Hydraulic Hybrid Fluid Conditioning System for Challenge X

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EXECUTIVE SUMMARY

The University of Michigan Challenge X Team is designing a series configuration hydraulic-diesel hybrid powertrain for the Chevy Equinox platform. This powertrain uses a small diesel engine that is less powerful and more efficient than that used in a conventional powertrain, but when coupled with the hydraulic powertrain, it maintains, or even exceeds, the original performance. Using a smaller engine minimizes energy consumption and emission of greenhouse gases. When braking, the hydraulic system can also recover energy normally dissipated as heat in a conventional system.

Maintenance of the hydraulic fluid is important to the well-being of the system. Small debris, high temperatures, and nitrogen gas in the fluid can cause serious problems through wear, breakdown, and cavitation. These problems necessitate the use of a fluid conditioning system to filter debris, maintain the temperature, and monitor the level of aeration in the fluid, which is the purpose of our project.

According to our sponsor, Steve Dockstader of the Challenge X Team, we need to design a fluid conditioning system that will cool to approximately 120°F, filter out debris as small as 3 µm, and ensure that less than 6% of the fluid volume is dissolved nitrogen gas. The system must handle the flow requirements of the connected systems (80 gpm, 200 psi). Our design should be fit within the chassis of the Equinox, weigh less than 60 lb, and cost between $400 and $1000.

We purchased a filter and cooler, summarized in Table 1. We selected these components through a Product Value Assessment (PVA), concluding that these best met our customer requirements. Their performances were validated at the Environmental Protection Agency (EPA).

We concluded that to ensure that the level of aeration in the fluid is less than 6%, it is more practical to develop a monitoring system for the fluid than deaerating it because the extent of the problem of nitrogen permeating through the bladder has not been determined by the EPA or other sources. An aeration detection system (ADS) will be used to measure the % volume of air in the hydraulic fluid.

The ADS we designed is a fully automated piston-cylinder vacuum system. The cylinder takes in a sample of fluid, controlled by a solenoid valve and the piston speed. The valve then closes, sealing the system, while the piston continues moving to apply a pressure drop on the sample. By Henry's Law, this causes the gas in the fluid to come out of solution due to a vacuum; the gas is then ejected. A cable-extension transducer measures the piston displacement at pre- and post-deaeration, from which we can calculate the amount of nitrogen that was originally dissolved in the fluid.

We did validation testing that proved that creating a vacuum does indeed deaerate hydraulic fluid. However, we were unable to detect a change in the fluid level to calculate the amount of air in the fluid. Most of the air in the fluid was dissolved, so its removal had a negligible impact on change in fluid volume. We were unable to create observable standards to test against, such as oil with 10 % volume of air. In the future, observable standards will help further validate our design concept and evaluate the accuracy and precision of our ADS.

Table 1: Design problems for the Challenge X Team and planned solutions.

Design Problem	Solution
Filtration of debris	Hydrotechnik KF3 Return Line Filter
Temperature regulation	Hydac EDL-4 Air Cooler
Air management	Aeration Detection System (ADS)
Location in Equinox	After front drive motor, going into low pressure accumulator

1. ABSTRACT

Challenge X is a three year competition sponsored by GM and the Department of Energy for the development of sustainable mobility technology. The University of Michigan Challenge X team is constructing a hydraulic hybrid powertrain for a Chevrolet Equinox platform. One requirement for the success of this powertrain is the integration of a hydraulic fluid conditioning system to ensure that the hydraulic oil is managed properly. Overheated fluid, contaminants, and entrained air accelerate the degradation of components and reduce the performance hydraulic system. Our system is responsible for maintaining oil temperature, cleanliness, and aeration level. Working with the EPA, we selected a hydraulic cooler and filter that achieves the performance level specified by our sponsor and withstands the demanding operating conditions of the vehicle. We approached the aeration concern by designing an Aeration Detection System (ADS) utilizing a piston induced vacuum to monitor the percentage of dissolved and entrained air within the oil for the Environmental Protection Agency.

2. PROBLEM DESCRIPTION

Challenge X is a three year competition sponsored by General Motors (GM) and the U.S. Department of Energy. Seventeen engineering schools in the U.S. and Canada are competing to re-engineer a Chevy Equinox to minimize energy consumption, emissions, and greenhouse gases while maintaining or exceeding the vehicle's utility and performance. For the competition, the University of Michigan Challenge X team chose to design a series configuration hydraulic-diesel hybrid powertrain. This is the only such design in the competition.

Background on Hydraulic Hybrids

A series hydraulic-diesel hybrid powertrain allows for the use of a less powerful and more fuel efficient diesel engine operating at its optimal setting and less frequently to obtain the same power as a less efficient engine directly powering the wheels. Figure 1 is a schematic of how a hydraulic hybrid powertrain operates. There are two accumulators; one high-pressure and the other low-pressure. Inside the accumulators are nitrogen bladders. When hydraulic fluid accumulates, the nitrogen bladders are compressed, and energy is stored. The low pressure accumulator acts like a reservoir containing hydraulic fluid. During braking, energy that is usually dissipated through heat is used to operate a pump that takes hydraulic fluid from the low-pressure accumulator to pressurize the high pressure accumulator. This energy stored in the high-pressure nitrogen bladder is then used to accelerate the vehicle. During acceleration, the pressurized fluid leaves the high pressure accumulator and powers the pump/motor. The fluid then returns to the low pressure accumulator. The diesel engine is used when the high-pressure accumulator is depressurized and the vehicle is running at steady state.

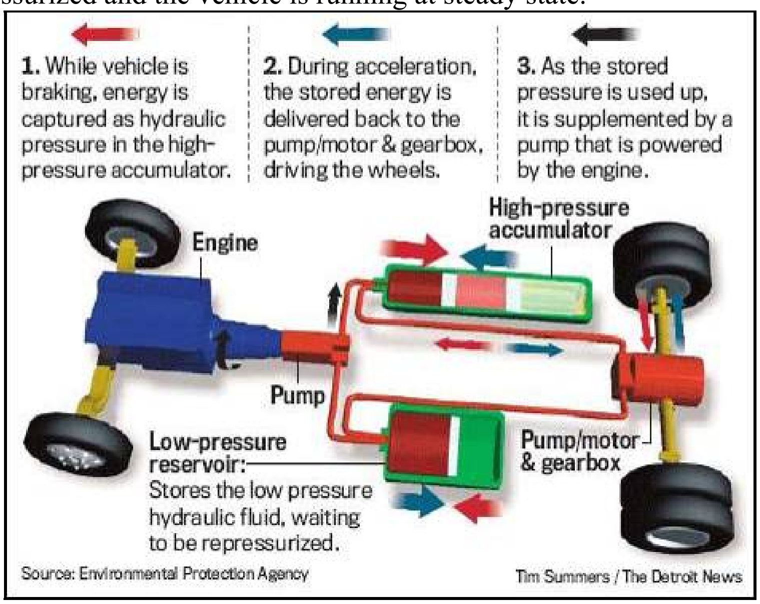


Figure 1: Schematic of how a hydraulic-diesel hybrid powertrian operates [1].

Problem

One requirement for the success of such a system is the integration of a hydraulic fluid conditioning system that at maintains the cleanliness and temperature, as well as the removal of gas from the oil. Our task is to design a conditioning system that is packaged and operational in an efficient manner. It also needs to be designed to handle the required flow.

Debris is introduced into the system through the natural wear of components over time. It is important to filter out debris in the oil, because it increases friction between moving parts and reduces service life. The majority of failures in hydraulic systems are the result of contaminated hydraulic fluid [2].

The temperature of the oil increases as it is pumped through the system due to the inefficiencies in various components. High temperatures promote thinning, oxidation, and breakdown of the hydraulic oil; cause deterioration of seals, packings, and hydraulic hoses; and cause malfunction or inefficiency in components because required clearances between such parts as valve spools and pump parts cannot be maintained [3]. To ensure that high temperatures do not affect the performances of other systems and to prevent a change in fluid properties, a cooling mechanism is required.

Gas can be introduced into the system in two ways; nitrogen penetration through the bladder and cavitations of the fluid due to the pressure drop from filtration. Air in the fluid is undesirable because it is highly compressible, compared to hydraulic fluid and would decrease the efficiency of the system. Also, at high pressure and high velocity the air particles can chip away at the metal pumps creating a rough surface and a reduction in efficiency.

The team leader of the University of Michigan Challenge X team and our sponsor is Steve Dockstader, a graduate student at the University of Michigan, Ann Arbor. He works closely with Neil Johnson at the Environmental Protection Agency (EPA), our other sponsor, who will also be helping the Challenge X team.

3. CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

We have clarified our problem definition from gathering background information relevant to our hydraulic fluid condition system, and we determined our customer requirements. We then took these requirements and translated them into engineering specifications.

3.1 Customer Requirements

The University of Michigan Challenge X team is the customer for which we are designing the hydraulic conditioning system. Challenge X is designing the hydraulic hybrid powertrain for GM and ultimately automotive consumers. Therefore, we are also keeping in mind the requirements of the manufacturer and consumer during our design process.

According to our sponsor we need to design a hydraulic fluid conditioning system that will:

- Cool the hydraulic fluid to prevent thermal breakdown of the fluid
- Filter out all possible debris
- Monitor and/or remove nitrogen introduced into the fluid

In our design, we need to take numerous things into consideration. It is very important that our designed system:

- Handles the flow requirements of the connected systems
- Is efficient such that the pressure drop across our system and the energy losses are minimized as the fluid passes through.
- Fits within the chassis of the Equinox
- Is light enough so that it does not affect the performance of the Equinox.
- Has a minimized cost of the system and its components.

There are some customer requirements that are not required, but we would like to keep them in mind during our design process. For example, it is desirable for the system to be compact enough to fit within one area, but the placement of all three components may not necessarily be optimal in one location. Also, a manufacturer may require the number of steps needed for installation be minimized, and a consumer may require the time it takes to replace the filter be minimized and the service life be maximized. While these are requirements to keep in mind, we will focus on satisfying the requirements most important to the Challenge X team.

3.2 Development of QFD

To develop the QFD, we first met with our sponsor to discuss the requirements that *must* be satisfied and discussed as a group the importance of the other requirements. We then brainstormed quantifiable engineering specifications that will help us meet our customer requirements and set quantified engineering targets for each specification. We used our background information on similar products to determine how these products meet customer requirements and which areas need to be improved.

We created two Quality Function Deployment (QFD) charts; one for the fluid conditioning system and one for the nitrogen monitoring system. We used the system QFD to determine which engineering targets are most important for the fluid conditioning system to reach. The nitrogen monitoring system QFD helped us determine what improvements need to be made to current designs to better serve our purpose. Both QFD charts can be found in Appendix A

3.5 Customer Requirements Translated into Engineering Targets

Meetings with Steve Dockstader, The Challenge X Team, Neil Johnson (EPA), and Andy Moskalik (EPA) provided us with specific information about the hydraulic hybrid systems and their components. Based on this information, we were able set our engineering targets. The engineering targets corresponding to the customer requirements are listed in Table 2.

Table 2: Customer requirements translated into engineering targets.

Customer Requirements	Engineering Targets
3.5.1 Filter out debris	3-5 micron particles
3.5.2 Control Temperature	Cool to approximately 120ºF.
3.5.3 Monitor Air in Oil	Ensure < 6% air/nitrogen in fluid volume
3.5.4 Handle Required Flow	Flowrate capability of 80 GPM
3.5.5 Handle Required Pressure	Pressure capability of 200 psi
3.5.6 Minimize Size	Approx 2ft x 2ft x 1ft
3.5.7 Minimize Weight	Less than 60 lbs
3.5.8 Minimize Cost	$400 - $600

It is most important to the Challenge X team that the fluid conditioning system maintains the cleanliness and temperature of the hydraulic fluid. Our design must have a filter, cooler. Since we do not know whether or not the fluid needs to be deaerated, our design will have a device to measure the amount of air in the fluid. It is very important that each component handles the required flow and pressure of the hydraulic system.

3.5.1 Filter out debris: Filtration of debris from hydraulic fluid has been researched extensively. There are many hydraulic fluid filters on the market. According to sponsor and our research [2], the smallest particles that need to be filtered are 3-5 microns in size.

3.5.2 Control temperature: Challenge X will be using Mobil 1 Synthetic Automatic Transmission fluid. They are using this because the synthetic Poly-Alfa-Olefin is the most cost effective fluid to meet the design criteria for the hydraulic system, and it is used by the EPA on their hydraulic hybrids. As the temperature of this fluid increases, the oil can reach a degradation point where the viscosity decreases to where it no longer provides lubrication to the necessary parts. Our research [18] suggests that the typical operating temperature of a hydraulic system remain between 110°-130°F and that we keep the temperature below 150°F to prevent degradation of the rubber (Buna-N: Nitrile) seals and accumulator bladders.

3.5.3 Monitor amount of nitrogen in oil: The main source of air/nitrogen into the system is permeation of nitrogen through the bladders within the accumulators. The EPA has investigated other less permeable bladder materials, but the Challenge X team will be using the standard Buna-N (nitrile) bladders. A centrifugal pump can withstand 0.5% air by volume; however, 6% can cause significant loss of efficiency and a slight level of cavitation damage [16]. The extent of this problem of aeration into the fluid system of a hydraulic hybrid vehicle has not yet been determined. Predictions have been made that it may take up to 10 years of vehicle use for this critical amount of nitrogen to enter the system [4]. Therefore, we must determine the extent of this issue by monitoring the amount of nitrogen both dissolved and entrained in oil. We have been asked to establish a practical method of managing the amount of air in the system

3.5.4 Handle required flow: The largest pump in the powertrain is a 80 cc/rev Bosch Rexroth Axial Piston Variable Displacement Motor. This pump produces a maximum flowrate of 80 GPM. Our fluid conditioning system should be able to withstand this flowrate.

3.5.5 Handle required pressure: The system should be able to handle up to 200 psi of hydraulic fluid pressure. This is the maximum pressure in the low pressure lines as the fluid leaves the low pressure accumulator, which is where we plan on placing the system due to component robustness and cost issues.

3.5.6 Minimize Size: Our size limitation on the chassis of the Chevrolet Equinox is approximately 4ft x 2 ft x 1ft. Our sponsor has not specified a location for us to mount our system, but due to the elimination of the transmission and the significantly smaller engine, there is a plethora of places to locate our three components. We plan to minimize the size of the system as much as possible.

3.5.7 Minimize weight: Our sponsor has not set a weight limitation, but we are aware that any weight added to a vehicle will affect its performance. When the previous ME450 team designed a deaerator for the EPA they were required to keep it less than or equal to 6 lbs. Since our design will consist of three components, we approximated a weight limitation of 60 lbs. This is comparable to the weight of the combined filter and cooler of the EPA's Ford Expedition.

3.5.8 Minimize cost: For the Challenge X competition the cost of system is not set in stone. We were asked to keep it "reasonable". From a manufacturer's point of view the cost should be minimized for mass production. After pricing some hydraulic filters and coolers we found a price range of $400-$600 to be realistic.

3.3 Hydraulic Fluid Conditioning System QFD results

Hydraulic fluid conditioning system QFD results can be found in Appendix A.1. The results show that when designing our fluid conditioning system it is most important for the following engineering targets to be met:

- Maximum flow rate through the system
- Pressure drop across the system
- Minimum size of particles the system can filter
- Maximum temperature reaches

Different hydraulic systems have different requirements for the fluid conditioning system. These requirements determine which components can be chosen. There isn't another hydraulic hybrid that has the same requirements as the Equinox. For this reason, we did not benchmark our fluid conditioning system.

3.4 Nitrogen Monitoring System QFD results

The nitrogen monitoring system QFD results can be found in Appendix A.2. We found an offline air measuring system for hydraulic devices to benchmark for our design. Results of the QFD show that when considering a device that will monitor the level of nitrogen present in the hydraulic system, we meet the following engineering specifications:

- 100 % of air in oil should be detected
- Minimize number of components
- Handle pressure requirements of the system

We found that our benchmarked design is effective in that it detects 100% of the air in the oil. For the purpose of our application, improvements could be made to the number components and pressure capability of the benchmarked design. We want the design to be as simple as possible, so we would like to have a fewer number of components. The benchmarked design is capable of handling the pressure requirements of our system, but it is highly over designed. This implies that when we can design our aeration monitoring device to have a lower pressure capability.

4. PRELIMINARY ENGINEERING PROBLEM ANALYSIS

To meet our customer requirements, we need to develop a system that will (1) remove debris, (2) regulate the oil temperature, and (3) monitor the amount nitrogen in the oil.

4.1 Fluid Conditioning System Engineering Analysis

A general problem we need to address is the placement of our fluid conditioning system relative to the other hydraulic components. Preferably, the components should be along a flow where it is:

- Low pressure
- Uni-directional
- The hottest location in the hydraulic system
- Unaffected by a pressure drop upstream
- Unaffected to cavitations forming upstream

The outlet from the low pressure reservoir to the front pump motor is the ideal location so far for this system because of the low pressure flow in addition to the one directional flow of fluid. Although it is possible to split up the components, it would be best to keep them together since all three of these devices (monitoring system, filter, and cooler) all have the similar issues regarding pressure and flow requirements, pressure drops, and potential to introduce cavitations.

We have determined that it would be best to place this system at the inlet of the low pressure accumulator. At this location, the pressure drop and potential cavitations have an insignificant effect on the hydraulic system. This is also one of the lowest areas of pressure in the system.

4.2 Filter System Engineering Analysis

In order to remove the debris, a filter will be used. The filter will be purchased rather than designed, so no any engineering analysis will be done for the filter. However, extensive research was done to determine the filters available on the market that will best meet our customer requirements for pressure capability, flowrate capability, micron filtration, and pressure drop. This is described in more detail in Section 7. We will test the efficiency our filter oil once it is installed into the fluid conditioning system. We plan to run oil of a known cleanliness through the system, and then measure the fluid again for cleanliness. We will use Equation 1 to calculate the efficiency.

$$\text{Filter efficiency} = \frac{\text{number of particles upstream} - \text{number of particles downstream}}{\text{number of particles of upstream}} \qquad (1)$$

4.3 Cooling System Engineering Analysis

In order to regulate the oil temperature, a cooler will be used. The cooler will be purchased rather than designed, and benchmarking will have to be conducted to determine which filter available on the market will best meet our customer requirements for pressure drop, flow rate, and heat dissipation. Greater heat dissipation rates means that the cooler regulates the temperature of the oil more effectively. We must select a cooler with a sufficiently high heat dissipation yet reasonable size and weight to fit in a vehicle. There are many types of heat exchangers available, and we must select the type that is most practical for mobile applications.

One equation we found [13] that can help us in measuring heat load of the system (P, in kW) is Eq 2. We can calculate the heat load from an *existing* hydraulic system by measuring the temperature of an oil reservoir both at start up and after the system has been in operation for a measured amount of time. This is a much simpler calculation than calculating the efficiency losses in each component that the fluid flows through.

$$P = \frac{V \times \Delta T}{32.4 \times \Delta t} \qquad (2)$$

V = fluid volume (L)
T = Temperature Change (°C)
t = Time Change (Minutes)

4.4 Aeration Management System Engineering Analysis

We have been asked to establish a practical method of managing the amount of air in the system. We discovered that the rate at which nitrogen enters the fluid system is still unknown and varies from application to application. Two possibilities for managing the amount of air in the system if it is above the critical level of 6% are as follows:

- Passive deaeration system that continually deaerates the nitrogen dissolved and entrained in the oil.
- Deaeration system that only runs when a critical percentage of nitrogen is detected by a device located in the system

4.4.1 Passive Deaeration Approach

The nitrogen can either be dissolved in the hydraulic oil or entrained (bubbles). According to Le Chatelier's Principle and Henry's Law, an increase in temperature or a decrease in pressure to the critical values for nitrogen will pull the gas out of solution. The first step for a deaerator design is to remove the nitrogen from solution, and then we want to collect the entrained nitrogen bubbles by a method of separating the gas from the liquid.

As previously mentioned, to remove the nitrogen from solution one can either decrease the pressure or increase the temperature. The increase in temperature can be obtained through a heating element, however there are several options available to cause a pressure drop. As shown by Equation 3, Bernoulli's extended equation, this pressure drop can be achieved through an decrease in velocity, an increase in height difference, and an increase in head loss. Our concept designs attempt to capture each of these methods of separating the gas from liquid.

$$\Delta P = P_{out} - P_{in} = -\gamma[(\frac{1}{2g})(V_{out}^2 - V_{in}^2) + (z_{out} - z_{in}) + h_f] \quad (3)$$

4.4.2 Aeration Detection Approach

We developed several concepts for fluid deaeration as shown in Appendix B.3. However, the extent of the problem of nitrogen permeating through the bladder has not been determined by the EPA or other sources. The EPA's prediction is for a dangerous amount of nitrogen to enter the system after 10 years.

Since the extent of nitrogen levels is unknown, we feel that it is most practical to place a nitrogen monitoring system that will signal a warning message to the vehicle owner when the level is too high. At this time, the owner can take the car to be serviced. This is similar to a current automobile engine oil change.

There are several engineering approaches to this:

- Compressibility – by compressing the fluid and noting the change in volume, the % volume of air may be calculable from the bulk modulus.
- Fluid Contamination – a laser could detect particles (bubbles) of various radii and what % of the volume they make up.
- Expandability – by expanding a fixed volume of fluid a vacuum will be created, pulling out entrained bubbles and separating them from the fluid.
- Physical Properties – assuming that as the % volume of air increases in the fluid, the fluid properties (electrical conductivity, thermal resistance, etc.) should change

5. FLUID CONDITIONING SYSTEM CONCEPT GENERATION AND SELECTION

5.1 Fluid Conditioning System Configuration Concepts

Our hydraulic fluid conditioning system is to be placed on the chassis of the Challenge X Chevrolet Equinox where we will have to deal with issues regarding packaging constraints and effects on the performance of the hydraulic system. Figure 2 shows five possible locations for this fluid conditioning system. Four of these locations are at the low pressure side of the system, and one is located at the high pressure side.

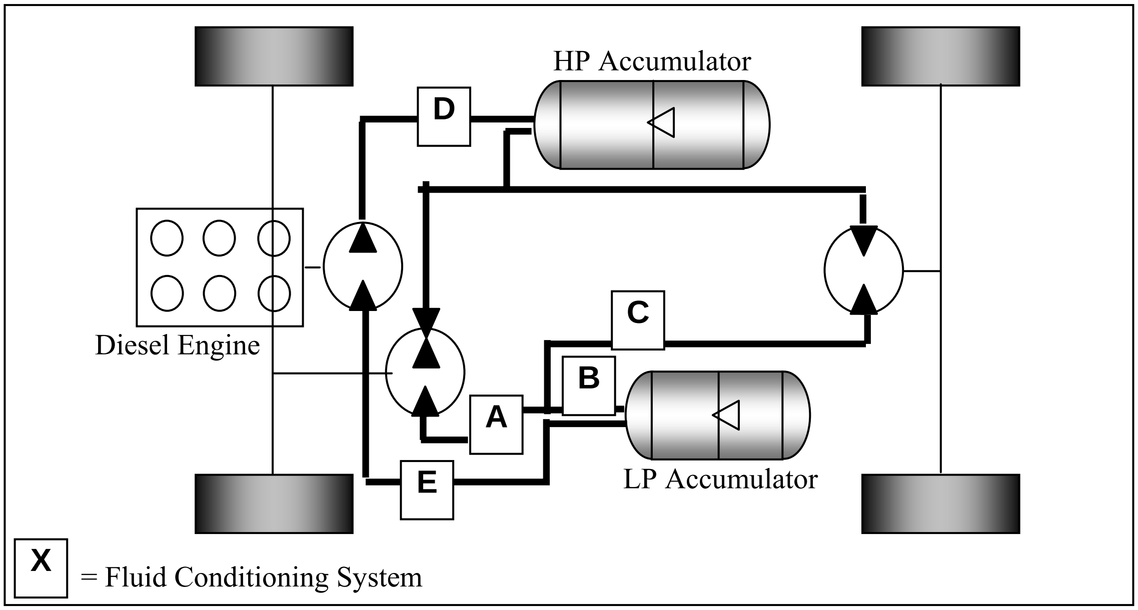


Figure 2: Possible Locations for Hydraulic Fluid Conditioning System

5.1.1 Location A: After Front Drive Motor into Low Pressure Accumulator

The EPA has a filter and cooler on their hydraulic hybrid Ford Expedition in a very similar location as this design.

