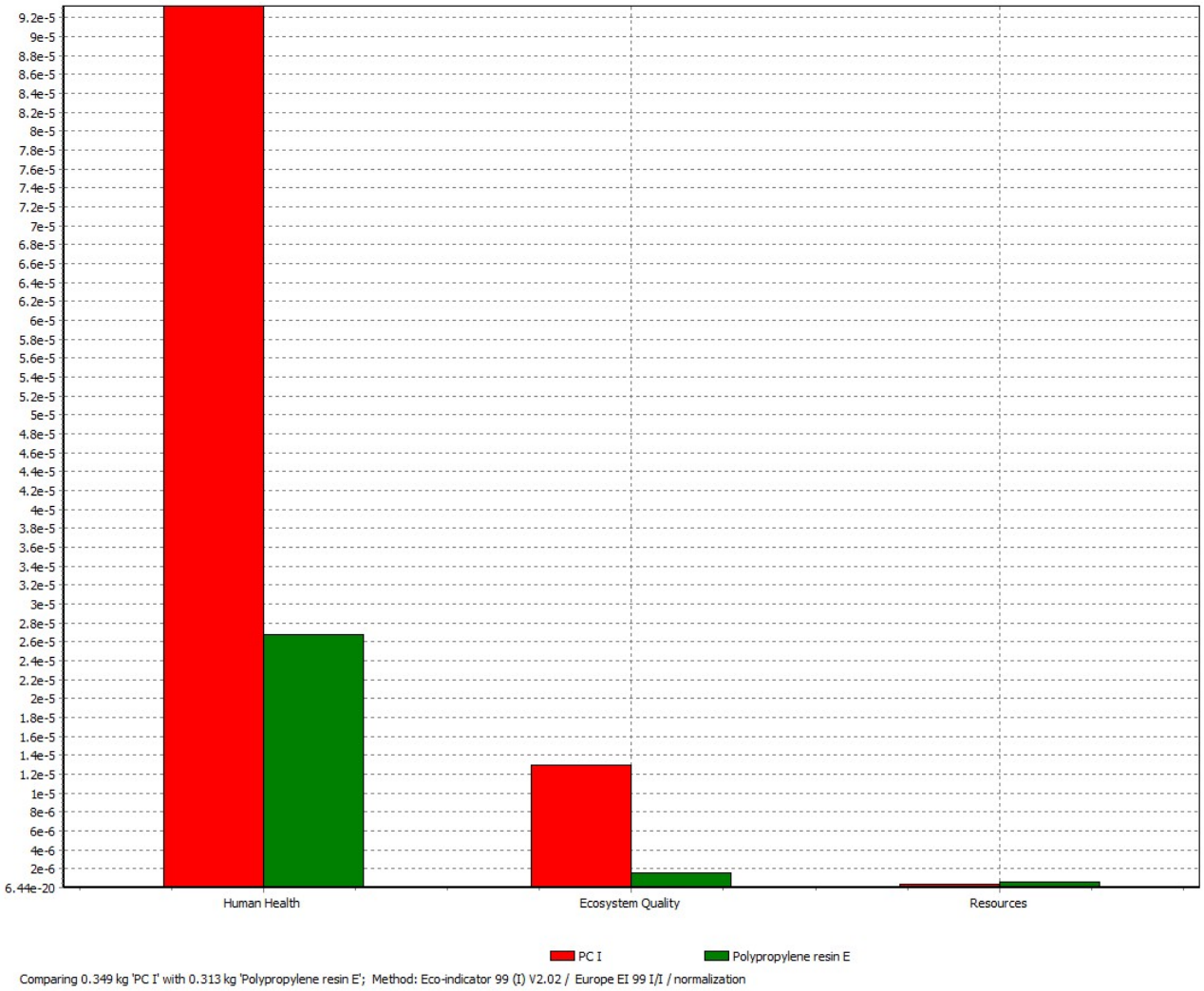


Figure 1.3: Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

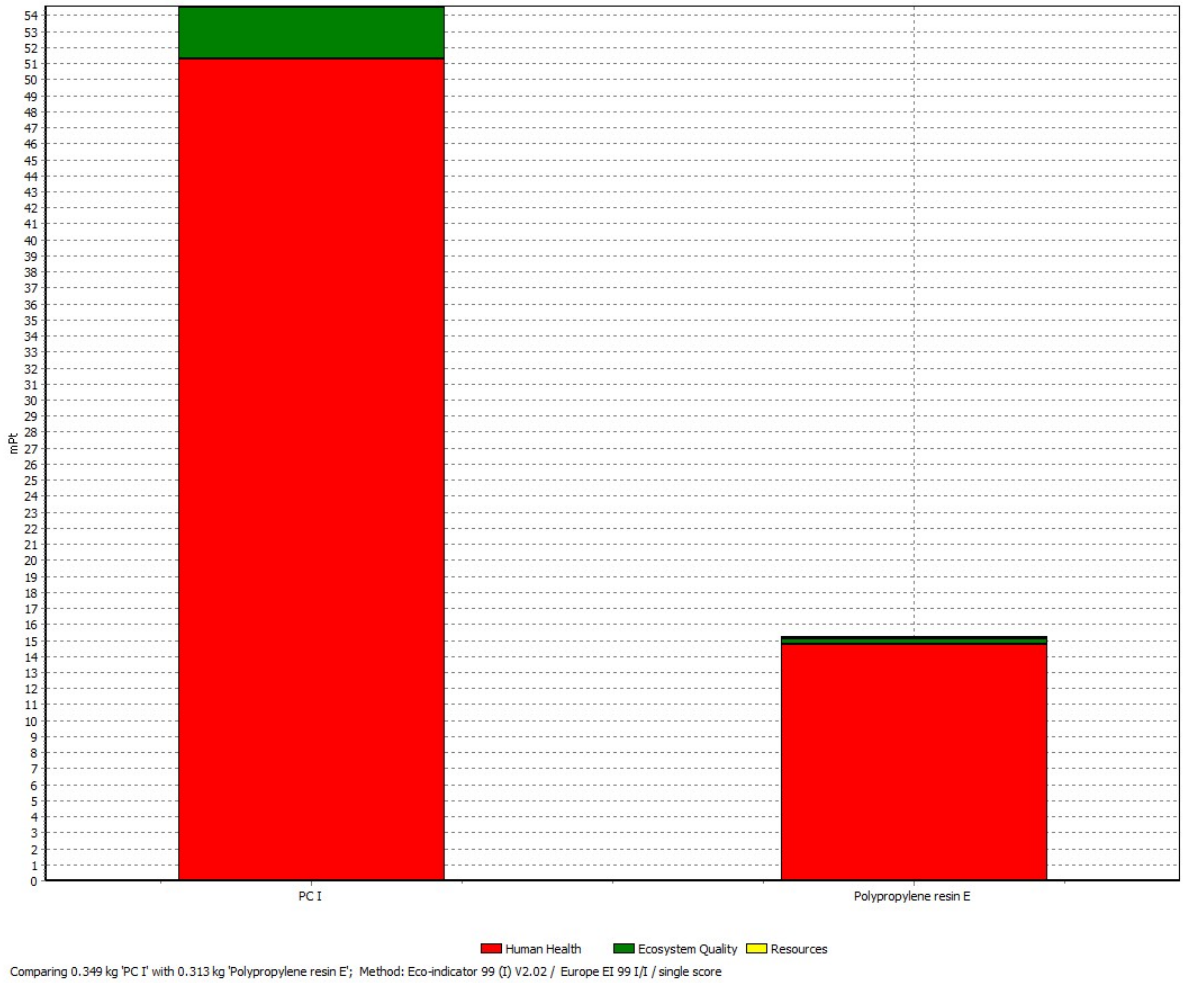
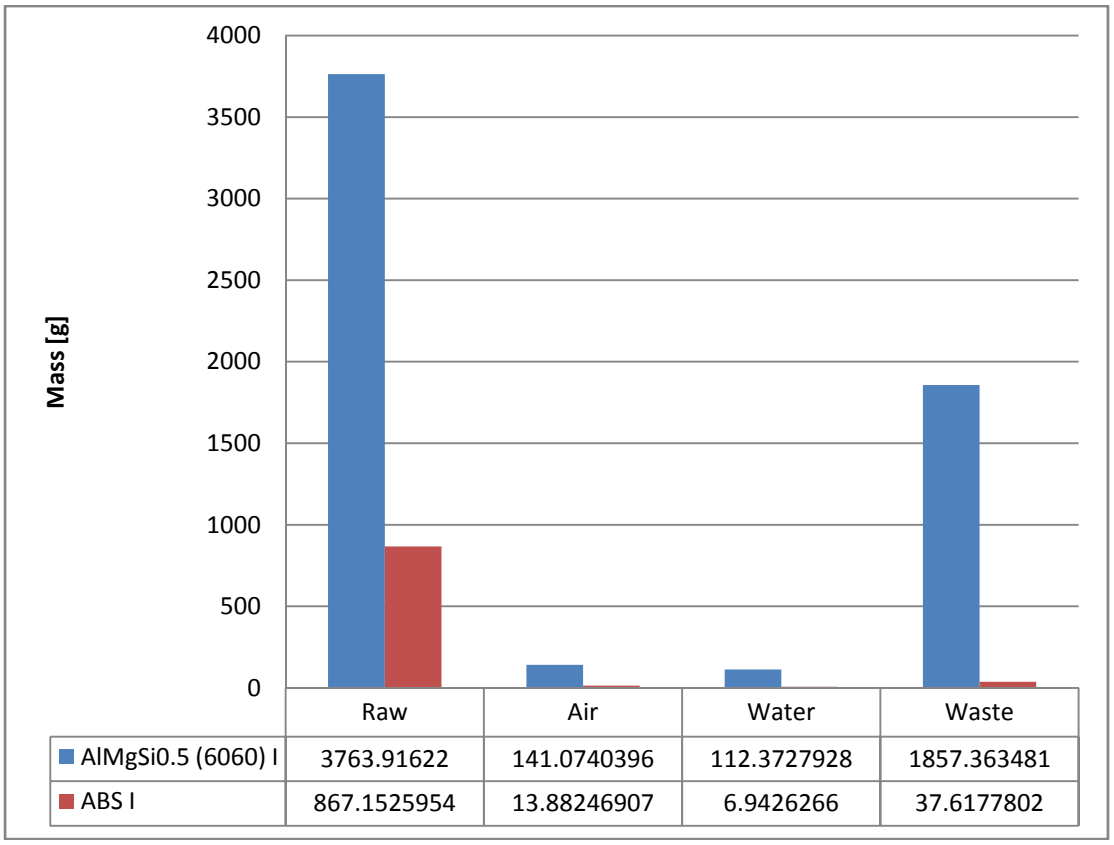


Figure 1.4: Single Score Comparison in "Points"

Based on the results from SimaPro 7, Polycarbonate appears to have a larger environmental impact than Polypropylene. In addition, Polycarbonate has a larger impact on human health. However, a cylinder made from polycarbonate would likely have a longer life cycle. A cylinder made of Polypropylene would probably have to be replaced sooner than it's Polycarbonate counterpart, therefore increasing the long term impact of using Polypropylene as a cylinder material.