Pros: Low pressure side, max flowrate of 80 GPM, low cavitation effects

Cons: Does not filter and cool all fluid, works only when accelerating and at steady state, must deal with two directional flow

5.1.2 Location B: After Front and Rear Drive Motors into Low Pressure Accumulator

Pros: Low pressure side, filters and cools all fluid flow, low cavitation effects

Cons: Max flowrate of 160 GPM, works only when accelerating and at steady state, must deal with two directional flow

5.1.3 Location C: After Rear Drive Motor into Low Pressure Accumulator

Pros: Low pressure side, max flowrate of 80 GPM, low cavitation effects, flow is uni-directional

Cons: Does not filter and cool all fluid, works only when accelerating and at steady state

5.1.4 Location D: After Front Engine Pump into High Pressure Accumulator

Pros: Most likely the hottest location of the system, flow is uni-directional, max flowrate of 55 GPM

Cons: High pressure side, only works when running at steady state

5.1.5 Location E: After Low Pressure Accumulator into Front Engine Pump

Pros: Flow is uni-directional, low pressure side, max flowrate of 55 GPM

Cons: Cavitations into the pump can be disastrous, only works when running at steady state

5.2 Fluid Conditioning System Location Selection Results

To evaluate these 5 designs, we used a weighted, 3 degree Pugh chart. Using this matrix resulted in:

- Greater insight into the problem specification and constraints
- Finding conceptual vulnerability, i.e bad designs that cannot be fixed
- Realization that further analysis may change a decision
- The generation of newer concepts

To perform this analysis, we compared each configuration concept relative to a reference (the EPA hydraulic hybrid Ford Expedition) for certain selection criteria. The results can be seen below in Table 3.

Table 3: Pugh Chart for Fluid Conditioning System Configuration Concept Selection

		CONCEPT VARIANTS					
SELECTION CRITERIA	**Wt.**	**A**	**B**	**C**	**D**	**E**	**REF**
Packaging	3	0	0	0	0	0	0
Passiveness	4	0	-	+	-	-	0
Maintainability	1	0	-	0	0	0	0
Heat Removal	3	0	+	-	+	0	0
Debris Removal	4	0	+	-	+	+	0
Cost	1	0	0	0	+	0	0
Safety	3	0	0	0	-	-	0
Resistance to Wear	3	0	-	+	-	0	
PLUSES		0	7	7	8	4	
SAMES		22	7	8	4	11	
MINUSES		0	8	7	10	7	
NET		0	-1	0	-2	-2	
RANK		1	3	1	5	5	
CONTINUE?		Yes	No	Yes	No	No	

Our results show us that we should further investigate the placement of our system at locations A (after front drive motor into low pressure accumulator) and C (after rear drive motor into low pressure accumulator). Both of these locations share similar characteristic, but location C has the benefit of uni-directional flow because the rear driveline is only used for acceleration and steady state, not regenerative braking. The two directional flow at location A requires use of parallel bypass lines for reverse flow.

Since our sponsor, Steve Dockstader, mentioned that the Challenge X team will first configure the Chevrolet Equinox for just front wheel drive and eventually incorporate rear wheel drive, we have decided to place our system at location A. Location C requires a rear wheel drive configuration.

6. AERATION DETECTION SYSTEM CONCEPT GENERATION AND SELECTION

6.1 Aeration Detection Benchmarking

We found two types of devices currently available that can detect the amount of air in hydraulic fluid. These two devices work on different principles: vacuum and compression.

6.1.1 FES – Aeration Measuring Device

This product uses an applied vacuum to separate the entrained gas from the oil. This hand operated device uses a digital micrometer to measure the location of the plunger relative to the end and the hand crank allows a vacuum to be placed on the fluid. The separated air is then expelled and the final distance measurement is taken. This company states that this product can measure 9% of air by volume with a 2% error.

Figure 3: FES - AMD

6.1.2 SMAC – Compressibility Aeration Measuring Device

This product uses compression to determine the amount of air in the fluid. By obtaining the pressure and volume information of the liquid-gas mixture compression, one can determine the volumetric ratio. The log-log graph (P/P_0,$1-V/V_0$) of the mixture of pressurized sample shows an inflection point. The y value of the inflection point ($1-V/V_0$) is equal to the volumetric gas ratio initially in the sample. No information on performance was able to be obtained.

Figure 4: SMAC

6.2 Aeration Detection System Concepts

An aeration detection system (ADS) will be used to measure the % volume of air in the hydraulic fluid. Our Functional Decomposition Diagram is located in Appendix E. The ADS will need to be able to take small samples periodically and make accurate measurements. Since the designs take small samples and some of them require gravity, they will operate when the vehicle is not running and the fluid is not flowing. This also allows us to assume that the fluid is at zero pressure since it is not flowing and is cut off from the accumulators. Five of these concepts work on the principle that the hydraulic fluid is completely incompressible and that the nitrogen gas can be both compressed and expanded depending on the applied pressure.

6.2.1 Vacuum Force ADS

In this design a sample of oil will be drawn and after reaching a set volume, the valve to the main line will close. Then a motor with a worm gear will slowly expand the volume of the cylinder. The torque will be measured via voltage, and the displacement measured via digital micrometer. The machine will be calibrated so torque and displacement relate to the % volume of air in the sample. If there is no air present and the reservoir is 100% oil, the volume will not expand.

Another method for measuring the amount of nitrogen in the fluid using a similar apparatus would require use of a digital micrometer to measure the displacement of the piston. In this design the chamber will be filled with fluid and the micrometer will record this location/volume. The small piston will move up to create a vacuum and separate all entrained and dissolved nitrogen. With the gas and liquid separated, a valve will open and the plunger will compress, allowing the air to leave the chamber into the atmosphere. When all air has left the chamber, the final plunger position will be recorded. Knowing the original volume (air and oil) and final volume (just oil) we can solve for the original % volume of air.

Pros: Simple, independent of gravity and can be placed in various positions
Cons: May not be precise enough, requires accurate torque and displacement measuring devices, need to develop calibration curve between applied force, displacement, and % volume of air.

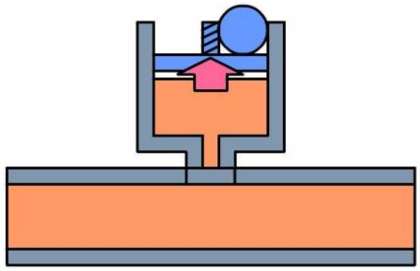


Figure 5: Vacuum Force ADS

6.2.2 Compression Force ADS

This design will draw a sample of oil, and close the valve to the main line after it reaches a set volume. The motor will compress this volume. The torque will be measured through input voltage, and the displacement measured by a digital micrometer. The machine will be calibrated so torque and displacement relate to the % volume of air in the sample. If there is no air present and the reservoir is 100% oil, the volume will not compress.

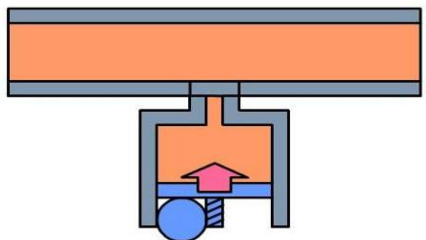


Figure 6: Compression Force ADS

Pros: Simple, independent of gravity and can be placed in various positions
Cons: May not be precise enough, requires accurate torque and displacement measuring device, need to develop calibration curve between applied force, displacement, and % volume of air.

6.2.3 Electrical Resistance ADS

In this design two electrodes will be placed a certain distance from one another and measure the resistance of a given volume of oil. This relies upon the principle that a change in composition of a material will cause its physical/electrical properties to change. The ADS will need to be calibrated so resistance relates to the % volume of air in the fluid.

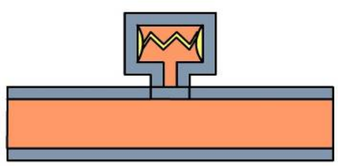


Figure 7: Thermal Resistance ADS

Pros: Simple, no moving parts, compact, can be placed in confined spaces, long service life
Cons: Precision may be very difficult, calibration required, no way to ensure fresh fluid in and force tested fluid back into flow, requires electricity

6.2.4 Digital Micrometer ADS

In this design a large chamber will be filled with fluid and a small piston will move up to create a vacuum and separate all entrained and dissolved nitrogen. The change in distance will be recorded by a digital micrometer, which equates to change in volume. Knowing the original and final volume of oil will provide the ability to solve for the original % volume of air. The narrow upper neck geometry of the container will allow for a greater displacement of the micrometer/plunger (improved accuracy).

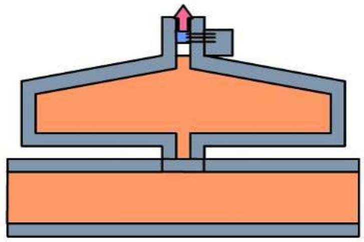


Figure 8: Digital Micrometer ADS

Pros: No calibration necessary, precise
Cons: Difficult pull oil into container, difficult to manufacture, larger size

6.2.5 Digital Laser ADS

This design works the same as the Digital Micrometer ADS, but measures the change in distance with a laser instead of a digital micrometer. This laser located at the end of the plunger will need to be able to measure the distance from the plunger end to the surface of the oil

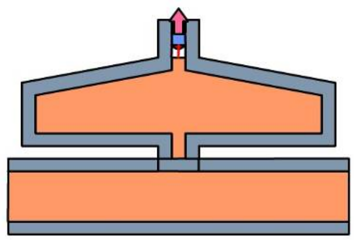


Figure 9: Digital Laser ADS

Pros: No calibration necessary, precise
Cons: Difficult to pull oil into container, expensive, difficult to manufacture, requires a special laser that can measure the distance to a liquid level

6.2.6 In-line Digital Micrometer ADS

This design works the same as the Digital Laser/Micrometer ADS designs, but fluid enters the chambers by being in flow with the rest of the system. Valves will lock the fluid in place when the small piston starts moving and the change in distance is measured.

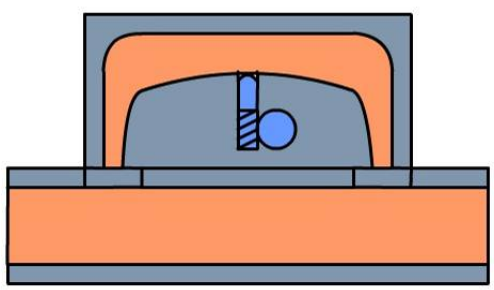


Figure 10: In-line Digital Micrometer/Laser ADS

Pros: No calibration necessary, precise,
Cons: Difficult to make, introduces pressure drop and inefficiencies into flow.

6.3 Aeration Detection System Concept Selection Results

Similar to our selection process for the fluid conditioning system configuration concept selection, we also used a Pugh chart to select the best ADS concepts (see Table 4). We compared our 6 concept designs relative to a commercial handheld aeration measuring device [19].

Table 4: Pugh Chart for Aeration Detection System Concept Selection

		CONCEPT VARIANTS						
SELECTION CRITERIA	**Wt.**	**Vacuum Force**	**Compression Force**	**Electrical Resistance**	**Digital Micrometer**	**Laser meter**	**In-line meter**	**REF**
Simplicity	4	+	+	+	0	-	+	0
Cost	1	0	0	0	0	-	0	0
Size	2	0	0	+	-	-	-	0
Precision	5	0	-	-	+	+	0	0
Ease of Production	3	-	-	+	-	-	-	0
Passiveness	3	+	0	+	0	0	-	0
Refresh fluid	4	0	0	-	-	-	+	0
PLUSES		7	4	12	5	5	8	
SAMES		15	10	1	8	3	1	
MINUSES		3	8	9	9	14	8	
NET		4	-4	3	-4	-9	0	
RANK		**1**	5	**2**	4	6	**3**	
CONTINUE?		**Yes**	No	**Yes**	No	No	**Yes**	

Our Pugh chart results indicate that the only concepts that are worth further investigation are the Vacuum Force ADS, Electrical Resistance ADS, In-line Meter, ADS. Our rankings show that the Vacuum Force performed the best at meeting the selection criteria compared to the other two. We will select this design for further engineering analysis.

7. FILTER AND COOLER SELECTION PROCESS

We chose a filter and cooler for our fluid conditioning system based on how well the components met our customer requirements. We used www.globalspec.com to find manufacturers of our components. We visited the manufacturer's websites and made a list of the components that could handle the flow rate and pressure requirements of the hydraulic system. To find which component best meets our customer requirements, we performed a product value assessment (PVA). PVA is a mathematical method used to compare the characteristics of products and predict which product will best satisfy the customer. Product value assessment uses weighted product characteristics to determine functionality, and price and cost expectation to show how the value of the product changes with price. A detailed explanation of our PVA can be found in Appendix C.

7.1 Components Selected Using PVA

When selecting a component for a hydraulic system it is most important for it to handle the flow rate and pressure of the system. The flow rate and pressure our components are required to handle is 80gpm and 200psi, respectively. All the components we considered met these two requirements. We then looked at other characteristics important to Challenge X and used a PVA to determine the components that best meet our customer requirements.

Equation 4 is the general PVA equation. In the numerator, weighted product characteristics determine the functionality of a product. In the denominator, price and cost expectation are used to show how the value of the product changes with price. c_i is the weight that represents the importance of the corresponding characteristic, Z_i is the product characteristic, P_i is the price of the filter being considered, and P_{exp} is the price the customer expects the filter to cost. This equation computes a number that is only meaningful when comparing products. The component with the largest PVA when compared to similar components best satisfies customer requirements.

$$PVA = \frac{c_1 Z_1 + c_2 Z_2 + \Lambda + c_n Z_n}{(1 + \frac{P_i}{P_{\exp}})} \qquad (4)$$

To maximize the functionality of our components we need to maximize the numerator. However, the functionality of our components increases as some characteristics decrease. For example, our filter better meets our customer requirements as the pressure drop across the filter decreases. To account for this, we assigned values to ranges of characteristic measurements. When appropriate, values were assigned such that a high value represents a range of low characteristic measurements. For example, a low range of pressure drops of 0-5 psi was assigned the value 8, whereas a high range of pressure drops of 21-25 psi were assigned the value of 4.

Ranges of characteristic measurements were assigned values to accurately compare a component characteristic. For example, when comparing the weight of two filters, a 5 lb. filter is not twice as functional as a 10 lb. filter. We know this because the weight of the Equinox is increased by up to 670 lbs. from other hydraulic components, so adding the weight of either filter is insignificant. Appendix C.2 shows for each component the ranges determined for each characteristic and the values assigned to the ranges.

Weights assigned to characteristics are determined based on the importance of satisfying customer requirements. For example, it is critical to the hydraulic system that the size of the filtered particles and the pressure drop are minimized. Therefore, particle size and pressure drop were assigned much higher weights than the other characteristics. Weights are normalized to ensure that the most important characteristic accounts for a higher percentage of the functionality. We normalized the weights by choosing a component and defining the characteristics of that component as the standard characteristics. We divided each weight by the corresponding standard characteristic to obtain the normalized weight, or factor. To redefine the terms in Equation 4, c_i represents the factor and Z_i represents the value assigned to a range of characteristic measurements.

The denominator of Equation 4 is meant to show how the value of the component changes with price. It is necessary for Challenge X to have a filter and a cooler that meet the requirements of their hydraulic system. They will use their sponsor money for the competition to buy these components no matter the cost. Since price is not an object, the price expectation can approach infinity, which causes the denominator to be one.

We computed the PVA for each cooler and filter using the simplified version of Equation 4. The PVA for the both components and the results are found in Appendix C. The filter and cooler with the highest PVA were the components that best meet our customer requirements and are the components we suggest Challenge X to use in their system.

7.2 Hydrotechnik Return Line KF3 Filter Selected

We suggest that Challenge X use the Hydrotechnik return line filter with model number KF3. This filter meets the system requirements, and according to our PVA results, shown in Appendix C.2, it has the most desirable characteristics compared to the other filters considered. Table 5 lists the filter's characteristics and shows how it meets customer requirements.

Table 5: Characteristics of Hydrotechnik KF3 filter with respect to customer requirements.

Characteristic	Customer Requirement	Performance
Maximum Flow Capability	80 gpm	100 gpm
Maximum Allowable Operating Pressure	200 psi	300 psi
Size of smallest particle filtered	3-5 μ	5 μ
Pressure drop at flow of 50 gpm	Minimize pressure drop	9 psi
Weight	Less than 40 lbs.	10.5 lbs.
Length	Minimize size	13.12”
Head diameter	Minimize size	6.25”

We used globalspec.com find 40 hydraulic filter manufacturers [17]. After visiting each manufacturer's website, we found that there are five manufacturers that offer a total of 13 filters that meet our system's requirements. These filters and their characteristics can be seen in Appendix C.1.

All the filters we considered meet the flow rate and pressure requirements of the hydraulic system. We used the following characteristics in our PVA, listed in order of importance:

- Size of smallest filtered particle
- Pressure drop corresponding to a flow rate of 50gpm
- Weight
- Length
- Diameter

.
It is important for the filtered particle size to be as small as possible because the main cause of hydraulic system failure is contaminated fluid. Finer filtering corresponds to cleaner fluid and an increased service life. However, a finer filter causes a greater pressure drop across the filter. Pressure drops within the hydraulic system decrease the performance of the entire system. Therefore it is very important to find a filter that can remove the required particle size without causing a large pressure drop. The Hydrotechnik KF3 filter meets this criterion better than the other filters considered.

According to Challenge X, there the weight and size requirements of our system are flexible. Weight and size were still considered in our filter choice, but it wasn't critical that choose the lightest and smallest filter. The Hydrotechnik KF3 filter was not the lightest or the smallest, but it also was not the heaviest or the largest.

The Hydrotechink KF3 filter can remove particles 5 μm in size while producing a pressure drop of only 9 psi. This is better than the other filters considered. Neither the weight nor size of this filter is excessive. This combination of characteristics makes the Hydrotechnik KF3 filter the best choice for Challenge X's fluid conditioning system.

7.3 Hydac EDL-4 Air Cooler Selected

We suggest that Challenge X use the Hydac air cooler with model number EDL-4. This cooler meets the system requirements, and according to our PVA results, shown in Appendix C.4, it has the most desirable characteristics compared to the other coolers considered. Table 6 lists the cooler's characteristics and shows how it meets the customer requirements.

Table 6: Characteristics of Hydac EDL-4 air cooler with respect to customer requirements.

Characteristic	Customer Requirement	Performance
Maximum Flow Capability	80 gpm	60 gpm
Maximum Allowable Operating Pressure	200 psi	230 psi
Heat dissipation	Maximize heat dissipation	55,990 BTU/hr
Pressure drop at flow of 45 gpm	Minimize pressure drop	15 psi
Weight	Less than 40 lbs.	35 lbs.
Height	Minimize size	19.67"
Width	Minimize size	16.57"
Depth	Minimize size	7.37"

Many types of heat exchangers are available to cool hydraulic oil. These include shell-and-tube, plate, and air-cooled. Shell-and-tube heat exchangers are used in applications with high temperature and pressure demands. Plate heat exchangers have channels that two different fluids can flow through to exchange heat. These types of heat exchangers are used in low-viscous applications with moderate temperature and pressure demands. Air cooled heat exchangers contain an integral fan for cooling the fluid. For mobile applications, air cooled heat exchangers are the most practical choice. Their compact design allows them to fit most equipment. Although shell-and-tube type heat exchangers have higher heat dissipation rates, their great size and weight makes them impractical for use in vehicles.

Using globalspec.com and thomasnet.com, we found nearly 600 heat exchanger manufacturers and distributors. First we narrowed down the options by looking at the companies that were based in the Midwest region of the United States. We then visited the companies' websites and found which ones manufactured air coolers. At this point we had about a dozen companies to choose from. We could then quickly eliminate companies whose heat exchangers did not meet our maximum flow capability (80 gpm) and maximum allowable operating pressure (200 psi) requirements. This allowed us to narrow our options down to four manufacturers. These manufactures and the characteristics of their coolers can be found in Appendix C.3. To choose a cooler from these four options, we used the following characteristics in our PVA, listed in order of importance:

- Heat dissipation rate
- Pressure drop corresponding to a flow rate of 45 gpm
- Weight
- Height, width, and depth

The most important characteristic to consider is the heat dissipation rate. This determines the cooling capacity of the heat exchanger. The Hydac ELD-4 had the highest heat dissipation rate of the four main candidates. It also had the lowest pressure drop. As stated in the Filter Selection section, size and weight constraints are flexible for our system. Although the Hydac EDL-4 was the heaviest cooler considered, and the ASA Hydraulik cooler had smaller dimensions, the benefits of the high heat capacity and low pressure drop of the Hydac system outweighed the disadvantages, as shown in the PVA in Appendix C. The cooling fan on the Hydac EDL-4 is powered by a 12 V DC motor.

The cooler dissipates 22 HP. According to Curis Caufy at Bosch Rexroth, the overall efficiency of the motor is 75%, assuming an average displacement of 30% of the maximum displacement. This produces a heat input to the oil of 3 HP. With two motors in the Equinox, this means that the cooler must remove 6 HP from the hydraulic fluid. Thus, the 22 HP cooling capacity of the ELD-4 cooler is sufficient for our system.

8. INITIAL ENGINEERING PARAMETER ANALYSIS FOR AERATION DETECTION

As shown in our Pugh chart, we decided to further investigate the feasibility of an aeration detection device by applying a vacuum. This entails taking a sample of the fluid flowing through the system and applying a drop in pressure to separate the entrained and dissolved air from the hydraulic oil. We performed a rigorous engineering design analysis to determine the dimensions, material, and components for our system. Many engineering changes have been made since the development of the design presented in this section. Please refer to Section 11 for all engineering change notices.

8.1 Measuring Percentage of Dissolved and Entrained Air in Sample

To measure the percentage of dissolved air and entrained air in our sample we developed a technique that requires applying a vacuum force. Reducing the pressure in the sample will cause the gas (both entrained and dissolved) and liquid to separate through Henry's Law. In the aerated mixture, both the entrained and dissolved nitrogen molecules make up a certain percentage of the volume. With the air and oil separated, we will be able to determine the amount of air that was in originally aerated in the oil as shown by the following equations:

$$\%\ \text{Air in Oil} = 1 - \frac{\text{Volume of Pure Oil} + \text{Expanded Gas}}{\text{Volume of Pure Oil} + \text{Volume of Entrained Air} + \text{Volume of Dissolved Air}} = \frac{\text{Change in Volume of Oil.}}{\text{Original Volume of Oil}}$$

We can obtain this information by measuring the piston location and displacement as well as the level of the oil relative to the top of the cylinder. These distances are shown in the Figure 11.

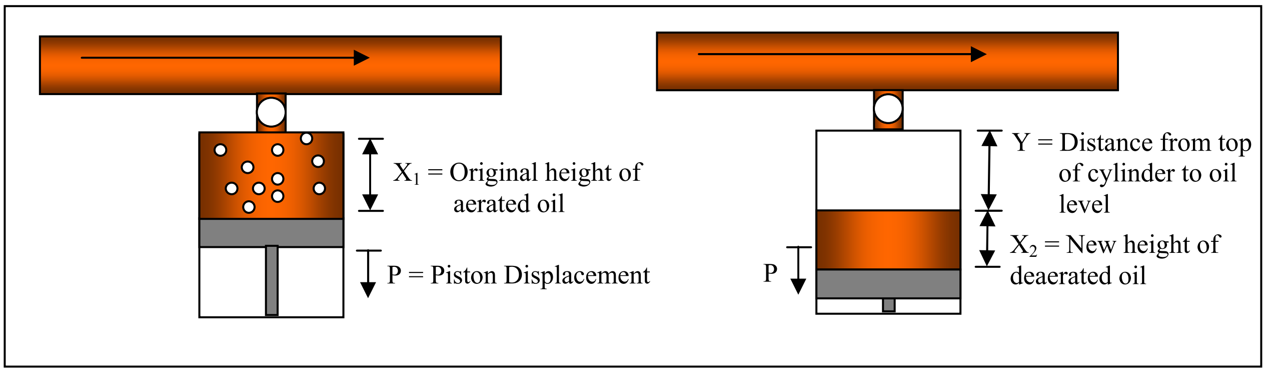


Figure 11: Measurement of Fluid to Determine Percentage of Air in Oil

We can calculate the change in volume of the oil by using the measurements of P and Y as shown in Figure 11 by Equation 5. To measure P and Y we will use a cable extension transducer and a photoelectric sensor, respectively.

$$\Delta X = P - Y \tag{5}$$

Taking this difference allows us to neglect the possible expanded volume of air if we apply a great enough vacuum force (ideal gas law). Thus, ΔX represents the amount of air that was present in the oil. Please refer to Section 8.6 for requirements for this measurement to work properly. We strongly believe that obtaining these measurements will allow us to determine the percent volume of nitrogen in the fluid.

8.2 Development of Device Dimensional Parameters

We began sizing our piston and cylinder to obtain a balance between length, diameter, and applied pressure. Minimizing the diameter of the cylinder has the benefits of minimizing the required force to obtain a desired pressure (*Force = Pressure*Cross Sectional Area*). A smaller diameter is also less sensitive to vehicle angle (gravitational force). The sensitivity to vehicle angle is an important consideration due to our need to accurately measure fluid level. For ease of material selection, we decided to choose a pipe inner diameter that is readily available on the market and would allow us to fit all of our measuring components at each end. We decided to use a 2 inch inner diameter pipe for our cylinder housing. The limiting factor for this decision was the size of our photoelectric sensor which will be placed on the top.

The length of the cylinder will affect the accuracy of our measurements greatly. As shown in Figure 12, the percent volume of air (V_1) that is in the sampled volume of fluid (V_0) is equal to the ratio of the height of the air (H') to the height of both the air and oil (H). Thus, when measuring a small percentage of air in the sample, a longer cylinder will have a greater H'. However, a longer cylinder requires a longer piston shaft which protrudes out of the cylinder when extended. Since the ADS will be placed on a vehicle we also need to consider packaging constraints. Our goal is to keep the length of the ADS when the piston is fully extended to less than 2 feet.

- $V_0 = \pi R^2 * H$
- $V_1 = \pi R^2 * H'$
- $V_1 / V_0 = (\pi R^2 * H') / (\pi R^2 * H)$
- $V_1 / V_0 = H' / H$

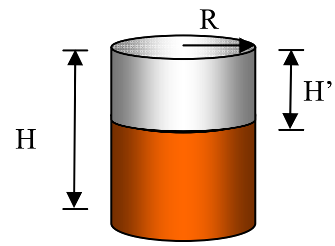


Figure 12: Proportion of Air in Volume Related to Height Ratio

To determine the height of our cylinder, we needed to first determine the required height of the initial fluid sample. This is determined from the resolution of our fluid level measuring device and the smallest percentage of air we desire to detect. The resolution of our photoelectric sensor is 0.1mm (0.00393 in) and we would like to detect at least 0.5% aeration. Based on the logic shown in Equation 6, we need the height of our sample to be approximately 4 inches. Equation 6 shows that if there is 0.5% volume air in our 4 inch sample, then the height difference between the aerated and deaerated fluid sample will be 0.00393 inches, the smallest change in height that the photoelectric sensor can detect. We also need to take into account the size of our piston head; therefore our cylinder length should be 5-6 inches.

$$0.5\%\ \text{volume air} = 0.1\text{mm}\ (0.00393\ \text{in.}) \Rightarrow 100\%\ \text{volume air} = 10\text{mm}\ (7.87\ \text{in.}) \qquad (6)$$

8.3 Force Parameters

The amount of pressure required to separate the entrained and dissolved gas from the hydraulic oil can be determined by Henry's Law. This simplified version of this law states that "the amount of gas absorbed by a liquid is directly proportional to the partial pressure of that gas in contact with the liquid and the solubility coefficient of that gas in the particular fluid", as shown below [19].

$$P = kC$$

P = Partial Pressure of Gas
k = Henry's Law Constant
C = Concentration of Dissolved Gas

The value of k is the same for the same gas, liquid, and temperature combination. As long as the temperature remains constant, the concentration to pressure ratio is the same.

$$\frac{C_1}{P_1} = \frac{C_2}{P_2} \Rightarrow \frac{C_2}{C_1} = \frac{P_2}{P_1} \qquad (7)$$

If we make certain assumptions, we can use Equation 7 to determine the pressure needed to apply a vacuum force. If we have a greater initial concentration, the equation shows that we will need to apply a smaller pressure compared to if we had a smaller initial concentration. Thus, we will turn to our desired resolution for our detection system because it is the smallest concentration that we will need to detect. We want to detect 0.1% concentration of air. Assuming that the cylinder is rigid and non-deformable, when the cylinder is closed off from the flowing fluid, the pressure inside of the cylinder will be atmospheric (14.69psi). This results in a required final pressure of 0.2938psi. This is a pressure drop of 14.4psi. This relates to the force required to actuate the piston. Multiplying the pressure by the area of the piston, we require a 98.96 lb. force for our chosen cylinder size.

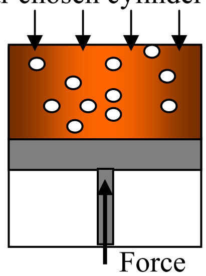


Figure 12: Force Applied to Piston is Equal to Pressure Times Piston Area

We also determined the force required to push the fluid back into the system. From meetings with Professor Kurabayashi, we found out that this can be calculated by assuming that the motion is slow and that the fluid is static. The required force is affected by the weight of the fluid (fluid density and height) and the cross sectional area of the cylinder. The weight of our fluid can be neglected because our volume is so small. Thus, if the fluid in the hydraulic system is pressurized at 200psi, the force required to put the sample of fluid back into the hydraulic line is 628 lbs. The greatest pressure that our piston will need to withstand is 200psi. This also occurs when the solenoid valve is open and a fluid sample is being drawn.

8.4 Piston Actuation Mechanism Parameters

With the amount of force required to actuate the piston calculated (628 lbs), we designed the mechanism to operate the linear motion of the piston. We chose to use a rack and pinion to translate the rotational motion of an electric motor into linear motion of the piston. This method will allow us to incorporate a mechanical advantage, use an electric motor with less torque, and position the piston precisely. We have decided to use a shaft diameter of 0.75 inch so that we can place a 0.1875 $inch^2$ rack with a 14-1/2 degree pressure angle within it similar to Figure 13.

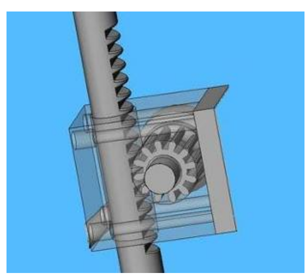


Figure 13: Example of Rack Integrated with Piston Shaft

We chose a gear with the same pitch (24 pitch) and had the smallest available pitch diameter. A smaller gear will require less torque from the motor. The smallest steel pinion gear that we found has a 0.5 inch pitch diameter.

8.4.1 Motor Selection Parameters

Based on the 628 lbs. force required to actuate the piston and the 0.5 inch diameter gear, the force torque required by the motor is 157 in-lbs. For this high torque application, we found many gear drive electric DC motors that can obtain handle this torque as well as run at a low RPM. We also want to incorporate into our final design a motor controller with a feedback loop to precisely control the motion of our motor. This also needs to be considered when choosing a motor.

8.5 Material Selection Parameters

We must select materials that can handle the operating conditions of the Aeration Detection System. This includes the materials of the piston and cylinder. The selected materials must handle the required pressures encountered by the system. They must also have the proper dimensions to carry the given loads. In addition to handling the engineering requirements, the selected materials should be economically reasonable and readily available.

8.5.1 Cylinder Material

We selected Cast Aluminum 195-T6 to make the cylinder. Aluminum is corrosion-resistant, which is desirable for long-term purposes. With a specific weight of 0.100 lb/in^3, it is much lighter than ferrous metals such as stainless steel. Cast Aluminum 195-T6 is a common and readily available material.

To handle the required pressure requirements, with a safety factor of 10, the minimum thickness of the cylinder must be at least 0.083 in. We determined this by modeling the cylinder as a thin-walled pressure vessel. The formulas for the hoop stress, σ_h, and circumferential stress, σ_a, are given in Equations 8 and 9 [22], where p is the internal pressure, r is the inner radius, and t is the thickness of the cylinder.

$$\sigma_h = \frac{pr}{t} \tag{8}$$

$$\sigma_a = \frac{pr}{2t} \tag{9}$$

The internal pressure, *p*, of our system is 200 psi. The inner radius, *r*, is 1 in. We need to determine the minimum thickness, t_{min}, of the cylinder to ensure that the material will not fail. We can define failure as the stress at which the material yields. The yield strength, σ_Y, of Cast Aluminum 195-T6 is 24,000 psi [22]. We substitute these values for σ_h and σ_a in Equations 8 and 9, respectively, and solve for t_{min}. This gives us two values of t_{min}, 0.00833 in and 0.00417 in. The former is for the hoop stress and the latter is for the circumferential stress. We must regard the larger number, 0.00833 in, to be the minimum thickness required for the cylinder, because anything thinner than this will cause the cylinder to yield. Using a safety factor of 10, the minimum thickness of the cylinder must be at least 0.083 in. This ensures that the cylinder will not yield from the internal pressure under regular circumstances.

8.5.2 Cylinder Top Cap Design

The cylinder cap will have a small channel where the fluid level sensor will be embedded, of diameter 7/16 inches. The end will poke into a hole drilled out for fluid exit flow, 11/32 inches in diameter. The ratio of the small exit area to the cylinder area is approximately 1:76. This allows monitoring of when oil has reached the surface much more accurately. Having this small exit channel, of height 1 inch, is equal to being able to detect when the fluid has reached the top of the cylinder within 0.013 inches. The cap should be part of the aluminum casting with the rest of the cylinder and machined afterwards.

8.6 Requirements for System Functionality and Concerns with Design

In order for our system to function properly, there are several requirements that must be met. Our cylinder must be completely filled with fluid and there cannot be any air inside of it initially. Having air in the system introduces issues with properly measuring our distances to determine the original percentage of air in the oil. Also, we must ensure that all tested fluid and air must be ejected at the end of our diagnostic test

The piston will be used to control the fluid flow into the cylinder chamber. Otherwise, the valve has the ability to cause a pressure drop on the incoming fluid. This reduction in pressure can separate the air from the liquid before any measurements are taken; this outcome is undesired. Our design requires that when the valve is opened to allow a sample of fluid to be taken, the piston is located at the same height of the valve. The piston will then slowly draw the sample to prevent any cavitation.

9. FLUID CONDITIONING SYSTEM FINAL DESIGN DESCRIPTION

From our concept selection Pugh charts and our component selection PVA analyses, we have determined the components and location for our system that best meet our customer requirements. We have selected a Hydrotechnik Return Line KF3 Filter and Hydac EDL-4 Air Cooler and have placed them in serial configuration.

9.1 Filtering and Cooling System Components and Locations

Through analysis, we discovered that it is beneficial to place the filter before the cooler. Due to the cooler's intricate flow, having clean fluid will prevent wear on the internal tubing of the filter as well as to promote better cooling since the fluid has fewer contaminants. Having particles in the fluid can actually cause the fluid to heat up as it flows through a tube configuration similar to that of the cooler and the contaminants can affect the thermal conductivity of the fluid resulting in less effective cooling. We found no benefits of placing the cooler before the filter because the filter performance is independent of fluid temperature. Our schematic for our configuration can be seen in Figure 14. We will utilize the same tubing as the rest of the vehicle, and we will purchase the check valves, thermostatic relief valve, and pressure relief valve from the same supplier.

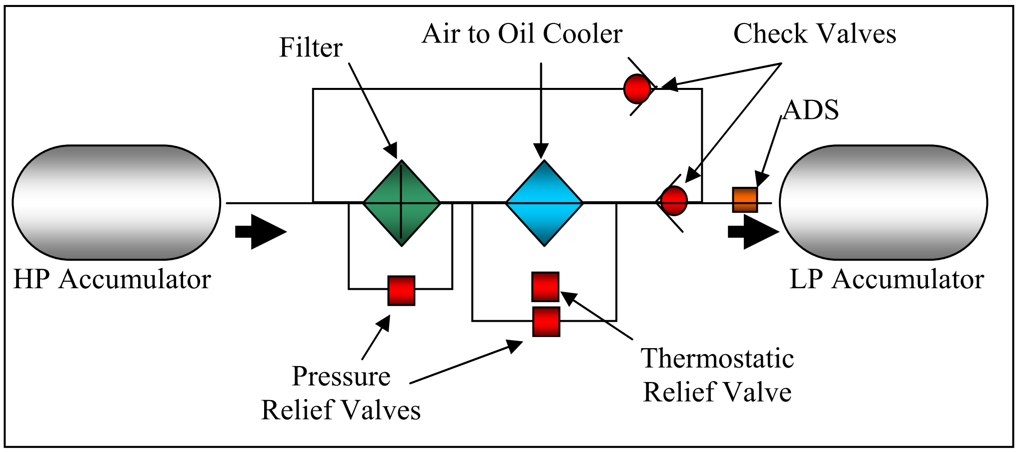


Figure 14: Schematic of Fluid Conditioning System

9.2 Control System Functions

In order for our system to function properly, we need to place check valves and relief valves at various locations to control our system. Several things that we took into account in our design were:

- Filters and cools the fluid only when flowing from high pressure accumulator to low pressure accumulator (during acceleration and steady state)
- Check valves ensure that there is no backwards flow into the system when the vehicle braking (fluid flows from low pressure accumulator to high pressure accumulator.
- When cooling is not needed, we have the ability to bypass it.
- We must filter as often as possible as long as there is no "backwash"
- If the pressure is too great in our system (heavy acceleration or clogged components), we can bypass it with a relief valve.

This configuration meets our customer requirements the best, but there are some downsides to our design's control system:

- Requires use of many bypass lines which add weight and complexity to the system
- The extensive use of valves can lead to cavitation from pressure drops
- Need to calibrate and configure the thermostatic relief valve and pressure relief valve to desired settings

9.2.1 Control System for Cooler

The purpose of the control system for the cooler is to bypass the cooling element when the oil is at a safe temperature, and divert flow from the cooler at high flow rates. Allowing cool oil to enter the cooler is unnecessary and will cause unwarranted pressure drops. Allowing the full flow fluid to enter the cooler can damage the cooler because the maximum flow rate that the cooler can handle is 45 GPM. However, the average flow rate in the Challenge X vehicle is approximately 50 GPM, and at times there can be bursts of flow up to 80 GPM.

We purchased the Hydac ELD-4 with an optional thermal relief valve. This controls the passage of the fluid through the cooling element. The fluid bypasses the cooling element when the valve is open, and enters the cooling element when the valve is closed. The thermal relief valve is completely open at temperatures lower than 113° F. The valve starts closing at 113° F, sending some of the flow through the cooler, and is completely closed at 131° F, sending the full flow through the cooler. This maintains the temperature at approximately 120° F, the desired operating temperature for hydraulic fluid [18]. The fluid should not reach the maximum allowable temperature of 150° F.

The Hydac ELD-4 also has an optional pressure relief valve. This controls the amount of fluid flow through the cooler. The full fluid flow enters the cooler when the valve is closed, and as the valve opens, the flow can be partially bypassed around the cooler. The pressure relief valve is completely closed at pressures lower than 3 bars, sending the full fluid flow through the cooler. As the pressure increases over 3 bars, the bypass valve opens, so that the cooler only handles its maximum allowable flow rate. This way, even if the flow rate in the vehicle exceeds 45 GPM, the flow rate through the cooler will not reach a dangerous level.

9.2.2 Control System for Filter

The control system for the filter includes only a pressure bypass valve. Fluid will bypass the filter through a spring loaded valve when the pressure drop through the filter is greater then 15 psi. The bypass valve is important because a pressure drop through the filter greater than 15 psi in addition to the pressure drop through the cooler will affect the performance of the hydraulic system [4].

The Hydrotechnik KF3 filter comes standard with a spring that will allow the fluid to bypass at 30 psid. However, we were able to order it with a different valve spring so that it will bypass at 15 psid. We ordered the filter through J.E. Myles Incorporated out of Troy, Michigan and we corresponded with Colin Myles. He verified that the filter we chose is indeed the correct filter for our application.

10 AERATION DETECTION SYSTEM INITIAL DESIGN DESCRIPTION

We developed an aeration detection system for the Challenge X vehicle (can be used in any hydraulic hybrid vehicles) that will be able to measure the percentage of air entrained and dissolved in the hydraulic fluid to determine the extent of the nitrogen leakage problem. This is our initial design which we used to design our prototype.

10.1 Aeration Detection System

Our initial design encompasses all of our engineering parameters described in the previous section. It utilizes components such as:

- T-junction solenoid valve to control the sampling of hydraulic fluid
- Photoelectric sensor to locate fluid level
- Cable-extension transducer sensor to measure piston displacement
- DC electric gear motor to actuate the piston
- Sealed piston to apply vacuum on fluid sample
- Rack and pinion to translate rotational motion from motor into linear motion

A SolidWorks CAD model of our ADS is shown below with all of our major components labeled.

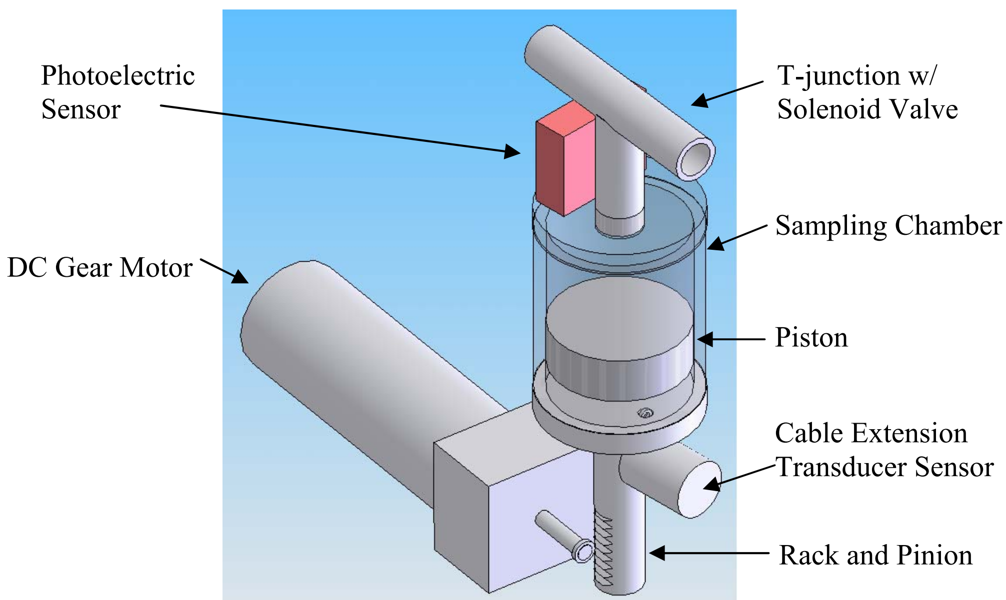


Figure 15: Isometric View of our ADS Design

Our ADS is designed to operate when the vehicle is on level ground and is stationary (hydraulic fluid not flowing but under pressure from accumulators). The vehicle must be on level ground for the device to obtain an accurate fluid level, and there will be lower likelihood of obtaining cavitations and sloshing of the fluid when sampling if the vehicle is not moving and fluid not flowing. Sampling will take place once per hour when the vehicle is in use and stationary. The following is a list of the operation steps of the device:

1. Piston is located against top of sampling chamber near valve
2. Solenoid valve opens and the piston draws sample of fluid to mid height of chamber
3. Solenoid valve closes and the piston applies vacuum 35psi vacuum inside of chamber
4. Cable extension transducer measures displacement of piston
5. After waiting 30 seconds for surface bubbles to settle, photoelectric sensor measures fluid height
6. All data is recorded and interfaced to computer
7. Solenoid valve opens and fluid is pushed back into system by the piston

10.2 Aeration Detection Sensor Dimensions

Our engineering parameter analysis allowed us to determine our key dimensions. Below are dimensioned versions of our CAD drawing. For further explanation behind these key dimensions, please refer to Section 8

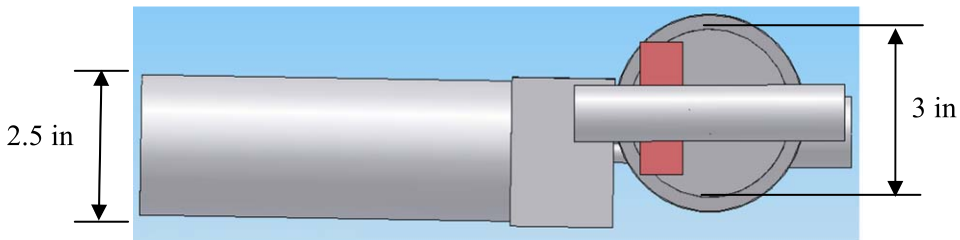


Figure 16: Dimensioned Top View of ADS Design

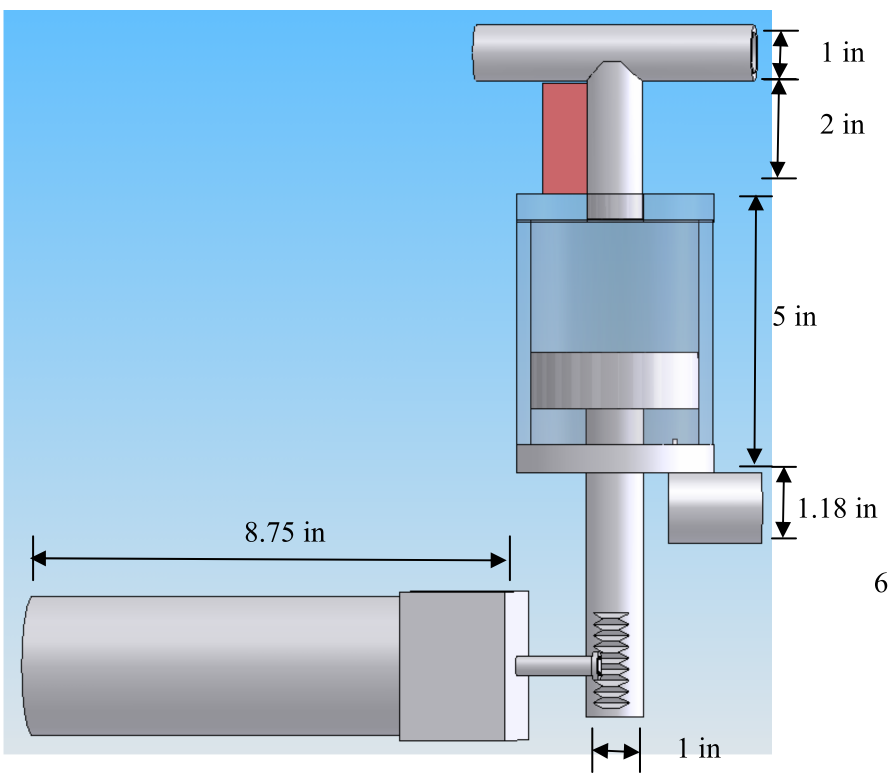


Figure 17: Dimensioned Front View of ADS Design

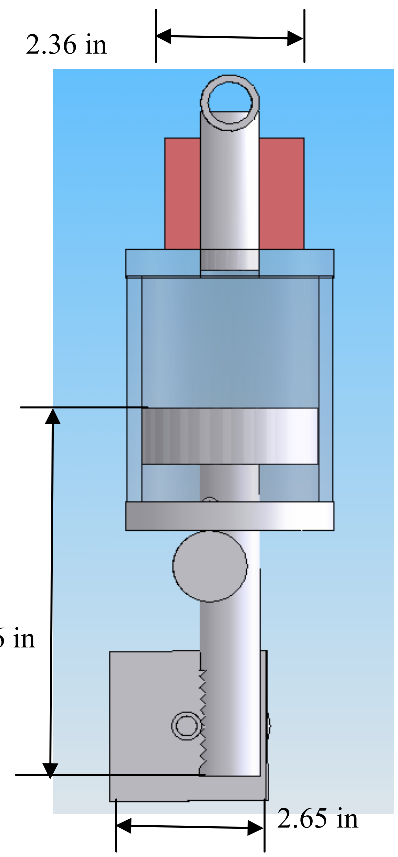


Figure 18: Dimensioned Right-Side View of ADS Design

10.2.1 Components for Initial Design
Table 7 lists both our major off the shelf and in house components for our initial design.

Table 7: Components Used in the Initial Design of ADS

Part	Manufacturer	Model	Details	Price
Cylinder Housing	McMaster-Carr	9056K241	Alloy 6061 Aluminum Round Tube 3-1/2" Od, 3" Id, .250" Wall Thickness, 1' Length	$33.88
Piston	McMaster-Carr	9035K11	Alloy 7075 Aluminum Disc 3" Diameter, .500" Thick	$11.85
Pinion	McMaster-Carr	6325K89	Steel Plain Bore 14-1/2 Deg Spur Gear 32 Pitch, 16 Teeth, 0.5" Pitch Dia, 3/16" Bore	$9.39
Rack	McMaster-Carr	6295K11	Steel 14-1/2 Deg Pressure Angle Gear Rack 32 Pitch, 3/16" Face Width, 3/16" H O'all, 2' Length	$19.17
Solenoid Valve	McMaster-Carr	4738K177	Brass Solenoid Valve W/ Buna-N Diaphragm 1" NPT Female, 120 Vac, 230psi max	$106.66
DC Gear Motor	McMaster-Carr	6470K54	Parallel-Shaft DC Gearmotor 1/2 hp, 60 rpm, 476 In-lbs Torque	$536.51
Photoelectric Sensor	Banner	Q50	LED, 60x20x50mm, resolution is 0.25mm	TBD
Cable Extension Transducer Sensor	Micro-Epsilon	MK30	range of 150 mm resolution is 0.1 mm	TBD
Piston Shaft	McMaster-Carr	8974K37	Alloy 6061 Aluminum Rod 1" Diameter X 6' Length	$27.15

10.3 Methods of Measuring Displacement and Oil Level
For our calculations, we need to take accurate measurements of the piston displacement and the level of hydraulic fluid within several microns. A variety of methods of measuring distances are available on the market. These include different types of calipers, micrometers, depth gauges, linear position sensors, and optical sensors. We needed to select the best measurement method applicable to our purposes and constraints.