After viewing the results, we would not switch from Polycarbonate. In the sizes of cylinders available, Polycarbonate had high safety factors against both yielding and leak before rupture. These high safety factors are required because of the potential of damage to the cylinder wall by the piston. Our primary concern with this project has always been safety, and we would not jeopardize the user and the device in order to reduce our environmental impact.

2. Impact for End Plates



	Raw	Air	Water	Waste
AlMgSi0.5 (6060) I	3763.91622	141.0740396	112.3727928	1857.363481
ABS I	867.1525954	13.88246907	6.9426266	37.6177802

Figure 2.1: Total Emissions for Cylinder on Mass Basis

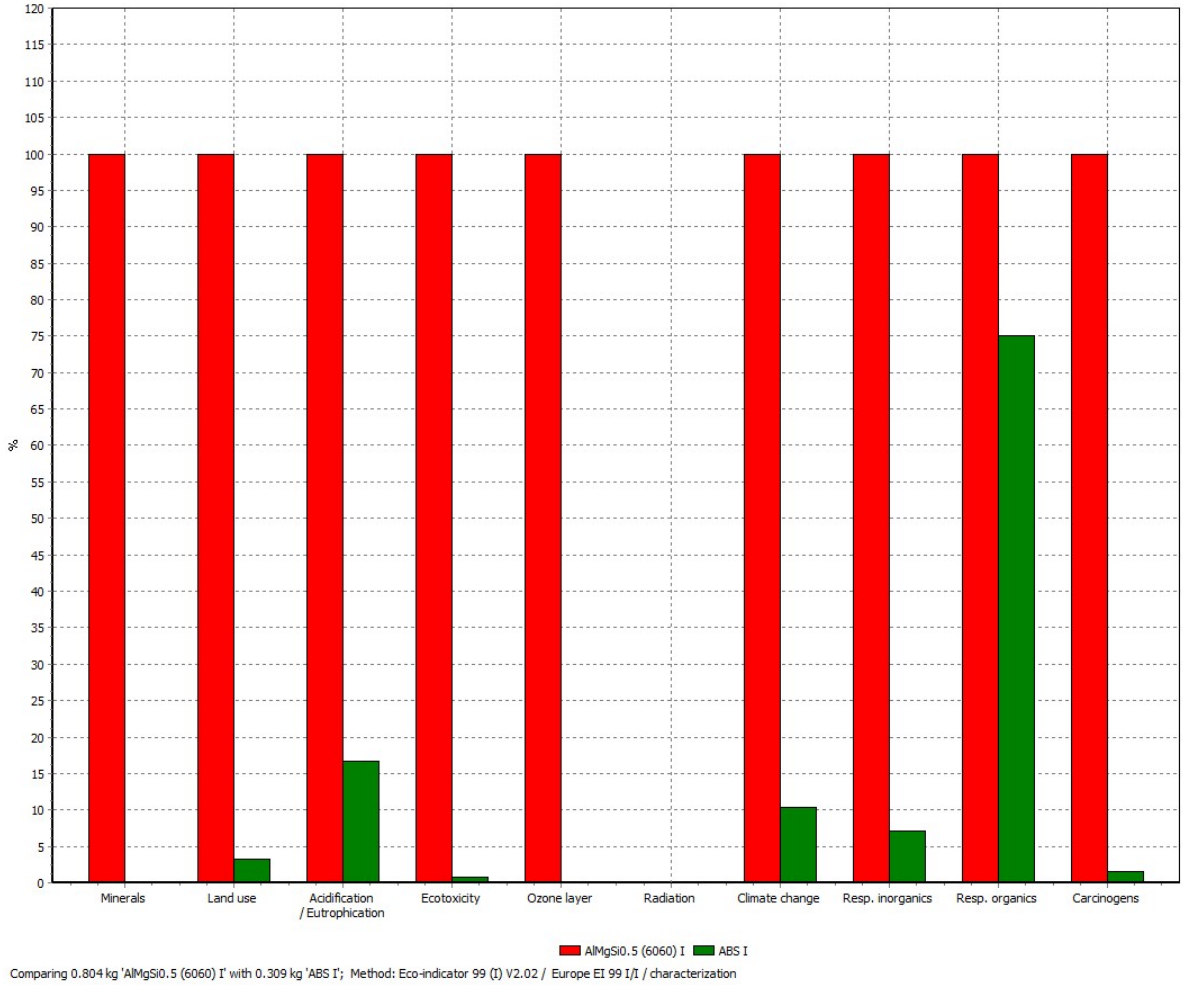


Figure 2.2: Relative Impacts in Disaggregated Damage Categories

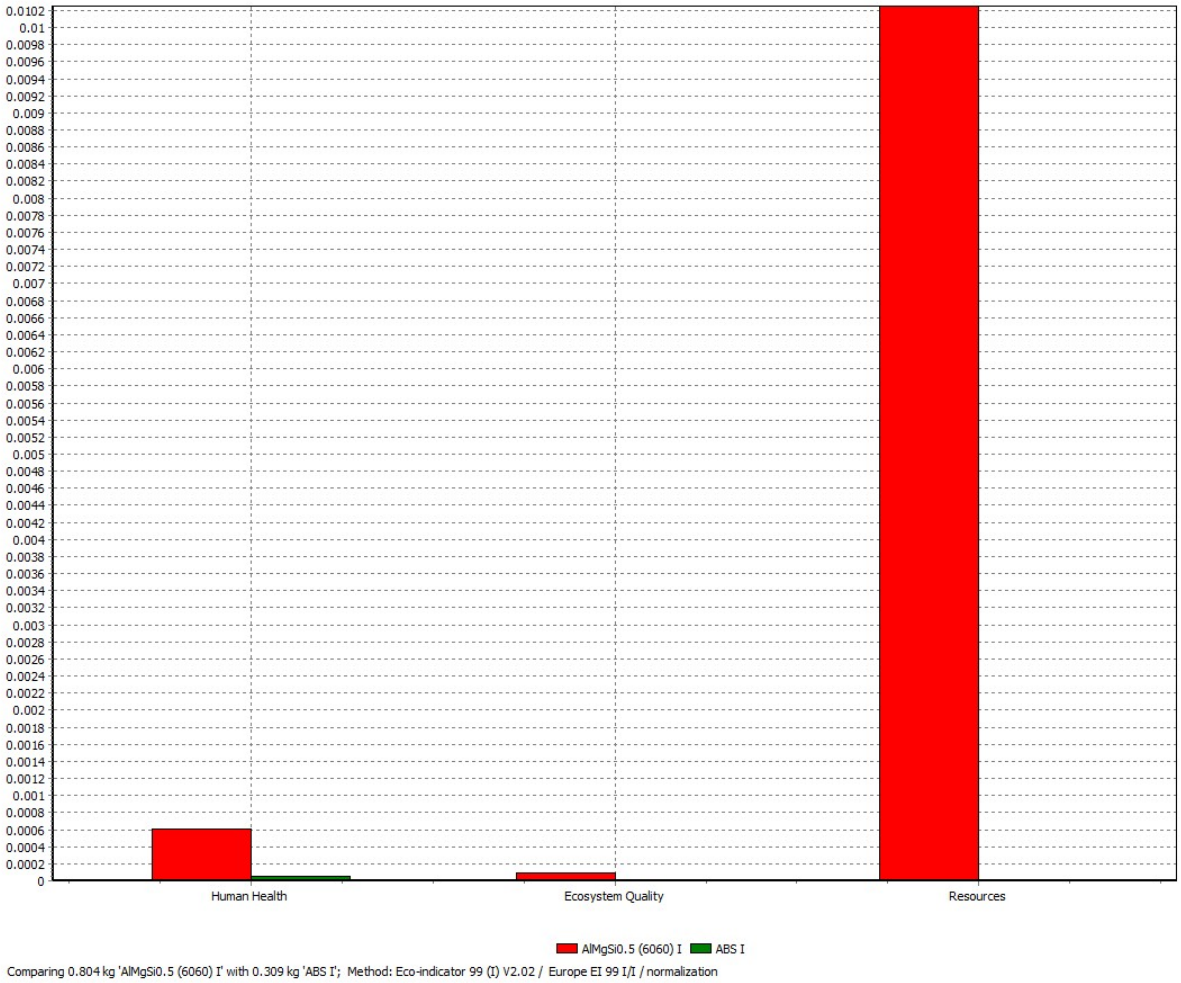


Figure 2.3: Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

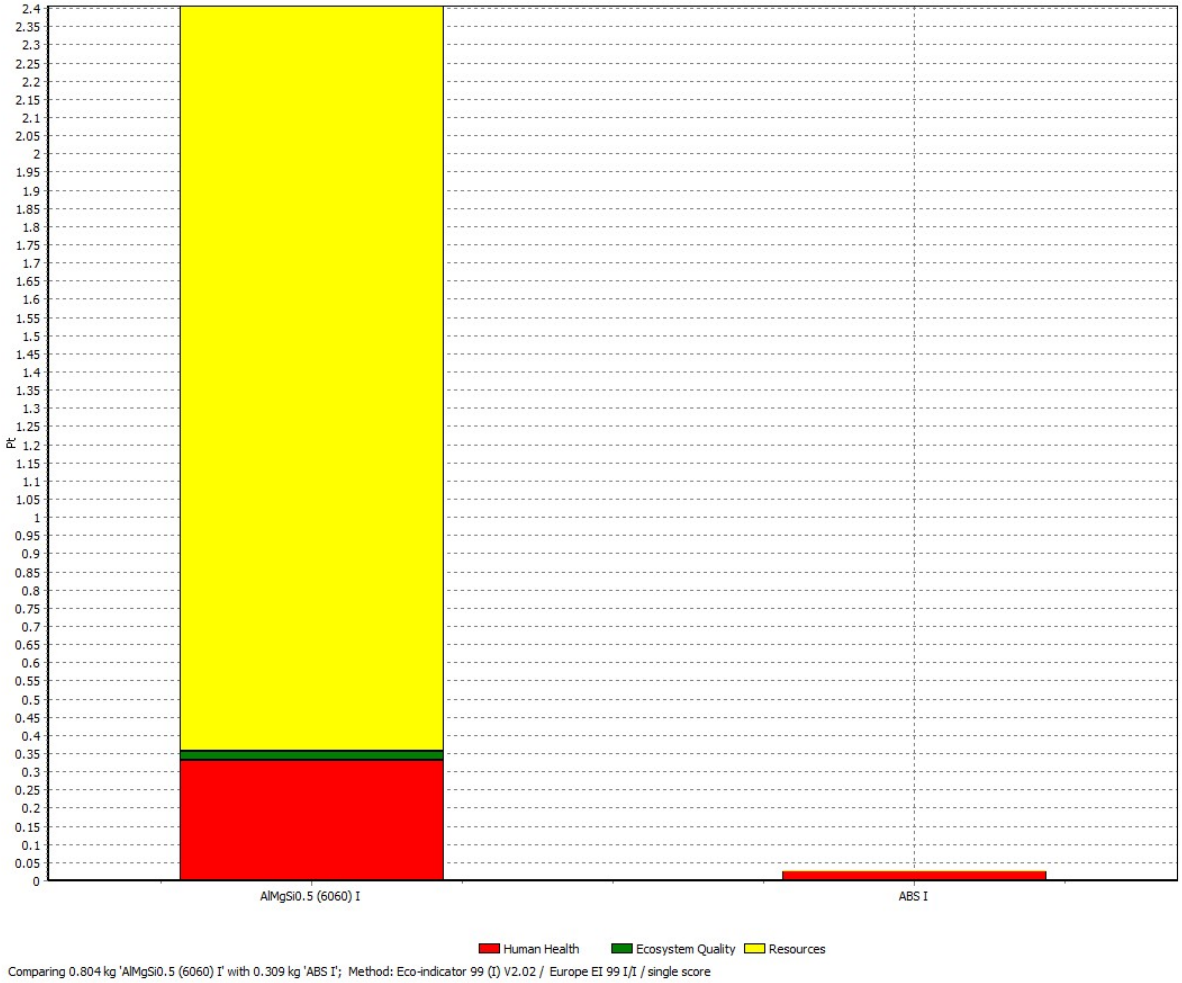


Figure 2.4: Single Score Comparison in "Points"