10.3.1 Piston Displacement Measured with Cable-Extension Transducer
To measure the displacement of the piston, we selected the Micro-Epsilon WPS-150 MK30 cable-extension transducer. The datasheet for this device can be found in the Appendix. This device attaches a cable to a moveable object. As the object moves, the cable extends and the transducer produces an electrical signal proportional to the cable's linear extension. The output is analog, and can be used to determine how far the object moved [20].

There are many advantages to using a cable-extension transducer over other displacement measuring methods. These systems are compact, easy to mount, offer high accuracies and resolutions. Their construction is designed for mobile applications and can withstand difficult ambient conditions. They are also economical compared to other measurement options.

The most important parameters that went into our selection process were the maximum usable range and the resolution. The range of the transducer had to be sufficient to measure the maximum possible displacement of the piston, but excessive ranges raise the price of the transducer. The WPS-150 MK30 has a range of 500 mm (19.68 inches), which is sufficient to measure the displacement of the piston. The resolution is 0.1 mm (0.00393 inches), which is ample for our purposes. Additionally, this transducer is compact and easy to mount. It measures 52 X 45.5 X 42.5 mm. and weighs only 45 g [21].

10.3.2 Method of Measuring Oil Level
The oil level in our initial design was to be measured with a photoelectric sensor. The sensor must be able to measure a range of 20 mm with a maximum resolution of 0.5 mm. Originally a laser was going to be used, because the resolution is very high (measured in microns), but it was too expensive (~$1000). A

more affordable LED-sensor can measure a range of 100 mm with a resolution of 0.25 – 0.5 mm (Banner – Model Q50). The sensor works by reflecting back light off the surface of the oil at an angle and calculates the gap. Because there will need to be a 20 – 50 mm buffer zone, the sensor was to be mounted slightly above the surface of the cylinder, which is made of transparent Plexiglas to allow light through.

Other sensors were considered, but were determined to not be useful. A ultrasonic proximity sensor would be precise enough, but does not work in vacuums. As mentioned above, a laser was determined to be too expensive. A floating magnet was also considered, but then the plunger would not be able to push all of the oil out.

10.4 Valve to Control Fluid Sampling

A solenoid valve will be used to permit fluid to enter the ADS. The solenoid valve will be a normally closed, small valve. When fluid is to enter the ADS, a current will be sent to the solenoid valve. This will power a coil to create a magnetic field, opening the valve and allowing fluid through. However, fluid will not be able to fill the ADS until the plunger is lowered, which will be done slowly so cavitation is avoided by regulating the flow through the valve. This will also help to avoid interrupting the main flow in the system, should it be running. After the ADS fills to the desired level, the solenoid valve will close again, thus sealing the system and permitting a vacuum to be created. The size of the solenoid valve should be small, such that the volume at the exit area of the valve connected to the ADS is minimized. This is important because as the vacuum is created, air will first collect in this area before inside the ADS, where it can be measured. We chose a McMaster-Carr brass solenoid valve with a Buna-N diagram, 1” diameter and can handle 230psi

10.5 Aeration Detection Sensor Location and Configuration

We decided not to place our Aeration Detection System as part of our fluid conditioning system since it does not actually condition the fluid; rather it acts as a passive monitoring device that can also be placed parallel to the hydraulic system. The benefits of placing the ADS after the fluid conditioning system as shown in Figure 9 are:

- Low pressure side of the system
- Any aeration or cavitation caused by pressure drops from our conditioning system will be detected before cycling through the other components
- Placing it downstream from the filter ensures that the ADS will not accidentally detect dirt particles for air bubbles.

One major disadvantage for placing the ADS after the fluid conditioning system is that the fluid will be at a lower temperature than it was before the cooler. As mentioned earlier in this report, according to Le Chatelier’s Principle, as the temperature of the fluid increases, it is easier for the gas to come out of solution. Thus, placing the ADS after the cooler will hinder the ability of our aeration detection system to pull the gas out of the liquid.

The ADS cylinder should be mounted vertically so that the fluid is above the piston, similar to Figure 15. Since the unit has a length of 2.5 feet when fully extended, it would be preferred to place it inside of the engine compartment where it can be protected from any road debris.

11. PROTOTYPE DESCRIPTION

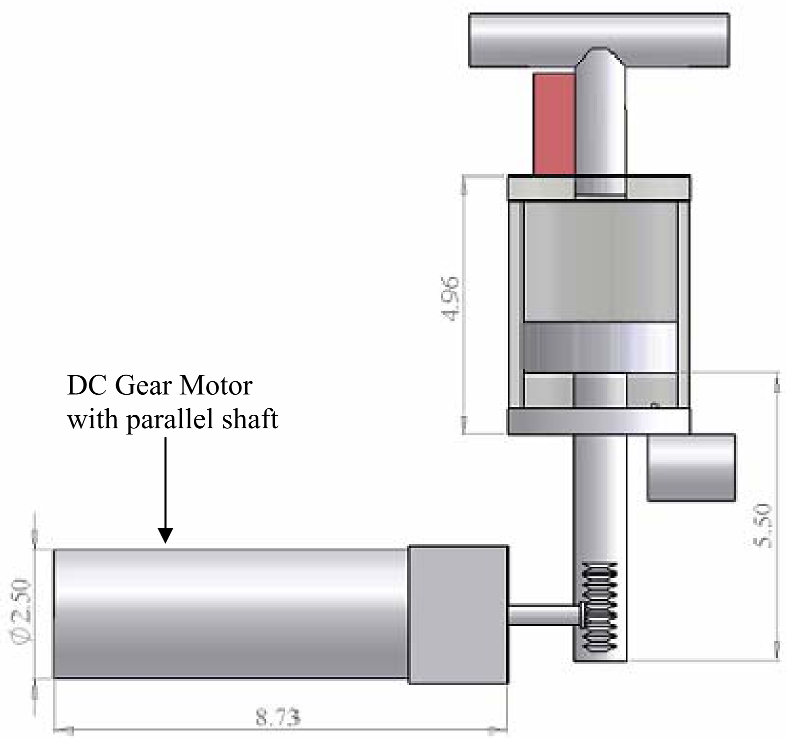
Many engineering changes were made to our ADS between our final design and our prototype. The prototype was meant to be a proof of concept, so it did not need to operate under the same conditions or be made with the same material that would be seen in the vehicle. Also, upon further evaluation we were able to simplify our design concept.

11.1 Changes to Prototype Mechanism

WAS:	IS:
1. Piston is flush against the top of sampling chamber near valve 2. Solenoid valve opens and the piston draws a fluid sample 3. Solenoid valve closes and cable extension transducer measures displacement of piston 4. Piston applies a vacuum force inside chamber 5. After waiting 30 seconds for dearation to take place, photoelectric sensor measures fluid height 6. Solenoid valve opens and fluid is pushed back into system by the piston	1. Piston is flush against the top of sampling chamber near valve 2. Solenoid valve opens and the piston draws a fluid sample 3. Solenoid valve closes and cable extension transducer measures height of the aerated fluid. 4. Piston applies vacuum force inside chamber 5. After waiting a delayed period for deaeration to take place, directional valve turns to atmosphere, solenoid valve opens, and piston pushes air out of the cylinder until fluid touches fluid level sensor. 6. Solenoid valve closes; directional valve turns to the flowing fluid, and cable extension transducer measures height of the dearated fluid. 7. Solenoid valve opens and fluid is pushed back into system by the piston.

Figure 19: Engineering change notice regarding the design concept and ADS process

WAS:

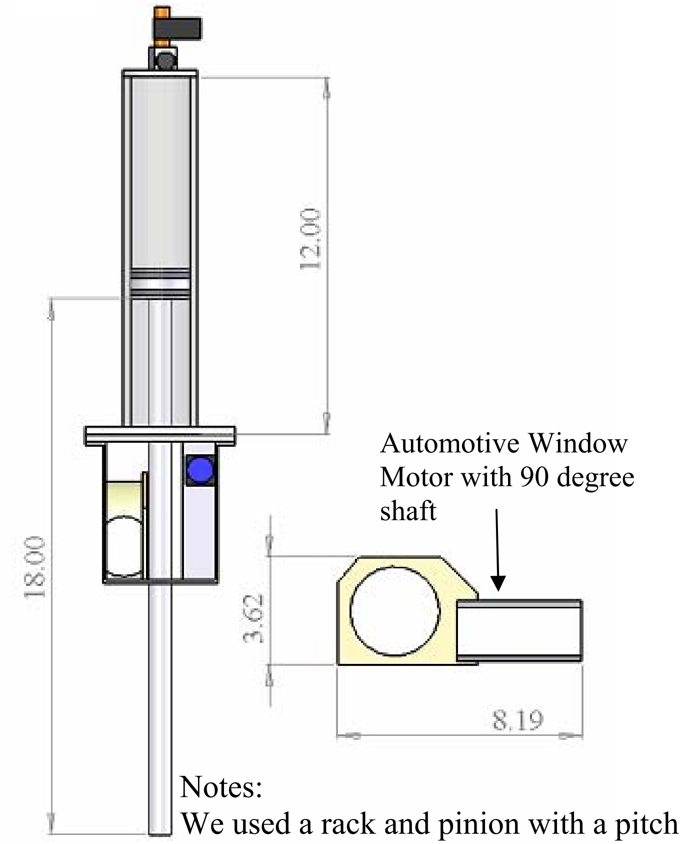


Notes:
We changed the cylinder length because removing the photoelectric sensor from our design changed the resolution of our fluid level measuring device. We changed the length of the rod accordingly.

We used an acrylic cylinder for the prototype instead of the aluminum cylinder we designed so that we could see our ADS work.

We pressurized the fluid going to the ADS to 50psi instead of the 200psi that would be seen on the vehicle to ensure safety and prevent a mess. This changed the force-torque requirement for the motor from 157in.-lb to 40in.-lb. For this reason we used an automotive motor with a 90 degree shaft instead of the DC gear motor chosen for the final design.

IS:



Notes:
We used a rack and pinion with a pitch of 24 instead of the original 32 because the bore size was too small to fit the shaft of our motor.

We used a solid piece of aluminum and O-rings for our piston head instead of sandwiching nitrile rubber between multiple pieces of aluminum to simplify the design and ensure a rigid seal.

Figure 20: Multiple engineering change notices were made between the final design and the prototype

11.1.1 Photoelectric Sensor Removed from Design
We realized that we would not be able to manufacture a vacuum sealed prototype and that any air leaks into the system would lead to an inaccurate measurement of Y in Figure 11. Instead of using the photoelectric sensor, we decided to eject all the air inside the cylinder after we separate it from the fluid, and then use the cable-extension transducer to measure the height of the deaerated fluid, X_2 in Figure 11. To do this we had to connect a directional valve to our solenoid valve so that we could eject the air to atmosphere. We also had to add an optical fluid level sensor to sense when the fluid touched it, indicating that all of the air was ejected. We made all changes as a team and they were approved by our sponsors. Figure 19 shows how the change in components change

11.1.2 Height and Material of Cylinder Changed
Since we eliminated the photoelectric sensor, the length of our cylinder is now based on the resolution of the cable extension transducer, 2mm (0.0787 in.). This resolution is different than the resolution previously reported for the cable-extension transducer. In automating the ADS (See Section 11.2), the analog to digital conversion decreased the resolution of our measuring device because of the number of bits used.

We found that a safe concentration of air range is between 1% and 6%. Therefore we would now like to detect at least 1% aeration. We used the same logic as before to determine that the height of the initial fluid sample required in order for our prototype to detect a 1% volume of air. Our calculations show that the initial fluid height needs to be 8in. We also need to account for the height of the piston head 1in. and the distance the piston may travel while creating a vacuum. Accounting for these heights leads to a cylinder length of 12in.

Since the prototype is meant to be used as a proof of concept, is beneficial to see inside the cylinder during the aeration detection process. For this reason, we used an acrylic pipe as the cylinder with an inner diameter of 2 inches instead of the aluminum cylinder in the original design.

11.1.3 Maximum Fluid Pressure Changed to 50psi
For the prototype, we borrowed a small accumulator from the EPA that could be pressurized to 3000psi. However, to pressurize the accumulator we used a bicycle pump that could produce a maximum pressure of 100psi. To ensure our safety and prevent a mess we decided to pressurize the accumulator to only 50psi. We then recalculated the maximum force our piston needed to withstand to be 157 lbs. This new pressure changes the force-torque required for the motor to produce to 40 in-lbs for our prototype.

Keeping in mind that we would be connecting the motor to a controller, we searched for motors that could be run on a low voltage and draw a small current. We found that an automatic car window motor would meet all of our requirements

11.1.4 Pitch of Rack and Pinion Changed to 24
The bore of the pinion originally chosen was too small to fit on the shaft of the motor. We used a pinion with a bore one size larger for our prototype. This changed the pitch to 24 but kept a pitch diameter of 0.5 in. We used a rack that also had a pitch of 24.

11.1.5 Piston Head Redesigned
Upon further evaluation of the sandwich design for the piston head and nitrile seals, we realized that it was not the simplest possible design. It would be difficult to cut nitrile rubber perfectly circular such that a perfect seal could be produced and multiple layers of aluminum would increase the complexity of our design.

We changed our design so that the head is made of one solid piece of aluminum with embedded O-rings to create a seal. There are O-rings on the market designed specifically for piston cylinder applications. We chose one that had a 2in. outer diameter to correspond to the inner diameter of the cylinder. In the solid piece of aluminum we used a lathe to groove two slots for two O-rings to be placed such that they were not stretched in tension. We were careful to check that the seal created did not let fluid through, but also allowed the piston to move freely (without excessive friction) inside the cylinder.

11.2 Electronics of Prototype

In our final design we mentioned that we wanted to automate the aeration detection process, but we did not develop a design for automation. At that time, we did not know how we could implement our ideas. After meeting with Professor Gillespie, we learned that we could control our motor using an OOPic, the programmable microprocessor shown in Figure 21.

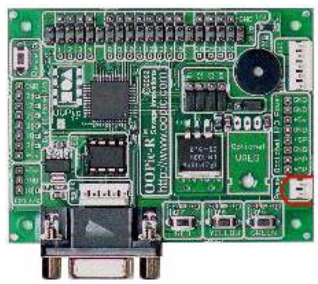


Figure 21: OOPic used to automate ADS

In order to use the OOPic all the hardware had to be physically interfaced to the OOPic. This required some extra components in order to correctly control all the components for the automated process. Figure XX is a schematic of how all hardware was interfaced with the OOPic.

11.2.1 Amplifier Needed to Interface Motor

We could not control the motor directly through the OOPic. The motor required at least 5VDC and 3A to operate and the OOPic supplies a maximum of 5VDC and 0.25A. We used a two channel amplifier that amplified the power from the OOPic in order to operate and control the direction of the motor.

The direction of the motor is controlled by the sign of the voltage sent to the motor. When the voltage is positive (negative) the motor spins clockwise (counterclockwise). In order to control the direction of the motor we needed to create a floating ground. Usually all voltages are measured with respect to ground, or a reference voltage of 0V. A floating ground changes the reference voltage. By connecting two resistors of the same resistance in series, we created a voltage divider that divided the output voltage from the OOPic in half, creating a reference voltage of 2.5VDC. We connected the output of the voltage divider to the negative reference input on the amplifier. We used a pulse width modulation output from the OOPic as the positive reference input on the amplifier. Pulse width modulation is a method predefined within the OOPic that allows us to specify the voltage (between 0Vand 5VDC) we output from the OOPic. When we output a 5V signal from the OOPic the amplifier will amplify a +2.5V signal and turn the motor clockwise. When we output a 0V signal, the amplifier will amplify a -2.5V signal and turn the motor counterclockwise.

11.2.2 Powering the OOPic and Amplifier

Both the OOPic and the amplifier have to be powered in order to operate. This requires an external power source. The OOPic needs a 5V power supply and for our purpose the amplifier needs 30V to operate properly. We used one of the power supplies available in the X50 lab to power both devices. These power supplies have 5V, -15V, and +15V output terminals, which allows us to use one power supply to power both components. We were sure to check that the output voltages were indeed the voltages that they were labeled.

11.2.3 Relay needed to Interface Solenoid Valve

We used a 120VAC solenoid valve from McMaster-Carr with model number 7994K55. Since the valve operates on 120VAC and draws 0.33A, we could not control the valve directly through the OOPic. We needed to find a relay that could be controlled by the OOPic and provide 120VAC while handling a current draw of 0.33A. A relay works like a switch. When it is powered, it completes the circuit and 120VAC from the wall is sent to the valve. We were able to find a solid state relay in the Digikey catalog with model number Z903-ND that met the requirements. The data sheet for this relay can be found in the Appendix.

11.2.4 Fluid Level Sensor and Cable Extension Transducer Interfaced Directly

The fluid level sensor and the cable extension transducer were both interfaced directly with the OOPic. This was possible components could be powered by the 5VDC provided by the OOPic. There is a special Input/Output area of the OOPic where the pins are arranged such that one row of pins will power a device and take an input from the device. This can be seen in the figure in Appendix F.

11.3 Electronic Automated Control of Prototype

Using the OOPic programmable microprocessor described above, we were able to interface the hardware of the prototype to a computer and fully automate the control of the prototype. We programmed the OOPic using the Visual Basic language. By taking inputs from the cable extension transducer and the optical sensor, the OOPic is capable of controlling the behavior of the prototype with its outputs to the motor and the solenoid valve.

11.3.1 Hardware Interfaced to Software by Object-Oriented Programming

OOPic programming is object-oriented. Every piece of hardware in the prototype is declared as an object at the beginning of the program, and each object has an associated set of properties and methods that the OOPic can use to read and control the hardware. Table 8 lists the physical hardware in our prototype and their associated objects in the program.

Table 8: Prototype hardware and associated objects in OOPic program.

Hardware	OOPic Object	Data Range	Description
Cable extension transducer	Analog to Digital Input/Output Line	0 - 255	Reads voltage signal from transducer and converts to digital signal
Optical Sensor	Digital Input/Output Line	0 – 1	Reads signal from optical sensor triggered by liquid
DC Motor	Pulse Width Modulator	0 – 255	Controls speed and direction of motor
Solenoid valve	Digital Input/Output Line	0 – 1	Controls opening and closing of solenoid valve

By declaring objects in the program for the hardware, we can now interface the hardware with the software. We can read inputs such as displacement measurements from the cable extension transducer and the state of the optical sensor. For the cable extension transducer a value of 255 corresponds to a full range displacement of 500 mm, and a value of 0 corresponds to no displacement. A signal of 1 from the optical sensor means that the sensor is dry, and a signal of 0 means that liquid is touching the sensor. We can also control output such as the speed and direction of the DC motor and the state of the solenoid valve. For the DC motor, a value of 255 corresponds to a voltage of +2.5 V, and a value of 0 corresponds to a voltage of -2.5 V. By setting the value to be 125 we can turn the motor off. For the solenoid valve, we close the valve by sending a value of 0, and open it by sending a value of 1.

11.3.2 Electronic Control Program Description

The control of the prototype consists of four major steps: an initial draw of aerated fluid into the cylinder, an application of a pressure drop onto the aerated fluid to take air out of solution, an ejection of the removed air into the atmosphere, and finally an ejection of the deaerated fluid into the hydraulic line. We programmed the OOPic to perform these functions automatically. An overview of the program is given below, and the full programming script is in Appendix E.

At the beginning of the experiment, the piston head is positioned at the top of the cylinder. As a first step, the cable extension transducer records and stores the initial position of the piston. The prototype begins taking the initial draw of aerated fluid by opening the solenoid valve and powering the motor so the piston moves downward. During this process, the transducer is continuously measuring the position of the piston and inputting the value to the OOPic. When the piston position has reached a level such that there is a column of 8 inches of aerated fluid in the cylinder, the OOPic signals the solenoid valve to close and the motor to turn off. We now have a cylinder filled with 8 inches of aerated fluid. At this point the transducer measures the height of the aerated fluid and displays the result onto the monitor.

The next step is to apply a vacuum to the aerated fluid to take dissolved air out of solution. With the solenoid valve still closed, the OOPic signals the motor to move the piston down. The transducer takes measurements of the displacement of the piston in time intervals of 0.1 seconds. Using this data, the OOPic can calculate the velocity of the piston. We programmed the OOPic to stop powering the motor when the velocity of the piston is slower than 20 mm/sec. When the velocity of the piston is this slow, it means that a maximum pressure drop that can be applied by the motor has been reached and continuing to drive the piston may burn out the motor. Once the motor has stopped there is a time delay of one minute to allow air to bubble out of the liquid.

Now that there is a volume of air sitting on top of the liquid in the cylinder, we must eject that air out into the atmosphere. The OOPic sends a signal to open the solenoid valve again and power the motor to move the piston up. The piston pushes the air out into the atmosphere. We need to stop the piston when all the air has been removed. The OOPic knows that all the air has been removed when it receives a signal from the optical sensor that liquid has touched it. When the OOPic receives this signal, it immediately closes the solenoid valve and turns off the motor. Now we have a cylinder filled with a certain volume of deaerated fluid. At this point the transducer takes a second measurement of the height of the fluid and displays it on the screen. We now have two displacements displayed on the monitor, one of the height of aerated fluid, and another of the deaerated fluid. By finding the difference between the two, we can determine the volume of air originally dissolved in the fluid.

Although we have now gathered all the data needed for our experiment, we must finish the job by ejecting the deaerated fluid back into the hydraulic line. In this final step of the process, the OOPic signals the solenoid valve to open again and the motor to push the piston upward. The piston continues moving upward until the transducer reads a position that is equal to the original position of the piston at the beginning of the experiment, when the piston was at the top of the cylinder. The OOPic then signals the motor to turn off, and the final state is the same as the initial state: the cylinder is empty and the piston is at the top of the cylinder. If desired, the experiment can now be repeated.

12. PROTOTYPE MANUFACTURING PLAN

Our prototype was manufactured as four main components. We made the piston assembly, the cylinder housing, the top cap for the sensor and valve, and the bottom bracket in separate stages. The following will go into detail the steps we took to manufacture these parts and information on the tools used. The information regarding the parts used in our prototype can be seen in the Bill of Materials in Appendix G.

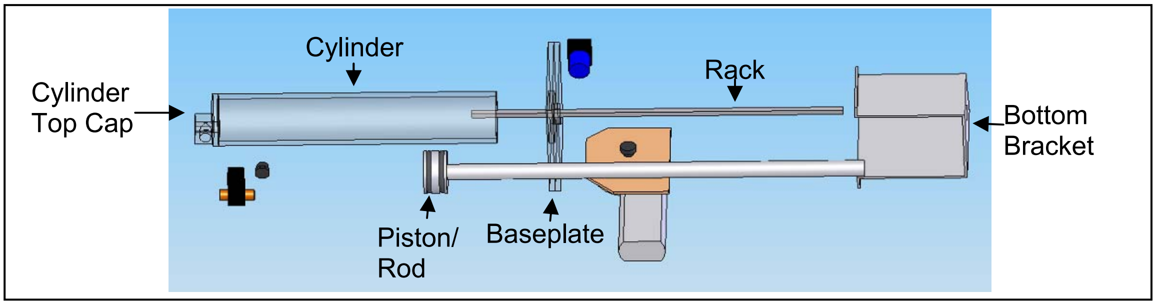


Figure 22: Exploded Diagram of Main Assemblies

12.1 Piston Manufacturing Process

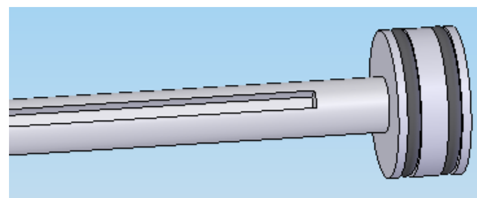


Figure 23: Piston Assembly CAD Dwg.

The manufacture of the piston head requires good accuracy and a tight tolerance level to ensure a strong seal with the surface of the acrylic cylinder. We created the piston/rod assembly with 2-3/8" aluminum stock, ¾" aluminum stock, and rubber o-rings with 0.25" width x 2" O.D. The grooves in the piston head allowed a very slight protrusion of the o-rings from the side to create the seal. Also, the piston head was attached to the rod by using a male to male connector threaded into each part; this allowed for easy disassembly if necessary. We were also every careful in machining down our piston head because we wanted to create a strong seal for our vacuum. In order to connect the cable transducer to the piston head, we had to attach a hook to the bottom surface of the piston to allow for the attachment. The rack was embedded into the rod by milling a 0.25" square slot along the length of the rod. The rack was press fit into this rod and did not require any other means of securing it.

Table 9: Detailed Steps to Manufacture Piston

Step	Action	Machine
1	Insert 2-3/8" Aluminum stock into chuck	Lathe
2	Face off end (600 rpm)	Lathe
3	Drill No 8 bit 3/8" deep for screw	Lathe
4	Tap hole using 1/4 X 20 tap	Lathe
5	Turn stock to a diameter of 2.005" up to 4" from face (600 rpm)	Lathe
6	Use 3/32" groove tool to create two 3/16" deep grooves for o-ring placement	Lathe
7	Cut piston to 1" length	Bandsaw
8	Insert 3/4" Aluminum stock into chuck	Lathe
9	Face off end (600 rpm)	Lathe
10	Drill No. 8 bit 3/8" deep for screw	Lathe
11	Tap hole using 1/4 X 20 tap	Lathe
12	Cut rod to 18" length	Bandsaw
13	Cut 1/4" X 20 screw to join rod and piston	Bandsaw
14	Using 1/4" end mill, cut 17" long and 3/16" deep groove for rack	Mill
15	Cut rack to 17" length	Bandsaw
16	Press fit rack into rod groove	

17	Drill 3/64" hole for transducer hook into bottom of piston head	Drill Press

12.2 Cylinder Manufacturing Process

We needed to prepare the purchased 2" I.D. acrylic tube for use in our prototype. After cutting the tube, we needed to face off the ends to ensure a smooth contact surface to epoxy the top cap. It is important to not to use cutting fluid during this process because it is undesirable to have oil impregnate the freshly cut surface and affect the bonding of the cap.

Table 10: Detailed Steps to Prepare Cylinder

Step	Action	Machine
1	Cut tube to 12" in length	Bandsaw
2	Face off ends using long end mill bit (1000 rpm)	Mill

12.3 Top Cap Manufacturing Process

Due to the design of the top cap and the availability of ¼" thick Plexiglas, manufacturing of the top cap required using epoxy to create our 0.75"x0.75"x1.5" rectangular prism by stacking layers of the material. Our circular and rectangular sections were cut using the laser cutter found in the Machine Shop. We made sure to take into account the 0.005" thickness of the laser itself during our BobCAD modeling to ensure the proper fit.

All drilling was done after the adhesive cured overnight. We clamped the cap in a vise and used the drill press to initially drill pilot holes and then holes of the final diameter. We were very careful to ensure that no cracking or splitting occurred during this step.

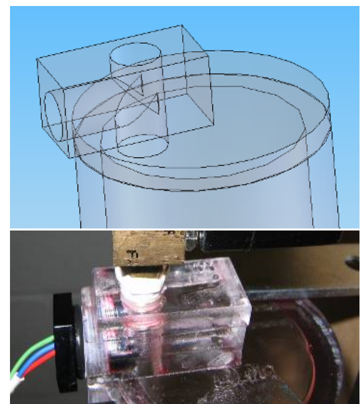


Figure 24: Top Cap (CAD and Actual)

The M12x1.00 tap used to create the threads for the optical sensor was very difficult to find. Al Wilson at the Chemistry Instrument Shop specially ordered this tap for his shop and allowed us to borrow it. However, the 1/8" pipe fitting tap used to tap the hole for the solenoid valve was easily found in the Mechanical Engineering Machine Shop. We had to use extreme caution when threading these two holes because we did not want to split the Plexiglas sandwich.

Table 11: Detailed Steps to Manufacture Cylinder Top Cap

Step	Action	Machine
1	Cut 1/4" plexiglass into 2.5" diameter pattern	Laser Cutter
2	Cut 1/4" plexiglass into 1.5"x0.75 " rectangular pattern (3 times)	Laser Cutter
3	Epoxy stacked plexiglass rectangles onto top of cap	
4	Drill 11/32" drill bit into top of plexiglass rectangle after pilot hole	Drill Press
5	Tap hole with 1/8" NPT	
6	Drill 7/16" drill bit into side of plexiglass rectangle after pilot hole	Drill Press
7	Tap hole with M12x1.00 tap	

12.4 Bottom Bracket Manufacturing Process

The bottom bracket of our design was used to house the motor and cable transducer as well as to act as a guide for the piston rod. The bracket was made out of a 1/16" aluminum plate bent into the shape shown in Figure 25. This bracket was attached to a plexiglass baseplate that consisted of two ¼" thick lasercut sheets.

We began by cutting the two baseplate components in the laser cutter. These two plates were adhered together using a thin epoxy and cured over night before being handled

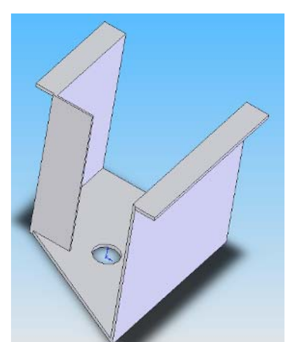


Figure 25: Bottom Bracket CAD Dwg.

We then cut the aluminum plate using the bandsaw and metal sheet cutter into the desired pattern taking into account the radius of bend (0.3") we would be applying to this 1/16" aluminum material (found in Machining Handbook). The hole for the rod guide was drilled into the plate before we bent it into the shape shown in Figure 25 using the metal bending machine.

Once both components were made, we aligned the two rod guide holes and fastened the baseplate to the bottom bracket using ¼" dia screws and nuts. We also drilled holes for the motor mount and cable transducer after we assembled the bottom bracket to the baseplate to ensure proper alignment of these devices relative to other components in the system.

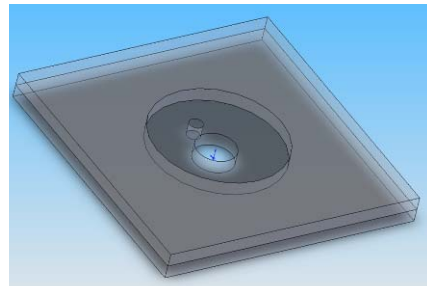


Figure 26: Baseplate CAD Dwg.

Table 12: Detailed Steps to Manufacture Bottom Bracket

Step	Action	Machine
1	Cut 1/4" Plexiglas into 5"x5" square with 2.5" hole pattern	Laser Cutter
2	Cut 1/4" Plexiglas into 5"x5" square with 0.75." hole pattern and 0.25" hole	Laser Cutter
3	Epoxy the two Plexiglas squares together	
4	Cut 1/16" aluminum plate into desired pattern	Bandsaw
5	Drill 3/4" hole into aluminum plate for piston rod alignment	Drill Press
6	Bend aluminum plate into desired pattern	Metal Bender
7	Drill four 1/4" holes in both aluminum and Plexiglas plates to mount together	Drill Press
8	Drill two 1/16" holes in aluminum plate for cable transducer mounting screws	Drill Press
9	Drill three 1/4" holes in aluminum plate for motor mounting screws	Drill Press

12.5 ADS Testing Apparatus

In addition to our ADS, we created an apparatus to hold the device during validation testing. We simply constructed this using ½" medium density fiberboard and L-brackets. We were able to mount the accumulator, pressure gauge, solenoid valve, and switch to the board. We supported the ADS using L-brackets mounted to the board, and these brackets served to apply a force at the top of the cylinder and at the bottom of the baseplate to ensure that these two components maintain a force against each other. Not only did this design eliminate the need to permanently attach the cylinder to the baseplate, but it also allowed us to slide the ADS in and out of the apparatus for any necessary adjustments.

Figure 27: ADS Testing Apparatus

12.6 Comments on Prototype Manufacturing

Although most of the tools we used were readily available at the Mechanical Engineering Machine Shop, we encountered several areas of difficulty in building our prototype. For instance, issues arose when integrating the pinion that we purchased because the automobile window motor that we selected had a pinion permanently fitted to the shaft and both were made out of hardened steel. We had to request the help of Kent Pruss in the Automotive Laboratory Machine Shop to use a special tool to bore down this shaft and then solder weld our purchased pinion onto the shaft. We also had difficulty finding the M12x1.00 tap to thread the hole for our optical fluid sensor. Al Wilson specially ordered this tap for our group to use. Sealing the connections for the solenoid valve and optical sensor into the Plexiglas cap also proved to be an issue. Use of Teflon tape did not completely seal these threaded sections and air leakage occurred.

13. FINAL DESIGN MASS PRODUCTION MANUFACTURING PLAN

We hope that this product will be mass produced in the future if hydraulic hybrid vehicles develop a strong market share. The production model of our ADS design would not be manufactured in the same way as our final prototype. The amount of machining that we performed was very time consuming and would not be efficient for large scale production. We can reduce the amount of assembly time and manufacturing time through part consolidation. By making the rod and piston as one piece that is die-cast with machined piston surfaces, we could greatly reduce the amount of time required for assembly; this would also enhance the performance and strength of the device. We would also like to have the cylinder and top cap die-cast as one part where the inside surface would be machined afterwards to achieve the proper tolerance grade and surface finish. Die casting for these types of aluminum components is more suitable than other metal forming methods.

We conducted a cost analysis of the production run of 100,000 units of our design. This required making several assumptions. We performed our calculations assuming no bulk purchase discount for the motor, solenoid valve, o-rings, cable transducer, and optical sensor. Although discounts for bulk purchases of these components will most likely ensue, we are unsure of the reasonable discount to perform our calculations. We also assume that the machining and assembly will still be a lengthy process, and we estimate this time to be 20 minutes per unit.

Table 13: Projected Mass Production Cost Analysis

Expense	Quantity	Cost per Unit	Cost
Aluminum	500000 lb	$5/lb	$2,500,000
Fasteners	1000000 units	$0.01 each	$10,000
Motor	100000 units	$70 each	$7,000,000
O-rings	200000 units	$0.05 each	$10,000
Sensors	100000 units	$20 each	$2,000,000
Valves	100000 units	$50 each	$5,000,000
Control Circuitry	100000 units	$5 each	$500,000
Die	1 mold units	$50,000 each	$50,000
Engineering	100 hours	$50/hour	$5,000
Die Operation	33,333 hours	$50/hour	$1,666,650
Machining	33,333 hours	$20/hour	$666,660
Assembly	33,333 hours	$15/hour	$499,995
		Total Cost	$19,908,305
		Cost per Part	$199.08

Our cost analysis shows that each manufactured Aeration Detection System would cost around $200. This price is most likely an over estimate based on our previously stated assumption that discounts for bulk component purchases from suppliers was not taken into account.

14. VALIDATION APPROACH

Every component that we have designed or purchased was tested to verify that they function as intended and specified by the manufacturer. These tests would be difficult to perform if the equipment was already mounted on the vehicle, and if they failed the tests, it would result in wasted time and energy for installing and removing the cooler. We tested both the filter and cooler together on a testing apparatus through simulation of the Challenge X vehicle operating conditions. We performed this testing at the EPA under the guidance of Neil Johnson. We spent over six hours at the EPA doing this testing, and the great amount of time and effort necessary to perform validation testing was certainly a surprise and a learning experience for us.

The filter tests validate that the pressure drop does not exceed the customer requirement of 15 psi. This is important because a pressure drop through the filter exceeding 15 psi will affect the performance of our system. We did not test the filter's ability to clean the fluid; the EPA does not have the technology to do this. Neil Johnson suggested that we could send a sample to a company that will tell us the cleanliness of our fluid for $50 per sample. We would have to send both a dirty and filtered sample for comparison. With the other costs of this project, we cannot afford to spend $100 on testing fluid cleanliness. We also do not want to install a previously clogged filter into the Equinox.

Cooler tests confirm that the cooler is capable of properly maintaining the oil temperature. They also verify that the cooler can withstand the necessary pressure requirements and flow rates. Similar to the filter testing, cooler validation testing also verifies that the pressure drop across the cooler is minimal.

14.1 Off-line Filter and Cooler Testing

We created a test setup as shown in Figure 20. We placed the filter and cooler in series, just as they would be in the Challenge X vehicle. A pump circulated hydraulic fluid through the system at flow rates from 0 to 40 GPM. 40 GPM is the average flow rate in the Challenge X vehicle. The EPA does not have equipment to test at higher flow rates. The fluid was continuously heated. We heated the fluid to 130 °F. It was not possible to heat the fluid to higher temperatures at such high flow rates.

We placed thermocouples and pressure gauges before and after the filter and cooler. We recorded the temperature and pressure of the oil going into and coming out of both the filter and the cooler. From this data, we can calculate the pressure drop through the filter, the pressure drop through the cooler, and the oil temperature drop through the cooler. Figure 28 shows the setup of the filter and cooler test.

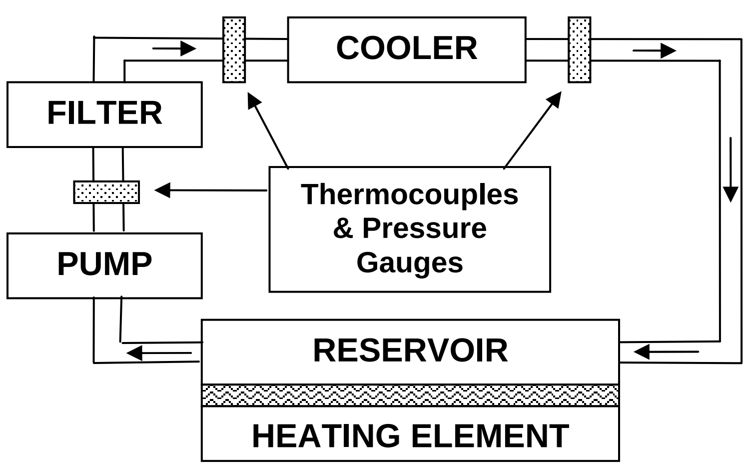


Figure 28. Setup of oil cooler testing apparatus.

14.1.2 Filter Testing Results

The filter test results are shown in Figure 29. This shows the pressure drop across the filter over varying flow rates from 0 to 40 GPM. These results show that the pressure drop does not exceed 15 psi over a range of flow rates from 0 to 40 GPM. The filter thus meets our customer requirements and can be installed in the Challenge X vehicle.

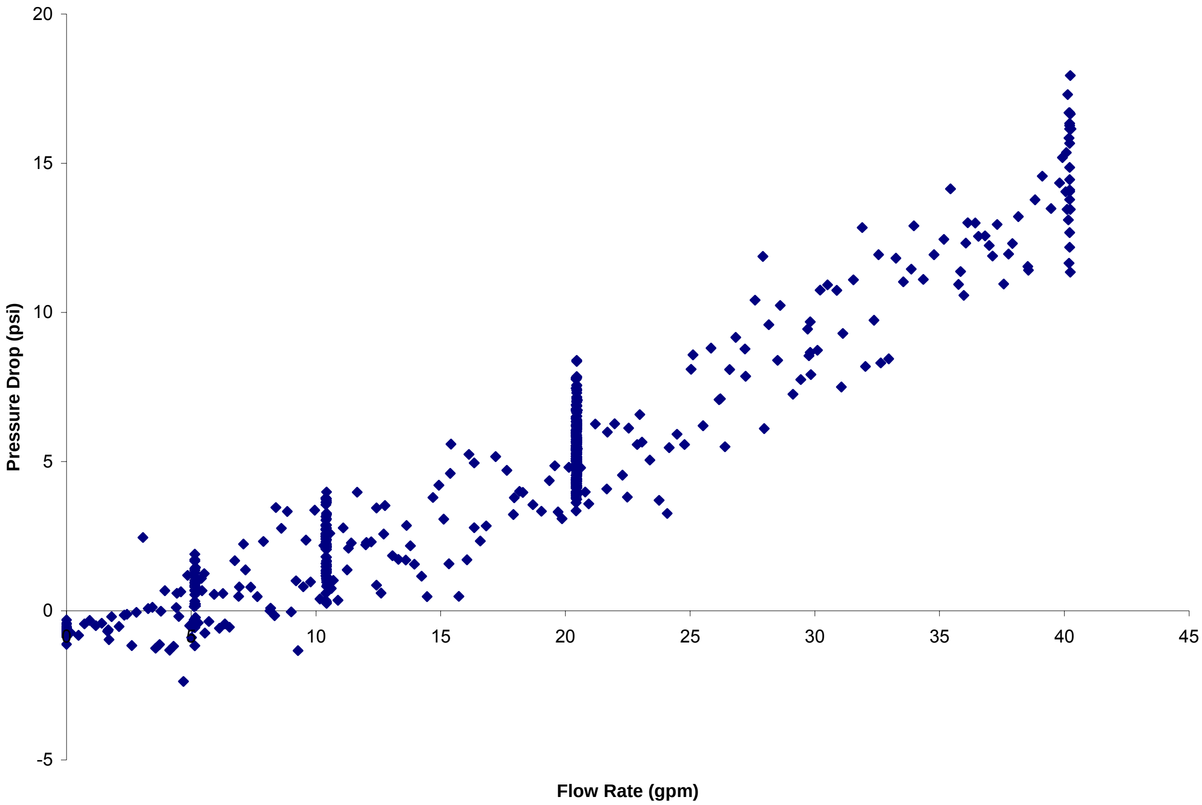


Figure 29: Pressure drop across filter over varying flow rates from 0 to 40 GPM.

14.1.3 Cooler Testing Results

The pressure drop across the cooler is shown in Figure 30 for varying flow rates from 0 to 40 GPM. These results show that the pressure drop does not exceed 15 psi over a range of flow rates from 0 to 40 GPM. The cooler thus meets our customer requirements and can be installed in the Challenge X vehicle.

The temperature drop across the cooler is shown in Figure 31 for varying flow rates from 0 to 40 GPM. With an incoming temperature of 130 °F, the cooler consistently brings the temperature down by approximately 10 °F to 120 °F. 120 °F is the optimum temperature of hydraulic fluid. Also, the testing shows that the cooler produces a steady temperature drop at all flow rates.

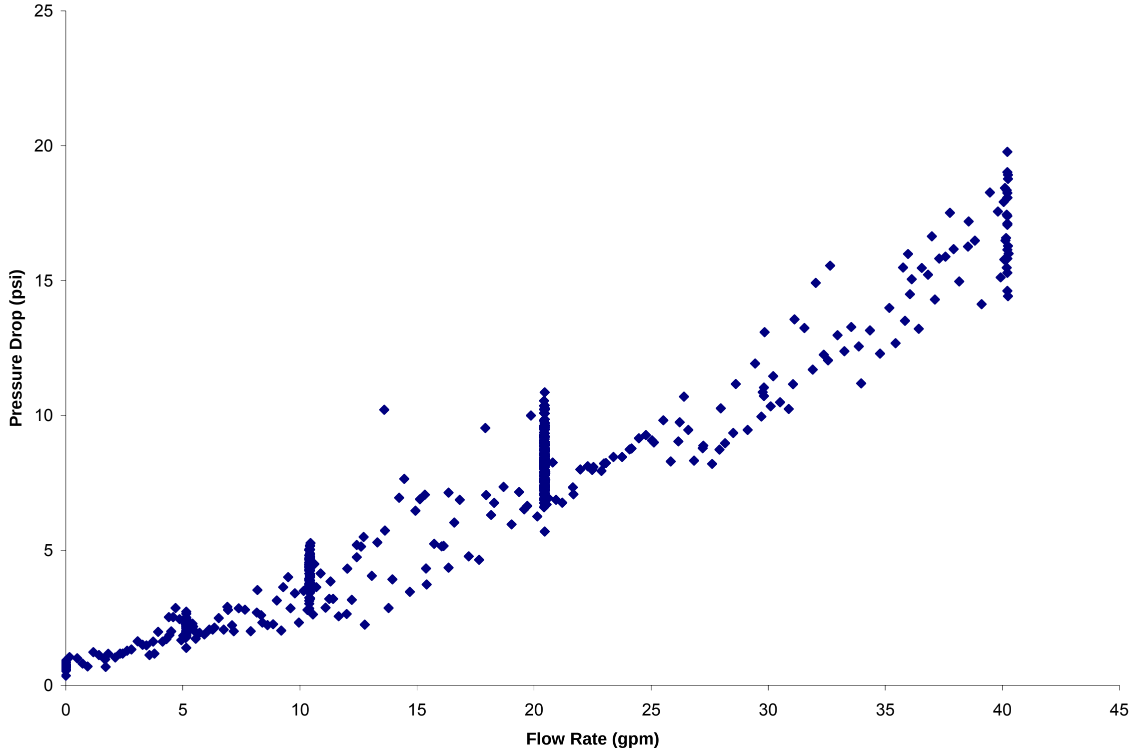


Figure 30: Pressure drop across cooler over varying flow rates from 0 to 40 GPM.

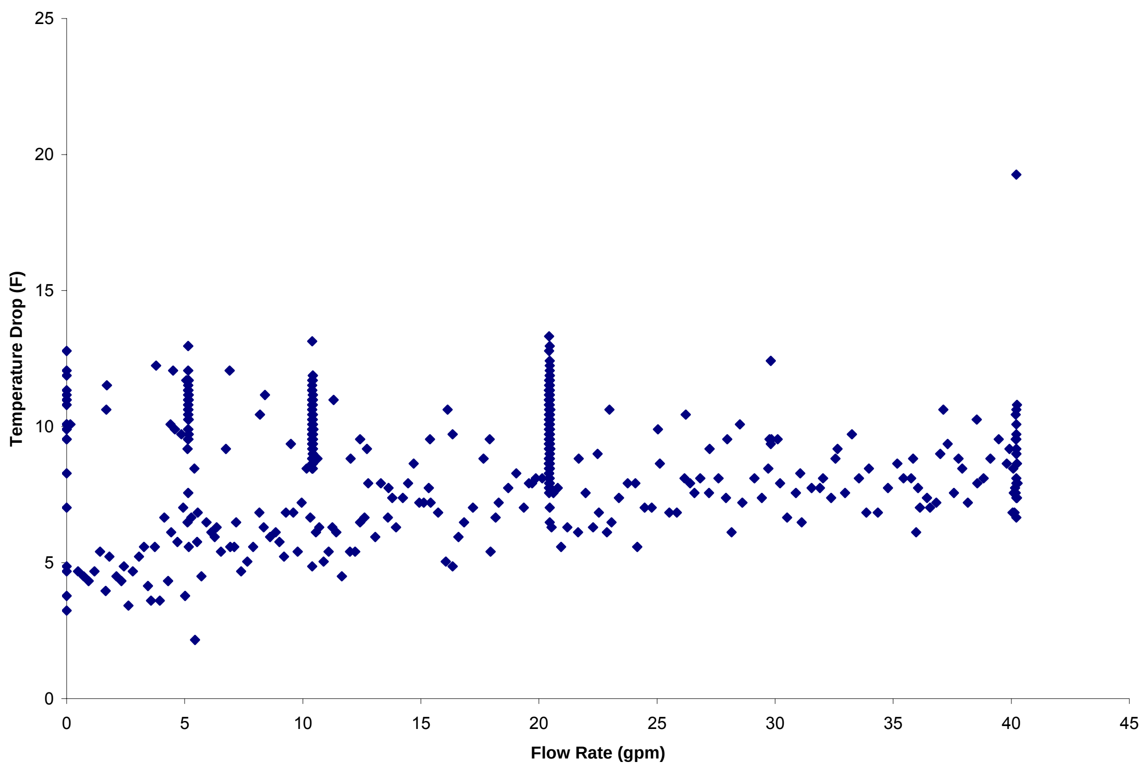


Figure 31: Temperature drop across cooler for varying flow rates from 0 to 40 GPM.

14.2 Aeration Detection System Testing

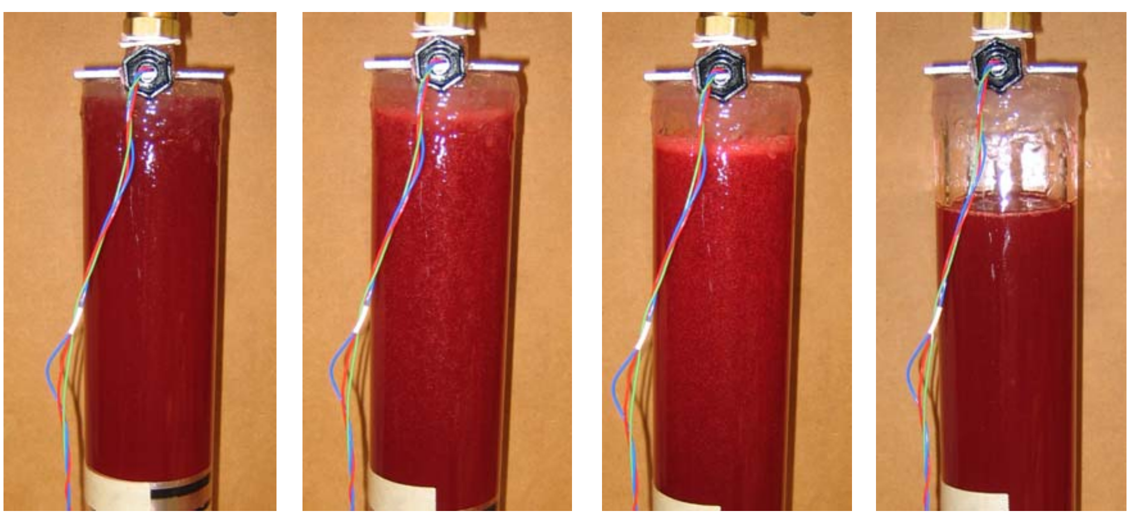
Our initial validation of our concept came from simply filling our cylinder with water, sealing the top, and creating a vacuum by hand. After we confirmed that our seals we're sufficient, we moved ahead to final construction and validation tests.