From using SimaPro 7, it appears that Aluminum 6060, which we approximated to be similar to the Aluminum 6061 used in our device, has a higher environmental impact than Acrylonitrile Butadiene Styrene (ABS). The full life cycle of the device should have no consequence on the environmental impact of the material chosen. While the total impact of Aluminum 6060 is greater than that of ABS, neither is large on the total points scale, as can be seen in Figure 2.4 above. Therefore, we would not switch from Aluminum as our end plate material because the difference in environmental impact is not worth the decrease in the safety factor against yield we would see if ABS was chosen as the material.

C.3. Manufacturing Process Selection

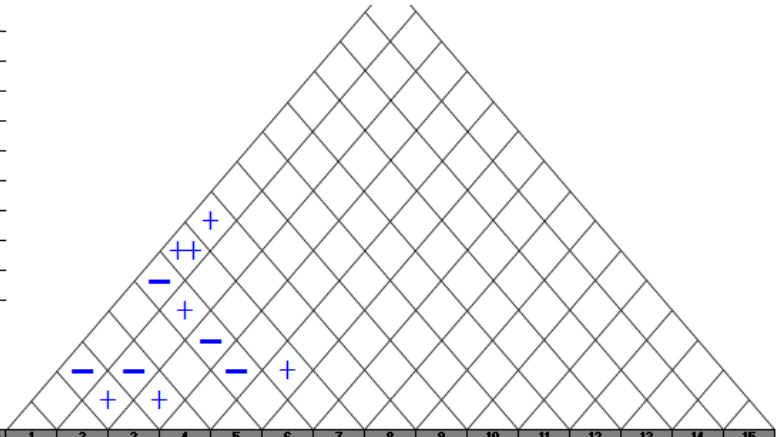
Given the ability of our project to detect and quantify air dissolved within liquids for which little data is available, we believe that commercial implementation would apply only to science and research personnel working in research facilities without gas chromatographs or mass spectrometers. This limits the production volume of our device to somewhere on the order of 100-1,000. The portability of our device is not something that may be required by this market, but the small sample size and ease of use would be advantageous.

However, different fluids may require different size chambers, which lead to resizing of the device. In order to preserve safety, we believe that the components materials should be kept the same. Forming molds that would involve mass producing the device out of plastics would be both cost inefficient due to the low production volume and less safe than the current design, which features aluminum for the end plates and piston, polycarbonate for the cylinder, steel for the lead screw shaft, and brass for the mounting nut. While the device does not deal with much stored energy, the possible high pressure fluids that could be experienced would more easily crack or burst a device made with plastics than one of the materials used for the prototype we have fabricated.

For the same reasons as above and due to very tight tolerances, we would suggest that fabrication processes be kept the same (milling and lathing) in addition to the materials. Precision in performing these processes for mass manufacturing can be efficiently achieved through the use of CNC manufacturing, as opposed to manual machining, which would likely lead to more machining errors and wasted material and time.