14.2.1 Validation Plan

For our validation testing we needed oil with air dissolved and/or entrained in it. We planned to control the % volume of air dissolved in the fluid we were testing with the accumulator. Our accumulator held 1000 ml, so we assumed if we filled it with 500 ml of oil, we would have 50% volume of air. To ascertain precision, we planned to do multiple tests from the same batch of aerated oil.

14.2.2 Validation Results

Our final validation tests proved that our concept works qualitatively, but we lacked the ability to define that success quantitatively. Our final validation tests spanned over several days due to repeated problems. Our first validation attempts were supposed to be fully automated, with our motor and valves being run through the OOPic, with feedback from the fluid level sensor. However, the amplifier was not outputting the necessary voltage; therefore we decided to control the electricity to the motor by hand. The rest of the system continued to be automated though. This worked up until the design expo, although the seals could have been better and we did not have time to collect data. When we went back to collect data, we found the solenoid valve we had been using was clogged and unusable. We decided to remove this valve and use the directional valve in its place, and mimicking the closed state of the solenoid valve by turning the directional valve in between the two lines. At this point, the fluid level sensor did not control either the motor speed or solenoid valve, so we ignored its function. Also the layers of Plexiglas had begun to crack and leak, and we were no longer able to create the vacuum we needed. We resealed the Plexiglas with dichloromethane, but when we restarted our validation tests the pressure was too high and broke the lid off the cylinder and opened old cracks. We resealed everything with epoxy this time and performed our final validation tests. The epoxy provided an incredible seal and we were able to make a strong vacuum within the tube. Figure 32 shows the dissolved air coming out of solution when the vacuum is applied. Thus this device works as a good deaerator.



1. Initial Sample 2. Vacuum Applied 3. Dissolved Air Emerges 4. Deaerated Sample

Figure 32: ADS system deaerating sample of fluid

We were unable to accumulate data to quantitatively define the deaeration we were observing. We increased the resolution of our transducer to approximately .25mm or 0.25% through our analog to digital conversion, yet out of almost ten tests we were only able to identify a % volume of air greater than 1% in one. This indicates to us that the dissolved air occupies little to no volume, and our assumptions in our validation test were wrong. The main challenge we faced in our validation tests was we were unable to do a proper design of experiment because we could not create standards to test against. In other words, we were unable to find or create oil that was 5%, 10%, 20% etc. volume of air to test our system against. Without this we are unable to validate the accuracy and precision of our system. Other products we benchmarked against appeared to obtain these standards to test against by cycling a known volume of air through an oil system until it became homogenously entrained. We lacked the time and resources to duplicate this, but it is certainly a possibility for future groups.

15. FINAL RECOMMENDED DESIGN

15.1 ADS Design Critique

The ADS design is unique and functionary but can be greatly improved and diversified in its applications. For one, the ADS is too large currently to conveniently fit inside a car. The motor also has to apply a lot of force to move the piston, whereas another actuator, perhaps a lead screw, would have been more appropriate. The piston often has trouble starting if left alone for many days, due to static friction. The linear transducer is also a fragile and expensive piece to the system. Other measurement devices that may be able to replace it are sonar or capacitive distance measurement devices. Currently there is both a solenoid valve followed by a directional valve our prototype. If the two could be combined into a three way solenoid valve it would be much better. The system also needs to be able to work in non-optimal conditions, such as if its in a car on an angle, or the car is driving and sloshing the fluid. Also, sampling time should be reduced from a minute to seconds. Reducing the sampling volume can help with this, although it may sacrifice accuracy.

We believe the ADS can also be made into a small, hand size tool with applications beyond hydraulics. A handheld ADS has potential in the biomedical field, to monitor oxygen levels in blood. It can also be used by environmental agencies in monitoring the dissolved oxygen levels in ponds and lakes.

A recent aeration monitoring system was released that is of great interest to this project. Pulse Air, an automated on-line tester, can measure the % volume of entrained air in a fluid from 0.5 – 50% within 1 or 2% [24]. Whether this could be used by the EPA or not, this is at least a great benchmark to design against, if not use the product altogether. Because this product just came to market last month, after our benchmarking period, we were not able to study it in depth. However, future teams and the EPA should seriously consider this product, its abilities, limitations, and potential.

15.2 Final Recommended ADS Design

Part of the engineering design process involves learning from your past failures. From our benchmarking, initial design, prototype, and validation testing, we discovered the many shortcomings and benefits of our ADS design. We have tried to build off of this knowledge to develop our final recommended design, which we recommend be pursued for further investigation. We found out that the concept works, but there were several inherent flaws in our prototype that prevented it from being a complete success. Table 14 shows a detailed list of the components that will build a better ADS than our prototype. If somebody were to use these components and the design shown in Figure 33, it is possible they might build a device that will be more adequate for performing the desired task.

Table 14: Bill of Material for Recommended Final Design

Quantitity	Part Description	Source	Part Number	Cost	Contact
1	2-3/8"OD x2"ID - 5' Aluminum Tubing	McMaster-Carr	4699T26	$35.10	www.mcmaster.com
1	2-3/8" ROUND 6061-T6511 ALUM	ASAP Source	RD:RDA6061:02375-6061-012	$30.06	www.asapsource.com
1	Steel 14-1/2 Deg Pressure Angle Gear Rack 24 Pitch, 1/4" Face Width, 1/4" H O'all, 2' Length	McMaster-Carr	6295K12	$20.00	www.mcmaster.com
1	Steel Plain Bore 14-1/2 Deg Spur Gear 24 Pitch, 12 Teeth, 0.5" Pitch Diameter, 1/4" Bore	McMaster-Carr	6325K31	$9.92	www.mcmaster.com
1	1/16 X 12 X 12" Aluminum plate	ASAP Source	SP:SPA6061:00063-6061	$6.62	www.asapsource.com
1	Optical Fluid Sensor	Honeywell	LLE102000	$20.00	www.honeywell.com
1	Brass Three-way Solenoid Valve	McMaster-Carr	49085K14	$225.65	www.mcmaster.com
1	DC motors with gear assembly	Bosch	1 397 220 375	$100.00	www.bosch.com
1	Cable Length Transducer Sensor	Micro-epsilon	MK30	$200.00	www.me-us.com
2	Rubber o-ring 2" OD, 1-5/8" ID, 3/16" Width	Stadium Hardware		$1.00	
2	#4-40x1" machine screws and nuts	Home Depot		$1.29	
3	1/4"x2"x20 machine screws and nuts	Stadium Hardware		$2.00	
4	1/4"x1"x20 machine screws and nuts	Stadium Hardware		$2.00	
6	1/4" Washer	Stadium Hardware		$0.50	

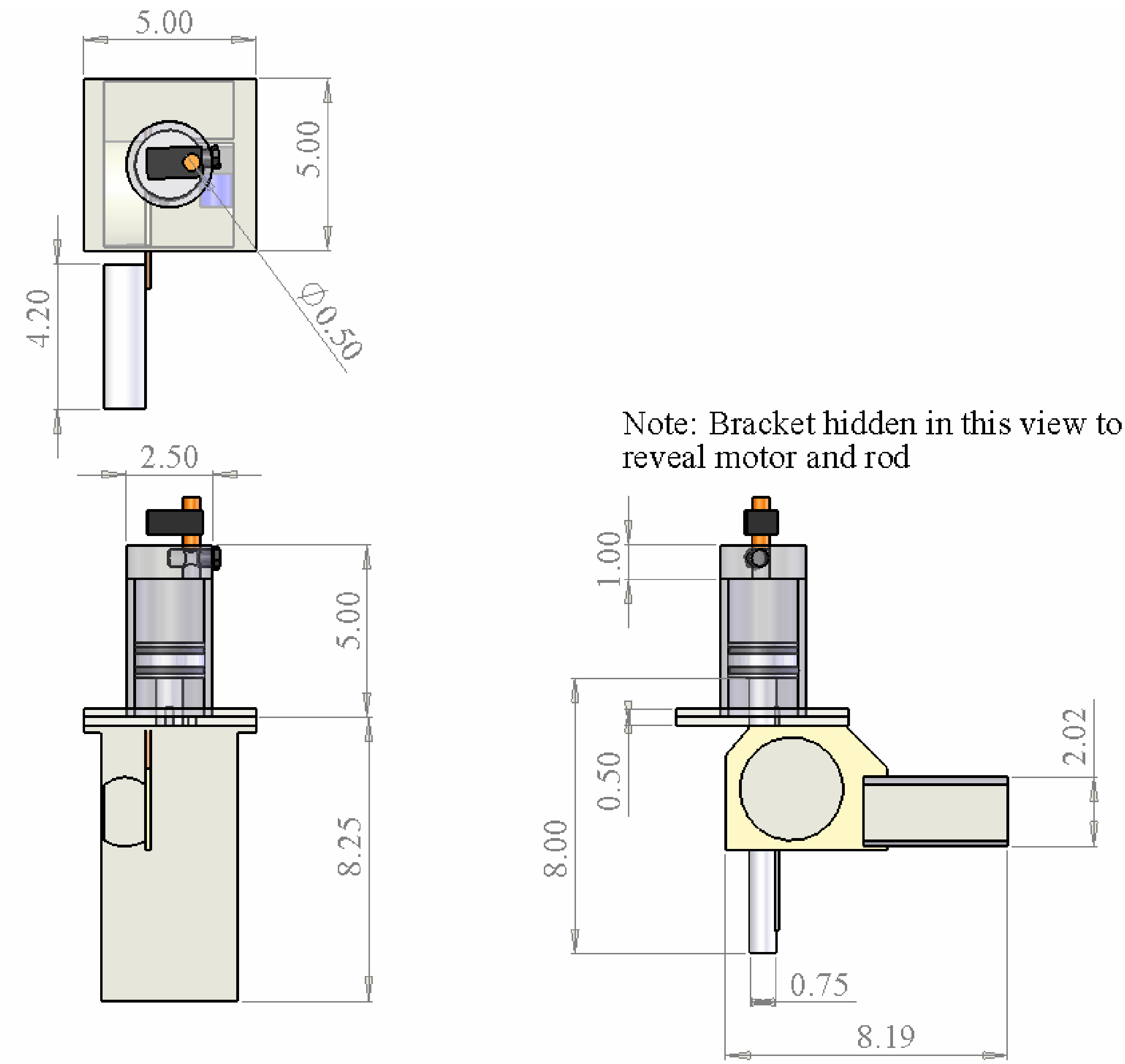


Figure 33: Dimensioned CAD Drawing of Final Recommended ADS Design

16. DISCUSSIONS

16.1 Failure and Safety of Design

We performed extensive failure and safety analysis for our final design using DesignSafe 3.0 software. This is to ensure that the ADS minimizes risk to the user population. We used a risk assessment methodology to approach our analysis. In this methodology we first identify the hazards in our system. Then we assess the risk associated with those hazards both qualitatively and quantitatively. Finally we apply risk reduction measures until we reach an acceptable risk level. We used the default risk scoring system in DesignSafe 3.0 to judge the risk level of each hazard, from high to medium to low (with low being an acceptable risk level). This was based on our ratings of the severity of the hazard, the exposure of the user to the hazard, and the probability of failure occurring. We identified the risks for two modes of operation: normal operation and installation/removal.

The major hazards and failure modes related to normal operation of the ADS are associated with the motor and rack/pinion, and the electronics. The motor can overheat during use, and if the flammable hydraulic fluid leaks from the cylinder and comes in contact with the hot motor, this could lead to a fire. Also, if the fluid leaks and comes in contact with the electronic circuitry controlling the system, this can be catastrophic. In addition, high voltages applied to the solenoid valve can be dangerous to the user.

Many risks endanger the user who installs/removes the ADS. The major hazards and failure modes related to installation/removal include pinch points in the rack and pinion if the system unexpectedly starts up. A hot motor could burn the user's hands. The user could get shocked by the high voltages throughout the system. There are also environmental and health hazards associated with the hydraulic fluid. The oil is hazardous waste, and improper disposal of the oil could lead to wastewater contamination. Prolonged exposure to the oil can cause skin irritation. When removing the ADS, hydraulic fluid could spill out of the line, creating a big spill and potentially exposing the user to large amounts of fluid.

Once identifying these risks, we applied appropriate hazard control to reduce the risks to an acceptable level. We eliminated hazards by design, applied guard systems, provided warning systems, and used training instructions for the user. To protect the user from pinch points and the hot motor, we designed a casing for the bottom section of the system, which encloses the motor and rack/pinion. Not only does this protect the installer/remover, it also separates the hot motor from possible contact with the flammable oil. As a guard system, we can insulate the electronic circuitry with a waterproof cover to protect it from fluid leakage. We can also cover the solenoid valve with insulation to protect the user from shock. In regards to the environmental/health risks associated with the oil, we can place warning signs alerting the user to properly dispose of the oil and to wash his or her hands thoroughly after contact with the oil. We must also provide training instructions to the user to advise the user to clamp the hydraulic line prior to installing/removing the ADS in order to prevent a fluid spill.

After applying these risk reduction methods, the DesignSafe software showed that all failure modes are now low risk, which is acceptable. In addition to those listed above, other low risk failure modes included fluid leakage, high fluid pressure, and others. The complete DesignSafe report showing all failure modes, risk reduction methods, and risk levels is found in Appendix I on page 78.

17. CONCLUSIONS

The University of Michigan Challenge X Team needs a fluid conditioning system for its hydraulic-diesel hybrid Chevy Equinox. The system must filter out debris as small as 3 μm, cool the hydraulic fluid to approximately 120°F to prevent thermal breakdown of the fluid, and ensure that less than 6% of the fluid volume is dissolved nitrogen gas. The system must handle the flow requirements of the connected systems (80 gpm, 200 psi). Our design should be fit within the chassis of the Equinox, weigh less than 60 lb, and cost between $400 and $1000.

We purchased a Hydrotechnik KF3 Return Line Filter and a Hydac EDL-4 Air Cooler to filter and cool the fluid. We selected these components through a Product Value Assessment (PVA), concluding that these best met our customer requirements. Their performance was positively verified at the Environmental Protection Agency (EPA).

We concluded that to ensure that the level of aeration in the fluid is less than 6%, it is more practical to develop a monitoring system for the fluid than deaerating it, because the extent of the problem of nitrogen permeating through the bladder has not been determined by the EPA or other sources. An aeration detection system (ADS) will be used to measure the % volume of air in the hydraulic fluid.

The ADS we designed is a fully-automated piston-cylinder vacuum system. The cylinder takes in a sample of fluid, controlled by a solenoid valve and the piston speed. The valve then closes, sealing the system, while the piston continues moving to apply a pressure drop on the sample. By Henry's Law, this causes the gas in the fluid to come out of solution due to a vacuum; the gas is then ejected. A cable-extension transducer measures the piston displacement at pre- and post-deaeration, from which we can calculate the amount of nitrogen that was originally dissolved in the fluid.

Due to time constraints, we only created a proof-of-concept prototype. We were able to prove our concept by creating a vacuum and observing the fluid deaerate. However, we were unable to quantitatively analyze this. Most of the air in the fluid was dissolved, so its removal had a negligible impact on change in fluid volume. This was because we were unable to create observable standards to test against, such as oil with 10 % volume of air. In the future, observable standards will help evaluate the accuracy and precision of our ADS.

18. RECOMMENDATIONS

The ADS system should be made of aluminum and the suggested components to achieve optimal performance. Efforts should be made to minimize any volume between the exit valve and the fluid level sensor at the top of the cylinder. This is because any fluid build up here introduces an unseen error in mearsurement. Seals need to be very tight to ensure a proper vacuum, and to improve the vacuum the piston can be dropped in stages with time.

Additionally, standards to test against should be developed to evaluate the precision and accuracy of the ADS. This is the next important step for this project. To improve precision a taller sample column should be taken. However, a long term goal for the ADS is to make it much smaller and compact.The new aeration measurement device on the market, Pulse Air, should also be evaluated in more depth. This new device can be used for both ideas for improvement to our current ADS system, as well as a possible alternative.

Finally, application beyond hydraulics should be considered for our ADS. For example, applications in medicine and environmental monitoring should be considered. There are no other products like the ADS on the market, and if a smaller version could be constructed that functioned automatically it could be well marketed across a number of fields.

19. ACKNOWLEDGEMENTS

We would like to thank:

- Steve Dockstader and the entire Challenge X team for providing us with funding and all information that we requested regarding customer requirements and constraints
- Neil Johnson for all of his information and insight in finding a filter and cooler and the extended hours he spent helping us test these two devices
- Andy Moskalik for giving us information and parts from previous ME450 projects and for his insight on deaerating
- Collin Myles at the J.E. Myles Inc. for his help in choosing the correct filter for our application
- Mark Firkis at Hydac for his help in understanding the functions of the cooler
- Bill Miller at Perferred Technical Resources for his help in understanding how to operate the cable-extension transducer.
- Kent Pruss in the Autolab Machine Shop for installing the pinion onto the hardened alloy shaft
- Al Wilson at the Chemistry Instrument Shop for ordering a tap for our optical sensor
- Professor Katsuo Kurabayashi for working through with us the equations and concepts for our initial deaeration attempts
- Robert Coury and Marvin Cressey for all of their help and advice in the machine shop
- Professor Albert Shih for all of his efforts in leading our section and giving us good feedback and advice on approaching our project. We would also like to thank him for obtaining sponsorship from the EPA for our team.
- Professor Gillespie for all of his help on choosing a motor, understanding the OOPic, choosing a relay, and troubleshooting our electronics.

20. INFORMATION SOURCES

We obtained information on the filtration, temperature control, and removal of gas from hydraulic fluid from multiple sources. These sources include the following:

- United States Patent and Trademark Office (www.uspto.gov)
- Delphion Intellectual Property Network (www.delphion.com)
- Engineering Village (www.engineeringvillage2.org)
- University of Michigan Art, Architecture, and Engineering Library
- Meetings with Neil Johnson (EPA), Andrew Moskalik (EPA), Steve Dockstader (Challenge X), Prof. Katsuo Kurabayashi (UofM), Challenge X Team, Prof. Ralph Yang (UofM), and Prof Albert Shih (UofM)
- Limited internet searches
- Product catalogs

We found several books from the Art, Architecture, and Engineering Library to be very useful in providing us with background information on hydraulic systems. We were able to obtain information on:

- the effects of high temperature on hydraulic fluid [12]
- the effects of cavitation on hydroabrasive erosion [14]
- calculating the heat exchanger requirements [12]
- filter selection and filter efficiencies [12]
- general conditioning of hydraulic fluid [13]

Neil Johnson [4] and Andrew Moskalik [15] of the advanced technology division at the U.S. Environmental Protection Agency and Steve Dockstader [5], the team leader of Challenge X for the University of Michigan, provided us with information regarding hydraulic hybrids. Steve explained the basics of hydraulic hybrids and constraints that we may encounter on the Challenge X Equinox platform. Neil on the other hand, explained the details and implications of placing a fluid conditioning system in a hydraulic system, described some engineering requirements, and showed us examples of a hydraulic hybrid Ford Expedition and UPS delivery vehicle. Andrew explained previous ME450 (Fall 2004 and Winter 2005) projects that he sponsored for fluid deaeration and gas venting. He provided insight on ways that those previous designs could be improved.

During our initial investigation into deaerator designs (see Appendix B), we met with Professor Ralph Yang to find our more information regarding semipermeable membranes that are permeable to nitrogen and impervious to oil. We also met with Professor Kurabayashi to discuss methods to model our flow. Our meetings resulted in obtaining the following ideas:

- Use of the rigid body motion equation and Newton's second law will allow us to determine the length of centripetal deaerator necessary to deaerate a certain percentage of nitrogen.
- Use of Henry's law will allow us to find the speed at which the cylinder needs to rotate to overcome the surface pressure at the collecting surface
- The bubbles can be modeled as small cubes
- With this information one can also determine the maximum pressure on the cylindrical tube

When began developing a deaerator design, we researched previous ME450 projects. We obtained information from a ME450 senior design (Fall 2004) project titled <u>Nitrogen Removal System for Hydraulic Devices</u> [6]. This information details different approaches to deaeration of hydraulic fluid.

From our patent searches, we covered two areas: deaerators and aeration detection systems. As for deaerators, we discovered two patents. One patented design [5,383,958] that includes a flow passageway with a device to restrict flow at its inlet to induce a pressure drop and has two discharge ports at its outlet

- one for the hydraulic fluid and the other for air. The fluid is drawn through this passageway via vacuum pump. This is the idea that the past ME 450 Team 13 used in their design. Another patent [6,863,712] found utilizes centripetal forces to channel the air and force it out of the system. A third by a company G.E. Totten and Associates also utilizes centripetal forces. These designs are further discussed in Appendix B.2.

As for aeration detection systems, we had trouble finding any relevant patents. However, we found a commercial micro aeration measuring device [19] that extracts a small sample a fluid like a syringe, then creates a vacuum, expels the resulting air, and remeasures the volume of liquid. Through calculations it is then possible to determine the % volume of air. However, this device is manually operated. This was one of our major motivating designs for our concept generation, discussed in section 6.

Examples of information obtained from the internet include material properties of the hydraulic fluid from the Mobil 1 Synthetic Automatic Transmission Fluid website [7] (hydraulic fluid used by the Challenge X team) and filter and cooling selection information [8, 9]. We were able to find useful information to help us choose a filter and cooling system to meet our customer requirements and packaging constraints on the internet. However, the majority of our filter and cooler selection information came from product catalogs and emails and phone calls to numerous manufacturers.

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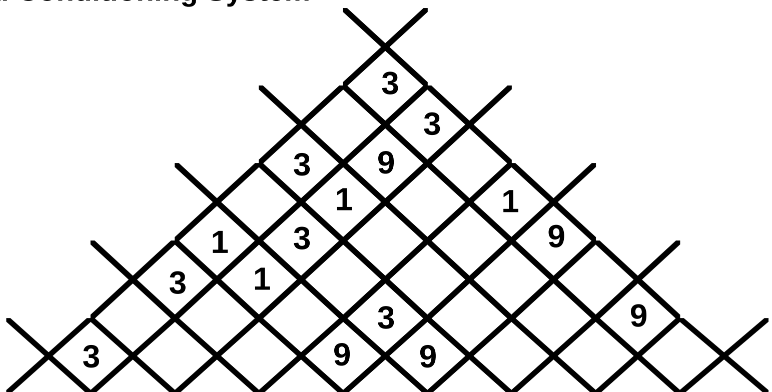
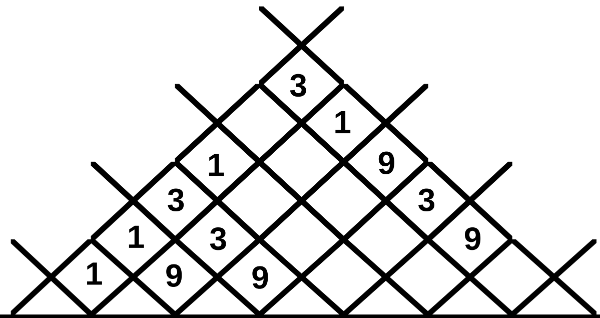
APPENDIX A.1
QFD for Hydraulic Hybrid Fluid Conditioning System



Customer Requirements	Challenge X	Min. size of filtered particles (-)	Max temp System Reaches (-)	Flow Rate Through System (-	System Size (-)	Number of Components (-)	Weight of System(-)	Pressure Drop through System (-	Power Consumption (-)	Total Cost for Components (-)
Filter out debris	8	9	1	9				9		3
Control Temperature	9	1	9	9	3	1		9	9	3
Handle Flow Rate	8	9	3	9	3	3		9	1	3
Handle Pressure	8	3	3	9	1	3		9	1	3
Minimize Size	4	1	3	3	9	9		3	1	1
Minimize Weight	4	1	3	3	3	3	9	3	1	3
Minimize Cost	5	3	3	3	3	9	3	3	3	9
Target Value		3-5	150	80	2x2x1.5	3	30	20		500
Measurement Unit		μ	°F	%	.	#	lb.	psi	HP	$
Total		200	176	336	122	150	51	336	120	160
Normalized		0.121	0.107	0.204	0.074	0.091	0.031	0.204	0.073	0.097
Importance Rating		**2**	**3**	**1**	**6**	**5**	**7**	**1**	**6**	**4**

APPENDIX A.2
QFD for Aeration Detection System



Customer Requirements	Challenge X	% Nitrogen Detected in Oil (-)	System Size (-)	Number of Components (-)	Weight of System(-)	Pressure Capability (-)	Power Consumption (-)	Total Cost for Components (-)	Offline Air Measuring System for Hydraulic Devices
Monitors Air in Oil	9	9		1		3	9	1	4
Handles Required Flow	7	3	1	1		1		1	5
Handles Required Pressure	7	3	1	1		9			5
Small Size	2	1	9	9		3		1	1
Compact	3	1	3	9				1	1
Light Weight	4	1	1	3	9	1		1	4
Low Cost	5	1	1	9	3	1		9	-

Target Value	100	-	1	10	200	0.1	100
Measurement Unit	%	in^3	#	lb.	psi	HP	$
Total	137	50	125	51	112	81	70
Normalized	0.22	0.08	0.2	0.081	0.179	0.129	0.112
Importance Rating	**1**	**6**	**2**	**6**	**3**	**4**	**5**

Offline Air Measuring System for Hydraulic Devices	100%	1260	8	10	2200	0	-

APPENDIX B.1
Hydraulic System Engineering Analysis with Inclusion of Deaerator

A general problem we need to address is the placement of our fluid conditioning system relative to the other hydraulic components. Preferably, the components should be along a flow where it is:

- Low pressure
- Uni-directional
- The hottest location in the hydraulic system
- Unaffected by a pressure drop upstream
- Unaffected to cavitations forming upstream

The outlet from the low pressure reservoir to the front pump motor is the ideal location so far for this system because of the low pressure flow in addition to the one directional flow of fluid. Although it is possible to split up the components, it would be best to keep them together since all three of these devices (monitoring system, filter, and cooler) all have the similar issues regarding pressure and flow requirements, pressure drops, and potential to introduce cavitations.