D. Quality Function Deployment

Author: Casey Timmons
Date: 9/20/2009
Notes:



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") \ Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1 Hydraulic Fluid Sample Size (gal)	2 Test time (min)	3 Level of Accuracy (ppm)	4 Steps in Process	5 Footprint of Machine(ft^3)	6 Cost ($)	7 Weight(lbs)	8 Self contained(yes/no)	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▲	▼	▼	▼	▼	x							
1	9	8.6	3.0	Small Sample Volume	⊙														
2	9	14.3	5.0	Accurate Measurements		O	⊙												
3	3	11.4	4.0	Easy to Use				O											
4	9	11.4	4.0	Fast Delivery		⊙													
5	3	14.3	5.0	Quantifiable Output			O												
6	9	5.7	2.0	Justifiable Cost		▲				⊙									
7	9	14.3	5.0	Precise Measurements	O		⊙												
8	3	2.9	1.0	Reasonable Size and weight					▲		O								
9	9	14.3	5.0	Safe								⊙							
10	1	2.9	1.0	In Line Testing					▲			▲							
				Target or Limit Value	0.5	10	50	5	1	400	20	Yes							
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	0	3	10	5	4	8	7	6							
				Max Relationship Value in Column	9	9	9	3	1	9	3	9							
				Weight / Importance	120.0	151.4	300.0	34.3	5.7	51.4	8.6	131.4							
				Relative Weight	14.9	18.9	37.4	4.3	0.7	6.4	1.1	16.4							

E. Functional Decompositions

Functional Decomposition #2

Design Problem – Create an accurate measurement device for determining gas concentration in hydraulic fluid.

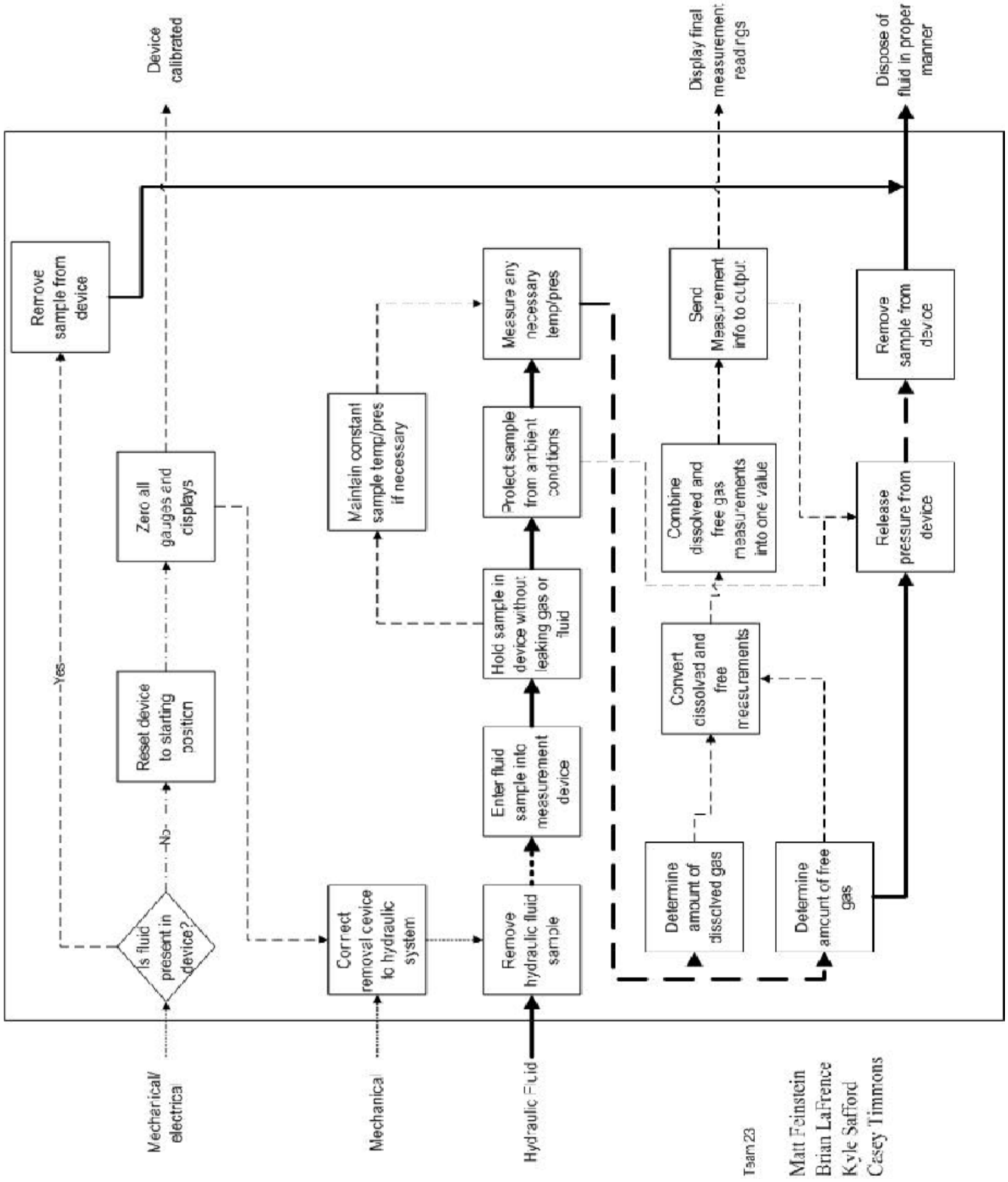
Level 1

1. Calibrate device
2. Transfer hydraulic fluid sample into device
3. Contain hydraulic fluid sample
4. Analyze gas concentration
5. Convert measurement to useable form
6. Output measurement
7. Dispose of fluid safely

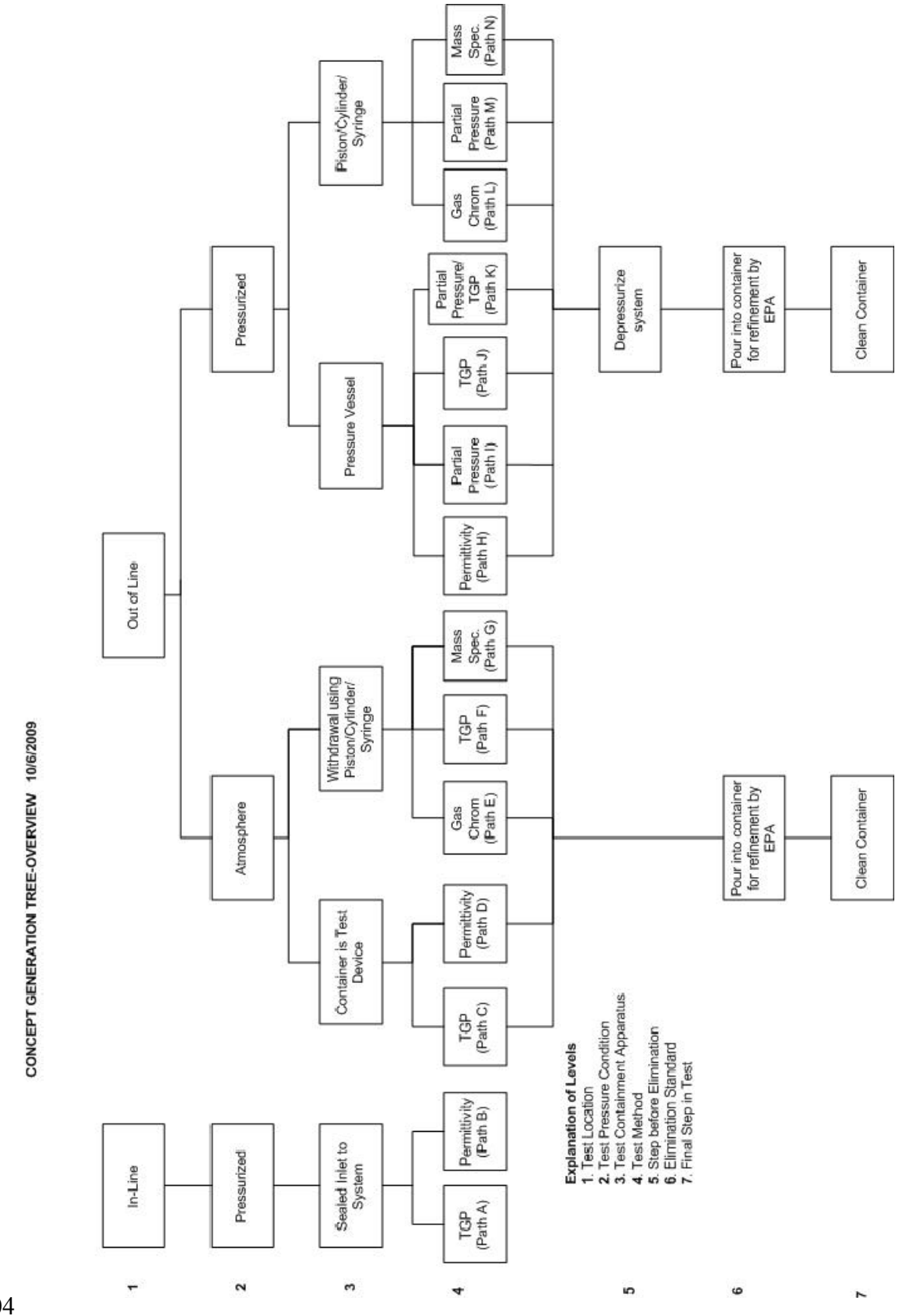
Level 2

1. Calibrate device
    - 1.1 Remove any leftover fluid from previous measurement
    - 1.2 Reset device to starting position
    - 1.3 Zero all gauges and displays
2. Transfer hydraulic fluid sample into device
    - 2.1 Connect removal device to hydraulic system
    - 2.2 Remove hydraulic fluid sample
    - 2.3 Enter fluid sample into measurement device
3. Contain hydraulic fluid sample
    - 3.1 Hold sample in device without leaking gas or fluid
    - 3.2 Maintain constant sample temperature and/or pressure if needed
    - 3.3 Protect sample from ambient conditions
4. Analyze gas concentration
    - 4.1 Measure any necessary pressures and/or temperatures
    - 4.2 Determine amount of dissolved gas present in sample
    - 4.3 Determine amount of free gas present in sample
5. Convert measurement to useable form
    - 5.1 Convert dissolved and free gas measurements into the same units
    - 5.2 Combine dissolved and free gas measurements into one total concentration value
6. Output measurement
    - 6.1 Send measurement information to output device
    - 6.2 Display final measurement readings
7. Dispose of fluid safely
    - 7.1 If applicable release pressure from device
    - 7.2 Remove sample from device into proper container
    - 7.3 Dispose of fluid in proper manner

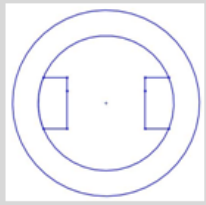
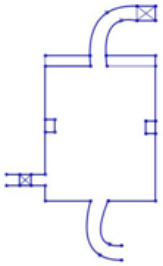
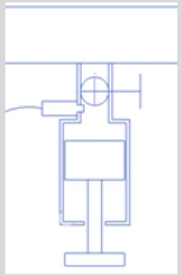
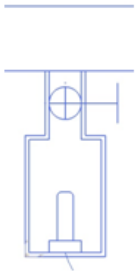
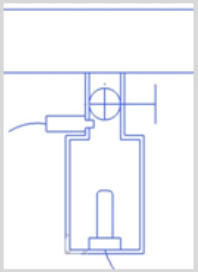
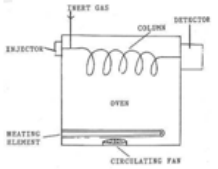
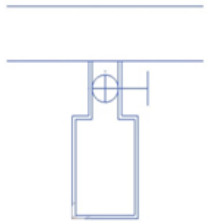
Functional Decomposition #1