For our fluid conditioning system, we determined that there are thirteen logical orders to place the filter, cooler, and fluid monitoring system relative to each other. Table C1 shows the order which we can place the three devices in series, and Table C2 shows all combinations of two devices in parallel with the third device in series. The thirteenth combination, not shown in the tables below, is having all three devices in parallel.

Table C1: All Possible Serial Combinations

	Inlet	Middle	Outlet
1	Filter	Cooler	Deaerator
2	Filter	Deaerator	Cooler
3	Cooler	Filter	Deaerator
4	Cooler	Deaerator	Filter
5	Deaerator	Filter	Cooler
6	Deaerator	Cooler	Filter

Table C2: All Possible Parallel/Serial Combinations

	Inlet		Outlet	
7	Filter		Cooler	Deaerator
8	Cooler		Filter	Deaerator
9	Deaerator		Cooler	Filter
10	Cooler	Deaerator	Filter	
11	Filter	Deaerator	Cooler	
12	Cooler	Filter	Deaerator	

There are several matters to take into consideration when choosing the best order to place these three components. This includes the interaction between each of them and the requirements for the inlet and outlet of each component (pressure, temperature, cleanliness, etc.).

APPENDIX B.2
Current Deaeration Technology

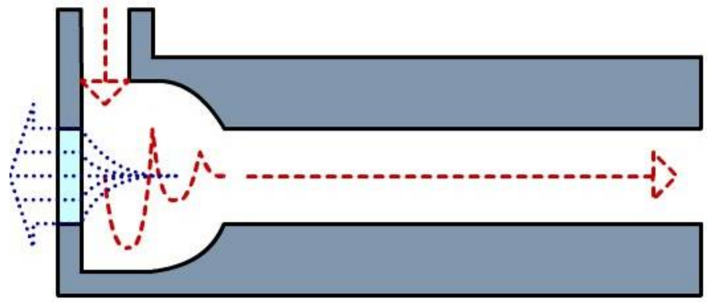
We found several designs for deaeration units for hydraulic flows, ranging from former 450 projects to NASA.

Deaerator Descriptions

Team #13, Fall 2005 ME 450 Project [6]	This device utilizes basic fluid dynamics principles. The hydraulic fluid is subject to a pressure drop, causing the nitrogen to separate from the oil. Then a change in the line allows the air to catch in an area, where it is released by a valve. The deaerated oil is then pumped back into the system to recover the lost pressure drop.
NASA Fluid Bubble Eliminator [10]	Oil is spun into a unit with a permeable membrane at its core. As the oil spins forward, the air is pushed to the center and through the membrane, where it then exits into the surrounding environment. The oil enters a normal flow at the end of spinning.
G.E. Totten's Bubble Eliminator [11]	Similar to NASA's design, oil enters the tapered cylinder tangentially creating a centrifugal motion. Air bubbles form in the center of the tube and are pushed back by the fluid pressure and released through a vent vale in the rear.

APPENDIX B.3
Deaerator Design Concepts
Our designs can be separated into two categories: those using a semi-permeable layer and those not. A semi-permeable layer would allow nitrogen in the oil to escape to atmosphere in the same way the bladders allow nitrogen to enter the oil in the first place. The benefits of using a semi-permeable layer include overall enhanced simplicity, because the need for valves is removed, and oil loss prevention, because only air can escape the layer.

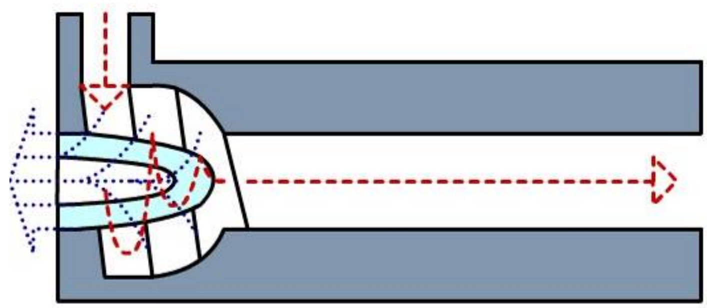
Simple Modified Bubble Eliminator Design
In this design the concept of G.E. Totten's Bubble Eliminator is remodeled with a semi-permeable layer instead of the vent valve they currently use. The design functions in the same way as described in section Appendix C.2.



Advantages: Overall a simple design, and allows entrained bubbles to be collected and removed without losing oil.

Disadvantages: This design faces the same challenges as GE Totten's design

Modified Bubble Eliminator Design with Helix Groove
This is similar to our Design 1, but with a grooved core to guide the swirling flow. The semi-permeable layer would be made to follow the contour of the outer radius to maintain a somewhat constant radius.

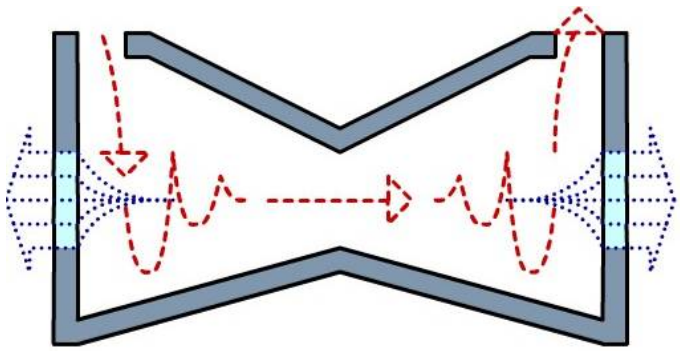


Advantages: A more focused circular flow should create larger centripetal forces, thus pushing more air out of the system.

Disadvantages: This would be very complex to manufacture and design, and requires more parts than other designs.

Hourglass Design
In this design the flow is brought in tangentially to create a circular flow, creating a column of air in the center to be pushed out the back through a semi-permeable layer. As it moves forward the radius

expands, creating a pressure drop and taking dissolved air out of flow and pushing it out a second semi-permeable layer.

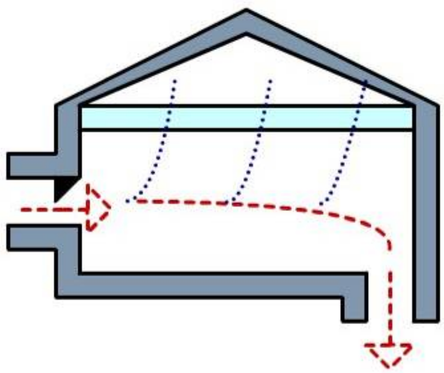


Advantages: Simply constructed, works by the same principle as the Bubble Eliminator.

Disadvantages: Hard to prove would work as predicted without building a prototype.

Membrane Accumulator

This is similar to team 13's design, but with a semi-permeable membrane used instead of a throttle valve to separate the gas and oil. Also, the needle valve is placed at the entrance of the accumulator.

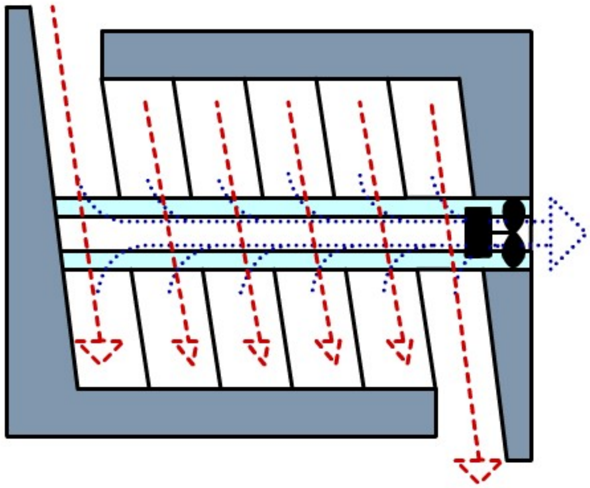


Advantages: We know this design generally works from past teams' projects.

Disadvantages: Would require an extra pump to repressurize the flow. Also it may not be able to remove the amount of nitrogen necessary.

Helix Deaerator

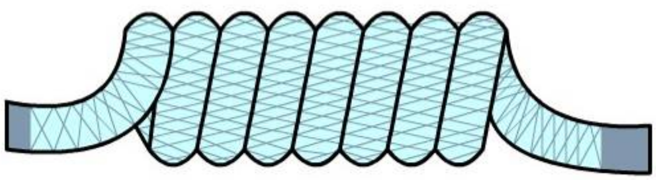
This design works off the same principle as NASA's deaerator by spinning a flow, forcing nitrogen to the middle of the apparatus where it exits through a semi-permeable tube. The differences in this design are the flow enters and exits in line and a vaccum is created through a fan inside the semi-permeable tube.



Advantages: This design works according to NASA and additionally has little pressure drop.

Disadvantages: This is complex and may not remove dissolved nitrogen.

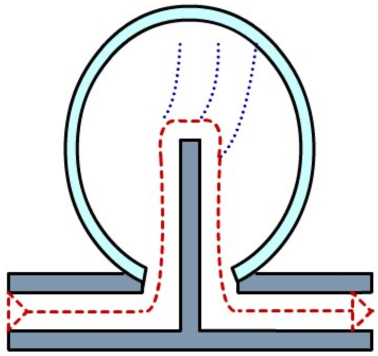
Coiled Tube
Here a section of the tubing is made of a semi-permeable material reinforced with a metal mesh and coiled. The coiling of the tube will create a centripetal force to push nitrogen to the middle of the center of the coil and help force it out.



Advantages: There is little pressure drop, the deaerator can be run in line with the rest of the system, and it is simple.

Disadvantages: This may not be able to remove air quickly or a lot of it.

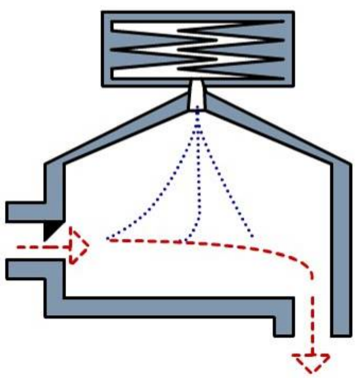
Semi-permeable Accumulator
In this design an accumulator made of semi-permeable material will allow nitrogen out in the same way it came in. The some of the fluid bladder Additionally, the top of this accumulator will be the high point of the hydraulic system to help accumulate nitrogen,



Advantages: Very simple design that uses the same principle used for the nitrogen to initially enter the system.

Disadvantages: Height requirement, loss of pressure in the hydraulic system, vulnerable to damage.

ME450 Fall 2004 Team 13 Design Enhancement
This design is based off the previous two ME 450 teams' designs. The changes include a shorter and wider throttle valve, to accommodate the height restraints associated with a truck chassis. Also, the needle valve is placed at the entry of the accumulator.



Advantages: We know this design generally works from past teams' projects, and is easy to improve upon.

Disadvantages: Would require an extra pump to repressurize the flow. Also it may not be able to remove the amount of nitrogen necessary, and some oil may escape.

APPENDIX C
Components Comparisons and Selections

APPENDIX C.1
Characteristics of Considered Filters

Company	Donaldson	Donaldson	Donaldson	Donaldson	Hydrotechnik	Norman	Parker	Parker	Parker	Parker	Western	Western
Model	HDK06	HDK06	HMK05	HMK05	KF3	30 MF	IL8	IL8	CN-40	CN-40	WO61	WO61
Type	Low Pressure	Low Pressure	Spin-On	Spin-On	Return Line	Medium Pressure	Medium Pressure	Medium Pressure	Medium Pressure	Medium Pressure	Low Pressure	Low Pressure
Maximum Flow Capability (gpm)	100	100	50	50	100	80	150	150	150	150	100	100
MAOP (psi)	350	350	350	350	300	800	500	500	1000	1000	600	600
Bypass Pressures (psi)	25	25	25	25	30	25	25	25	25	25	25	25
Port Size (in)	2.5	3.5	1.25	1.25	1.5	1.5	1.5	1.5	1.5	1.5	1	1
Particle Size (micrometer)	3	9	6	9	3	5	2	5	2	5	3	5
Max Pressure Drop (pisd)	11	2.5	10.5	7	7	25	9	6	30	20	20	16
Weight (lbs)	26	26	7.5	7.5	10.5	5.5	40	40	4.5	4.5	7.9	7.9
Length (in)	25	25	14.51	14.51	13.12	9.24	17.11	17.11	8.01	8.01	9	9
Head Diameter (in)	6.75	6.75	5	5	6.25	4.63	6.25	6.25	4.8	4.8	4.85	4.85

One could find information on these companies at the following websites:

- Donaldson Co. (MANF): http://www.donaldson.com/en/engine/hydraulics/index.html
- Hydrotechnik: http://www.hydrotechnik.co.uk/index.htm
- Norman Filters: http://www.normanfilters.com/
- Parker-Heffin: http://www.parker.com/ead/cm1.asp?cmid=475
- Western Filter: http://www.westernfilter.com/ind-products.html

APPENDIX C.2
Values Assigned to Ranges of Filter Characteristics

Particle Size								
Micrometers	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Normalized Particle Size	8	7	6	5	4	3	2	1

Max Pressure Drop								
Pounds per Square Inch	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**	**36+**
Normalize Pressure Drop	8	7	5	4	3	2	1	1

Weight								
Pounds	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**	**36+**
Normalized Weight	8	7	6	5	4	3	2	1

Length							
Inches	**7-9**	**10-12**	**13-15**	**16-18**	**19-21**	**22-24**	**25+**
Normalized Length	7	6	5	4	3	2	1

Head Diameter			
Inches	**4-5**	**5-6**	**6-7**
Normalized Head Diameter	9	6	3

APPENDIX C.3
Filter PVA and Results

Weight	Factor	Company	Donaldson	Donaldson	Donaldson	Donaldson	Hydrotechnik	Norman	Parker	Parker	Parker	Parker	Western	Western	
		Model	HDK06	HDK06	HMK05	HMK05	KF3	30 MF	IL8	IL8	CN-40	CN-40	WO61	WO61	
		Type	Low Pressure	Low Pressure	Spin-On	Spin-On	Return Line	Medium Pressure	Medium Pressure	Medium Pressure	Medium Pressure	Medium Pressure	Low Pressure	Low Pressure	
		Normalized Particle Size	7	1	4	1	7	5	8	5	8	5	7	5	
		Normalized Pressure Drop	7	8	7.5	7	7	3	7	5	2.5	4	4	4	
		Normalized Weight	3	3	7	7	6.5	7.5	1	1	8	8	7	7	
		Normalized Length	1	1	5	5	5	6.5	4	4	7	7	7	7	
		Normalized Head Diameter	3	3	6	6	3	9	3	3	9	9	9	9	
Weight	**Factor**	**Product Value Assessment**													
0.9	0.225	**Particle Size**	1.575	0.225	0.900	0.225	1.575	1.125	1.800	1.125	1.800	1.125	1.575	1.125	
0.9	0.12	**Max Pressure Drop**	0.840	0.960	0.900	0.840	0.840	0.360	0.840	0.600	0.300	0.480	0.480	0.480	
0.4	0.0571	**Weight**	0.171	0.171	0.400	0.400	0.371	0.429	0.057	0.057	0.457	0.457	0.400	0.400	
0.1	0.02	**Length**	0.020	0.020	0.100	0.100	0.100	0.130	0.080	0.080	0.140	0.140	0.140	0.140	
0.1	0.0167	**Head Diameter**	0.050	0.050	0.100	0.100	0.050	0.150	0.050	0.050	0.150	0.150	0.150	0.150	**MAX PVA**
		PVA	2.656	1.426	2.400	1.665	2.936	2.194	2.827	1.912	2.847	2.352	2.745	2.295	**2.936**

APPENDIX C.4
Characteristics of Considered Coolers

Company	Hydac	Thermal Transfer Products	ASA Hydraulik	Oiltech
Model	ELD-4	DH-337	ASA 0115 DC	LDC
Type	DC 12V/24V	DC 12V/24V	DC 12V/24V	DC 12V/24V
Maximum Flow Capability (gpm)	60	70	50	
MAOP (psi)	230	300	370	300
Heat dissipation @ 60 GPM (BTU/hr)	55990	45000	43200	13300
Pressure Drop @ 45 GPM (psi)	15	20	16	22
Weight (lbs)	35	20	27	33
Length (in)	19.69	30	16.93	18.34
Width (in)	16.57	24	14.17	18
Depth (in)	7.37	1.5	6.98	8.62

APPENDIX C.5
Values Assigned to Ranger of Cooler Characteristics

Heat Dissipation								
BTU / hour	**43000-44500**	**44500-46000**	**46000-47500**	**47500-49000**	**49000-50500**	**50500-52000**	**52000-53500**	**53500+**
Normalized Heat Dissipation	1	2	3	4	5	6	7	8

Max Pressure Drop								
Pounds per Square Inch	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Normalize Pressure Drop	8	7	6	5	4	3	2	1

Weight								
Pounds	**0-5**	**6-10**	**11-15**	**16-20**	**21-25**	**26-30**	**31-35**	**36+**
Normalized Weight	8	7	6	5	4	3	2	1

Length								
Inches	**14-17**	**17-20**	**20-23**	**23-26**	**26-29**	**29-32**	**32-35**	**35+**
Normalized Length	8	7	6	5	4	3	2	1

Width								
Inches	**14-17**	**17-20**	**20-23**	**23-26**	**26-29**	**29-32**	**32-35**	**35+**
Normalized Length	8	7	6	5	4	3	2	1

Depth								
Inches	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**
Normallized Depth	8	7	6	5	4	3	2	1

APPENDIX C.6
Cooler PVA and Results

Company	Hydac	Thermal Transfer Products	ASA Hydraulik	Oiltech
Model	ELD-4	DH-337	ASA 0115 DC	LDC
Type	DC 12V/24V	DC 12V/24V	DC 12V/24V	DC 12V/24V
Normalized Heat Dissipation	8	2	1	1
Normalized Pressure Drop	8	3	7	1
Normalized Weight	2	5	3	2
Normalized Length	7	3	8	7
Normalized Width	8	5	8	7
Normalized Depth	2	8	3	1

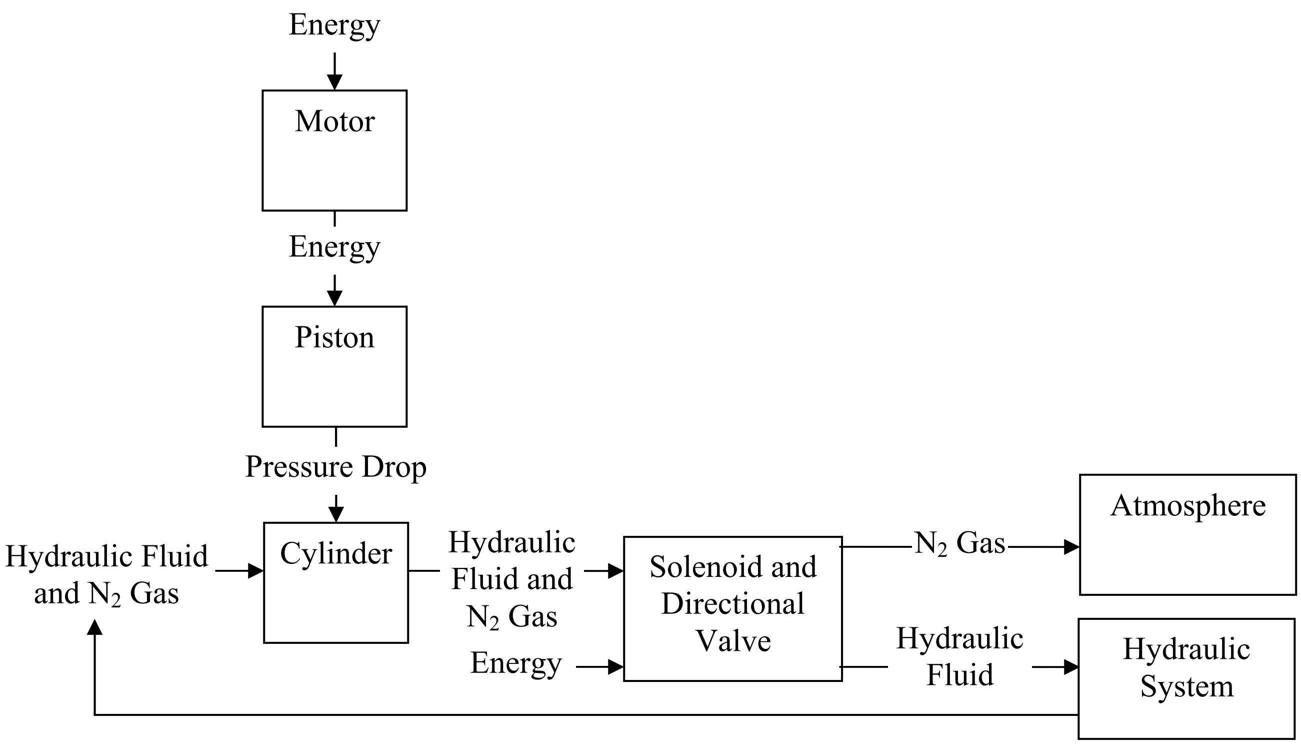
Weight	Factor	Product Value Assessment					
0.9	0.45	Heat Dissipation	3.600	0.900	0.450	0.450	
0.5	0.1667	Pressure Drop	1.333	0.500	1.167	0.167	
0.5	0.1	Weight	0.200	0.500	0.300	0.200	
0.3	0.1	Length	0.700	0.300	0.800	0.700	
0.3	0.06	Width	0.480	0.300	0.480	0.420	
0.3	0.0375	Depth	0.075	0.300	0.113	0.038	
							MAX PVA
		a = 0	6.388	2.800	3.309	1.974	6.388