F. Methods Tree



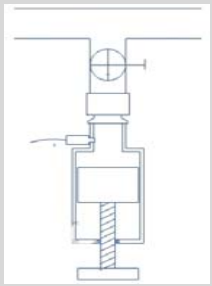
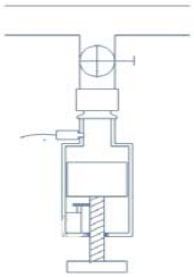
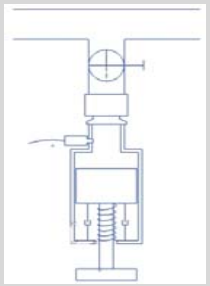
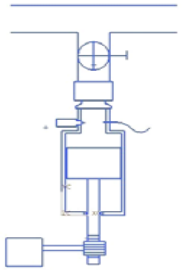
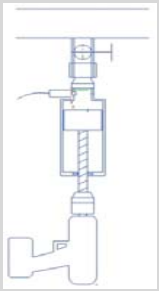
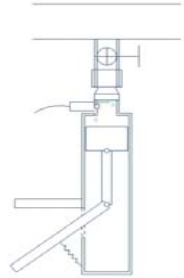
G. Measurement Techniques Pugh

		Concepts of Gas Measurement Techniques of Feasible Paths						
		B	H	M	J	K	L	I
Description		Permittivity: In line, sensors in hydraulic fluid (Path B)	Permittivity: Out of line, control volume, pressurized (Path H)	Partial Pressures: gas removal using pressurized piston cylinder (Path M)	Partial Pressures: TGP Probe, pressurized control volume (Path J)	Partial Pressures: Combo TGP and gas removal using control volume (Path K)	Gas Chromatographer using syringe, pressurized (Path L)	Partial Pressures in a pressure vessel (Path I)
Sketch								
Selection Criteria	**Weight**	Rating	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	-	-	0	0	0	+	+
Accuracy of Measurement	3	-	-	0	0	0	+	0
Precision of Measurement	4	+	+	+	+	+	+	0
Speed	2	+	+	+	0	0	-	0
Ease of Use	2	+	+	+	+	+	+	+
Cost	2	-	-	+	0	0	-	+
Size	1	+	+	0	+	+	-	+
Weight	1	+	+	+	+	+	-	+
Small Sample Volume	2	+	+	+	+	+	+	+
In-Line	1	+	-	-	-	-	-	-
Quantifiable Output	3	+	+	+	+	+	+	+
Power Input	4	+	+	+	+	+	-	-
Total Score		11	9	19	16	16	7	10
Rank		4	6	1	2	2	7	5

H. Functions and Components Pugh

		Concepts for Piston/Cylinder Functions										
		Depressurization				Temperature Measurement		Pressure Measurement		Piston Shaft Actuation Method		
Description		**Open valve**	**Increase Volume**	**Expansion Valve**	**Pipe/hose system**	**Thermometer**	**Thermocouple**	**Gauge**	**Transducer**	**Screw**	**Gear**	**Spring**
Selection Criteria	**Weight**	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	+	+	+	+	+	+	+	+	+	0	0
Accuracy of Measurement	3	0	0	0	0	-	+	-	+	+	+	0
Precision of Measurement	4	0	0	0	0	0	+	0	+	+	+	0
Speed	2	+	+	+	+	0	+	+	+	-	+	+
Ease of Use	2	+	+	+	+	+	+	+	+	+	+	+
Cost	2	+	+	-	-	+	-	+	-	0	-	+
Size	1	-	0	-	-	0	0	0	0	0	0	0
Weight	1	-	0	0	0	0	0	0	0	0	-	0
Quantifiable Output	3	0	0	0	0	+	+	+	+	0	0	0
Power Input	4	+	+	+	+	+	0	+	0	0	0	0
Total Score		12	14	9	9	12	16	14	16	11	8	6
Rank		2	1	4	4	2	1	2	1	1	2	3

I. Piston/Cylinder Concepts Pugh

		Concepts of Piston/Cylinder System Actuation					
		A	B	C	D	E	F
Description		Manual Screw	Automatic Screw	Manual Spring	Automatic Gear	Hand Drill Attachment	Gun
Sketch							
Selection Criteria	**Weight**	Rating	Rating	Rating	Rating	Rating	Rating
Safety	4	+	+	+	+	-	+
Accuracy of Measurement	3	0	+	0	+	0	+
Precision of Measurement	4	0	+	-	+	0	+
Speed	2	-	+	0	+	+	+
Ease of Use	2	-	+	-	+	0	-
Cost	2	+	-	+	-	+	-
Size	1	+	+	+	-	+	-
Weight	1	+	0	+	-	0	0
Small Sample Volume	2	0	0	0	0	0	0
In-Line	1	0	0	0	0	0	0
Quantifiable Output	3	+	+	+	+	+	+
Power Input	4	+	-	+	-	0	+
Manufacturability	3	+	-	+	-	-	-
Total Score		14	10	12	7	1	12
Rank		1	4	2	5	6	2