APPENDIX D
Programming Script for OOPic Automated Electronic Control

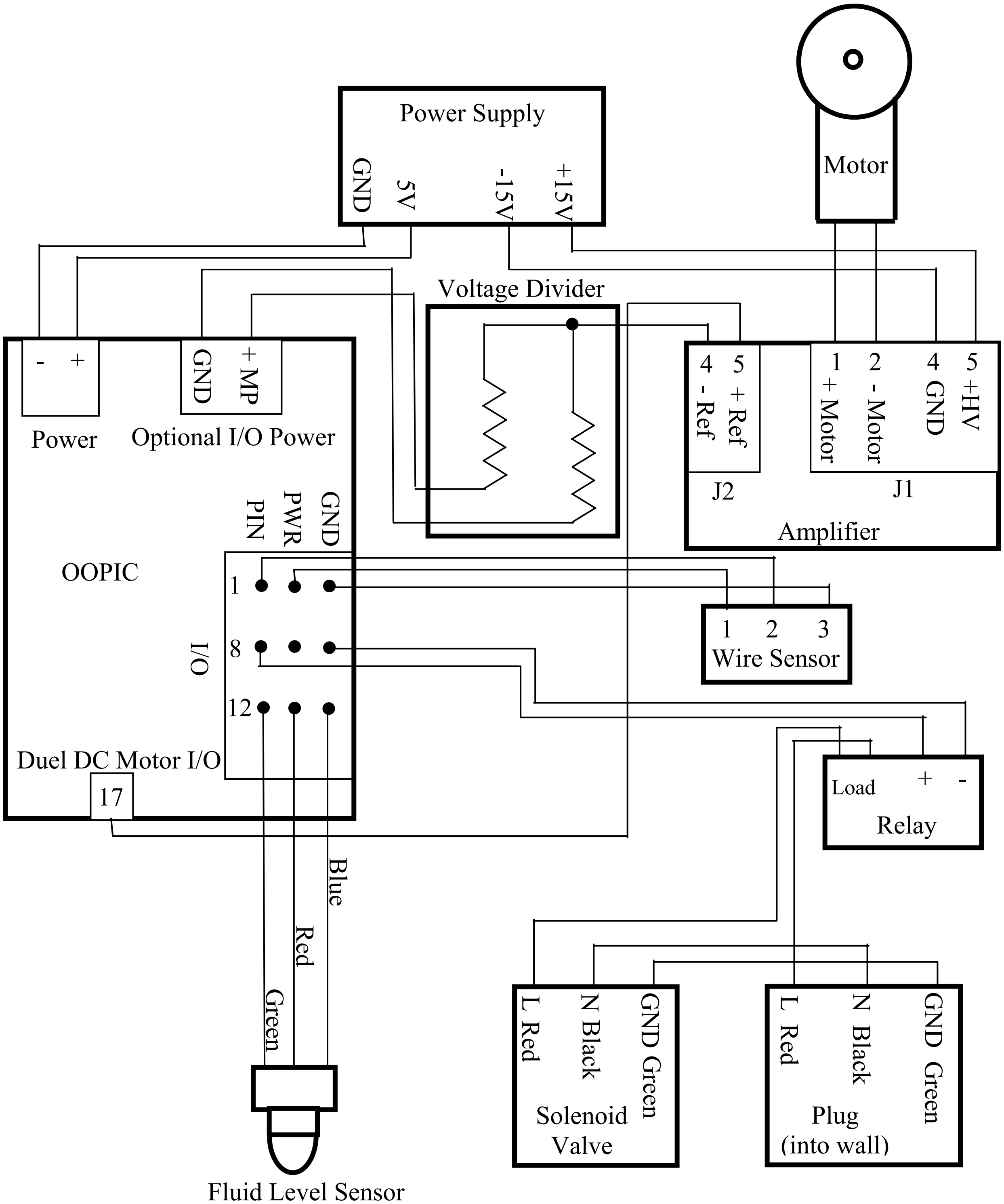
```
'  Declarations

Dim Volts As New oA2D          'Transducer voltage
Dim Motor As New oPWM          'DC Motor control
Dim Aerated As New oByte       'Variable for initial voltage before applying
vacuum
Dim Deaerated As New oByte     'Variable for final voltage after air pushed
out
Dim V1 As New oByte            'Variable for finding piston speed
Dim V2 As New oByte            'Variable for finding piston speed
Dim Sensor As New oDIO1                'Optical sensor
Dim Valve As New oDIO1         'Solenoid valve
Dim Initial As New oByte       'Variable for top piston position
Dim Screen As New oSerial      'Output to monitor


' Main Program

Sub Main ()

        '  Activate DC Motor, Transducer, and Solenoid Valve

        Motor.IOLine = 17              'DC Motor on pin 17
        Motor.Operate = 1              'DC Motor power on
        Volts.IOLine = 1               'Transducer on pin 1
        Volts.Operate = 1              'Transducer active
        Valve.IOLine = 8               'Solenoid Valve on pin 8
        Valve.Direction = cvOutput
        Initial = Volts                'Store top piston position
        Screen.Baud = cv9600
        Screen.Operate = cvTrue

        '  Step 1: Take inital draw of fluid/air into cylinder

        Do While Volts > 105
                Motor = 255    'Motor runs when transducer is extended
                Valve = 1      'Valve is open when transducer is extended
        Loop
        Motor = 125            'Motor turns off when voltage < 125
        Valve = 0              'Valve closes when voltage < 125
        Aerated = Volts.Value  'Initial voltage before applying vacuum
        OOPic.Delay = 300      'Wait 3 seconds before applying vacuum
        'Display initial height of aerated fluid onto monitor
        Screen.String = "Initial Volume: " + Str$(Aerated)
        Screen.Value = 13
        Screen.Value = 10

        '  Step 2: Apply vacuum to fluid and stop when motor can't move

        Do      'Run motor until volts differential over .1 seconds < 10
                V1 = Volts.Value
                Motor = 255
                OOPic.Delay = 10
```

```
        V2 = Volts.Value
    Loop While V1 - V2 > 10
    Motor = 125            'Motor turns off and holds for 1 minute
    OOPic.Delay = 6000

    '  Step 3: Push out excess air

    Sensor.IOLine = 12     'Optical sensor on pin 12
    Sensor.Direction = 1   'Optical sensor is an input
    Valve = 1              'Open valve
    Do      'Run motor in reverse until optical sensor triggered
        Motor = 1
    Loop Until Sensor.Value = 0
    Motor = 125                          'Motor turns off
    Valve = 0                    'Valve closes
    Deaerated = Volts.Value      'Final voltage after pushing out air
    OOPic.Delay = 300
    Valve = 1                    'Valve opens after delay
    'Display final height of deaerated fluid onto monitor
    Screen.String = "Final Volume: " + Str$(Deaerated)
    Screen.Value = 13
    Screen.Value = 10
    Do                     'Return piston to original top position
        Motor = 1
    Loop Until Volts = Initial
    Motor = 125
End Sub
```

APPENDIX E
Functional Decomposition Diagram



APPENDIX F
Schematic of physical interfacing of electronic components



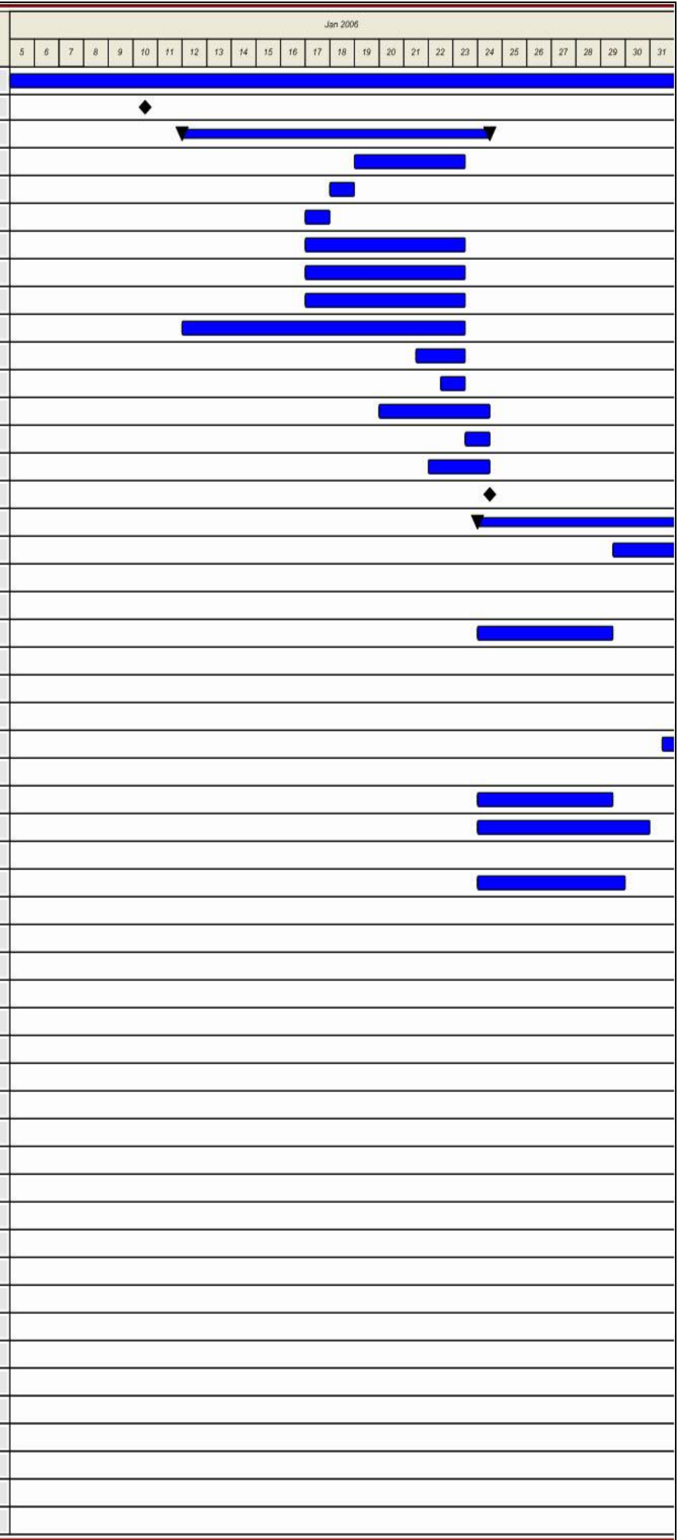
APPENDIX G
Bill of Materials

Quantitity	Part Description	Source	Part Number	Cost	Contact
1	2-1/2"OD x2"ID - 6' Clear Acrylic Extruded Tubing	United States Plastic Corp	44554	$43.32	www.usplastic.com
1	0.236" x 12" x 12" Acrylic Sheet	United States Plastic Corp	44350	$4.64	www.usplastic.com
1	Steel 14-1/2 Deg Pressure Angle Gear Rack 24 Pitch, 1/4" Face Width, 1/4" H O'all, 2' Length	McMaster-Carr	6295K12	$20.00	www.mcmaster.com
1	Steel Plain Bore 14-1/2 Deg Spur Gear 24 Pitch, 12 Teeth, 0.5" Pitch Diameter, 1/4" Bore	McMaster-Carr	6325K31	$9.92	www.mcmaster.com
1	1/16" Aluminum plate	University of Michigan		$0.00	
1	Optical Fluid Sensor	EPA	Honeywell: LLE102000	$0.00	
1	3-way Ball Valve	EPA	McMaster: 46095K41	$0.00	
1	Brass Mini Solenoid Valve	EPA	McMaster: 7994K55	$0.00	
1	Automotive Window motor	Auto Salvage Yard	Siemens: F87B7827145AA	$0.00	
1	Cable Length Transducer Sensor	Micro-epsilon	MK30	$200.00	www.me-us.com
2	Rubber o-ring 2" OD, 1-5/8" ID, 3/16" Width	Stadium Hardware		$1.00	
2	#4-40x1" machine screws and nuts	Home Depot		$1.29	
3	1/4"x2"x20 machine screws and nuts	University of Michigan		$0.00	
4	1/4"x1"x20 machine screws and nuts	University of Michigan		$0.00	
6	1/4" Washer	University of Michigan		$0.00	

Quantitity	Part Description	Source	Part Number	Cost	Contact
1	Electronic Relay	Digikey	Z903-ND	$7.38	www.digikey.com
1	OOPic	University of Michigan		$0.00	www.oopic.com
1	Power Supply	University of Michigan		$0.00	
1	Amplifier	University of Michigan		$0.00	

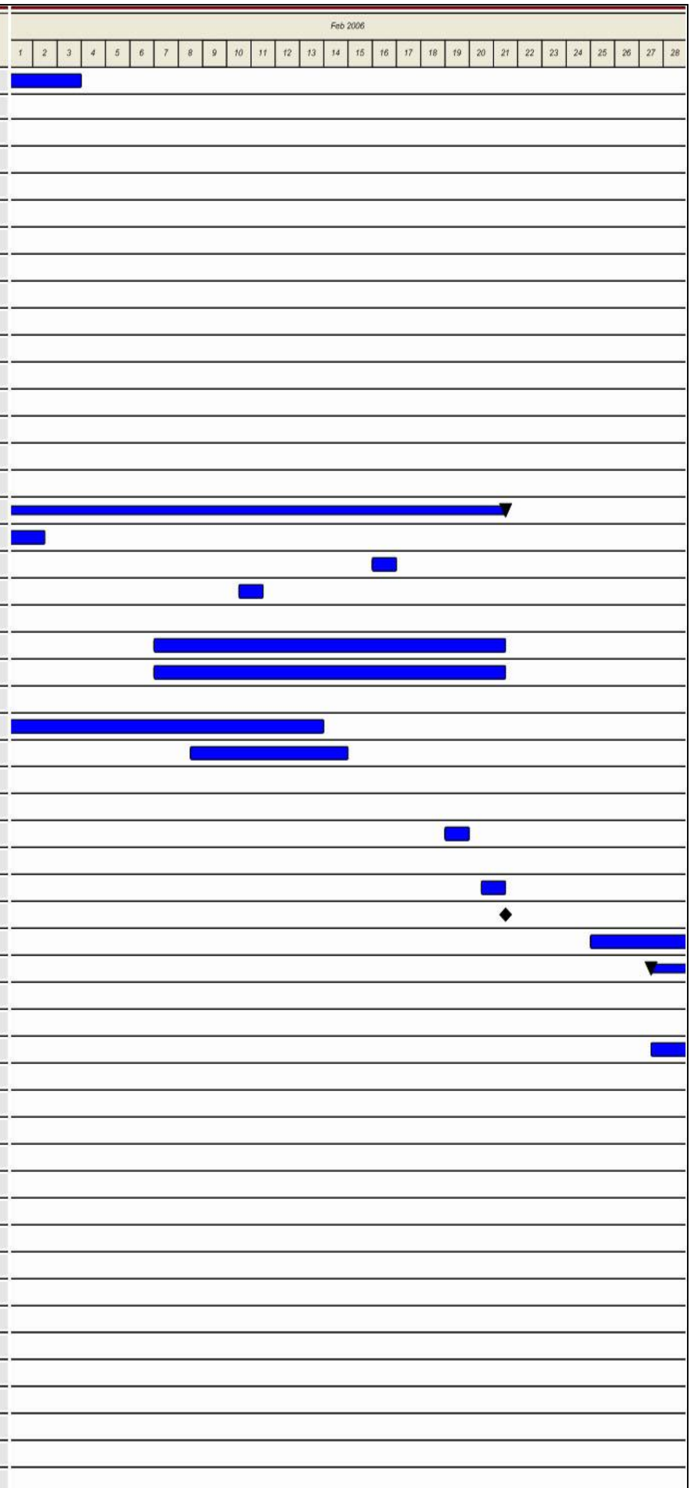
APPENDIX H.1
Gantt Chart – January

ID	Task Name	Description	Duration
1	Background Research	Find our more on hydraulic systems and hydraulic hybrids	4w 2d
2	Sponsor Meeting	Information Gathering	0w
3	**Prep for Design Review #1**		**1w 5.5d**
4	Create Executive Summary		4.5d
5	Work on Revised Abstract		1d
6	Meet with Sponsors	Meet with Neil Johnson and Steve Dockstader	1d
7	Work on problem description/definition		6.5d
8	Customer Requirements and Engineering Specifications	Create Initial QFD	6.5d
9	Create Project Plan	Gantt Chart	6.5d
10	Work on Problem Analysis		1w 4.5d
11	Document all Information Sources		2d
12	Complete Conclusions		1d
13	Finalize Design Review #1 Report		4.5d
14	Team Roles worksheet		1d
15	Prepare Design Review #1 Presentation		2.5d
16	Design Review #1	Engineering Specs and Literature Review	0w
17	**Prep for Design Review #2**		**4w .5d**
18	Revise Design Review #1 Report	Make corrections from comments on report	4d
19	Meet with Neil Johnson and Andy Moskalik	Obtain info on Expedition setup and deaeration concepts/feedback	1d
20	Meet with Challenge X Team to verify requirements		1d
21	Brainstorm Design Ideas		5.5d
22	Benchmark Coolers	Look at all brands/types available that meet our requirements	2w .5d
23	Benchmark Filters	Look at all brands/types available that meet our requirements	2w .5d
24			
25	Meet with Professors on Deaerator Ideas/ Calculations		1w 6.5d
26	Meet with Professors about Semi-permeable membranes		6.5d
27	Discuss pros and cons of each design		5.5d
28	Choose a design		1w
29	Meet with Challenge X to provide update on our status		1d
30	Develop Technical Aspects of Design		6d
31	Analysis Designs		1d
32	Design Review #2	Concept Generation, Selection, Preliminary Engineering Analysis	0w
33	Spring Break		1w 3d
34	**Prep for Design Review #3**		**2w 2.5d**
35	Meet with Challenge X team to Obtain Confirmation/Approval for parts	Make sure that they approve of parts order for the vehicle	1d
36	Finalize Design for Aeration Detection System	Start shopping around components and determine manufacturing process	1d
37	Perform research on mechanisms to actuate, measure, and control	Valves, plungers, housing, micrometers, servos, gearing	1w .5d
38	Meet with Professors about Fluid Monitoring	Prof Ceccio on cavitations and multiphase flows	4d
39	Order Cooler and Filter		1d
40	Perform Calculations and Analysis on Fluid Monitoring System	Make predictions for performance before manufacturing	1w .5d
41	Begin assembling testing apparatus for measuring Aeration Detection System	Need to be able to test amount of nitrogen in oil	2.5d
42	Test flow in vehicle and measuring performance of cooler		4d
43	Install Filter and Cooler in the Challenge X vehicle	Run hoses, install valves, and build mounting points	6.5d
44	Manufacture and assemble Aeration Detection System		4d
45	Design Review #3	Final Design and Engineering Analysis	0w
46	**Prep for Design Review #4**		**1w 4d**
47	Fix and improve design		3.5d
48	Continue in vehicle performance testing.		6d
49	Design Review #4	Alpha Prototype Review	0w
50	Prep for Design Expo		2w
51	Design Expo		0w
52	Prepare Final Report		2w 5d
53	Final Report Due		0w



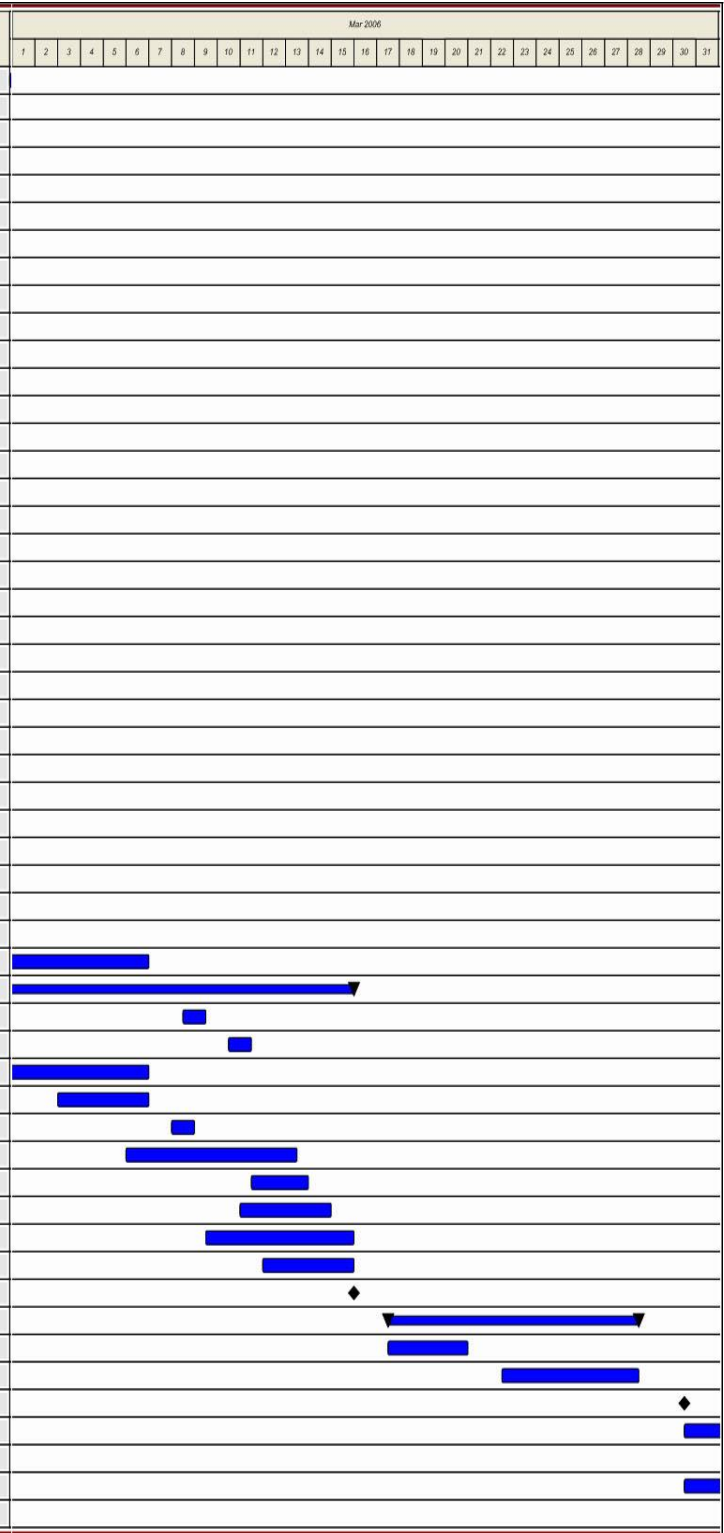
APPENDIX H.2
Gantt Chart – February

ID	Task Name	Description	Duration
1	Background Research	Find our more on hydraulic systems and hydraulic hybrids	4w 2d
2	Sponsor Meeting	Information Gathering	0w
3	**Prep for Design Review #1**		**1w 5.5d**
4	Create Executive Summary		4.5d
5	Work on Revised Abstract		1d
6	Meet with Sponsors	Meet with Neil Johnson and Steve Dockstader	1d
7	Work on problem description/definition		6.5d
8	Customer Requirements and Engineering Specifications	Create Initial QFD	6.5d
9	Create Project Plan	Gantt Chart	6.5d
10	Work on Problem Analysis		1w 4.5d
11	Document all Information Sources		2d
12	Complete Conclusions		1d
13	Finalize Design Review #1 Report		4.5d
14	Team Roles worksheet		1d
15	Prepare Design Review #1 Presentation		2.5d
16	Design Review #1	Engineering Specs and Literature Review	0w
17	**Prep for Design Review #2**		**4w .5d**
18	Revise Design Review #1 Report	Make corrections from comments on report	4d
19	Meet with Neil Johnson and Andy Moskalik	Obtain info on Expedition setup and deaeration concepts/feedback	1d
20	Meet with Challenge X Team to verify requirements		1d
21	Brainstorm Design Ideas		5.5d
22	Benchmark Coolers	Look at all brands/types available that meet our requirements	2w .5d
23	Benchmark Filters	Look at all brands/types available that meet our requirements	2w .5d
24			
25	Meet with Professors on Deaerator Ideas/ Calculations		1w 6.5d
26	Meet with Professors about Semi-permeable membranes		6.5d
27	Discuss pros and cons of each design		5.5d
28	Choose a design		1w
29	Meet with Challenge X to provide update on our status		1d
30	Develop Technical Aspects of Design		6d
31	Analysis Designs		1d
32	Design Review #2	Concept Generation, Selection, Preliminary Engineering Analysis	0w
33	Spring Break		1w 3d
34	**Prep for Design Review #3**		**2w 2.5d**
35	Meet with Challenge X team to Obtain Confirmation/Approval for parts	Make sure that they approve of parts order for the vehicle	1d
36	Finalize Design for Aeration Detection System	Start shopping around components and determine manufacturing process	1d
37	Perform research on mechanisms to actuate, measure, and control	Valves, plungers, housing, micrometers, servos, gearing	1w .5d
38	Meet with Professors about Fluid Monitoring	Prof Ceccio on cavitations and multiphase flows	4d
39	Order Cooler and Filter		1d
40	Perform Calculations and Analysis on Fluid Monitoring System	Make predictions for performance before manufacturing	1w .5d
41	Begin assembling testing apparatus for measuring Aeration Detection System	Need to be able to test amount of nitrogen in oil	2.5d
42	Test flow in vehicle and measuring performance of cooler		4d
43	Install Filter and Cooler in the Challenge X vehicle	Run hoses, install valves, and build mounting points	6.5d
44	Manufacture and assemble Aeration Detection System		4d
45	Design Review #3	Final Design and Engineering Analysis	0w
46	**Prep for Design Review #4**		**1w 4d**
47	Fix and improve design		3.5d
48	Continue in vehicle performance testing.		6d
49	Design Review #4	Alpha Prototype Review	0w
50	Prep for Design Expo		2w
51	Design Expo		0w
52	Prepare Final Report		2w 5d
53	Final Report Due		0w



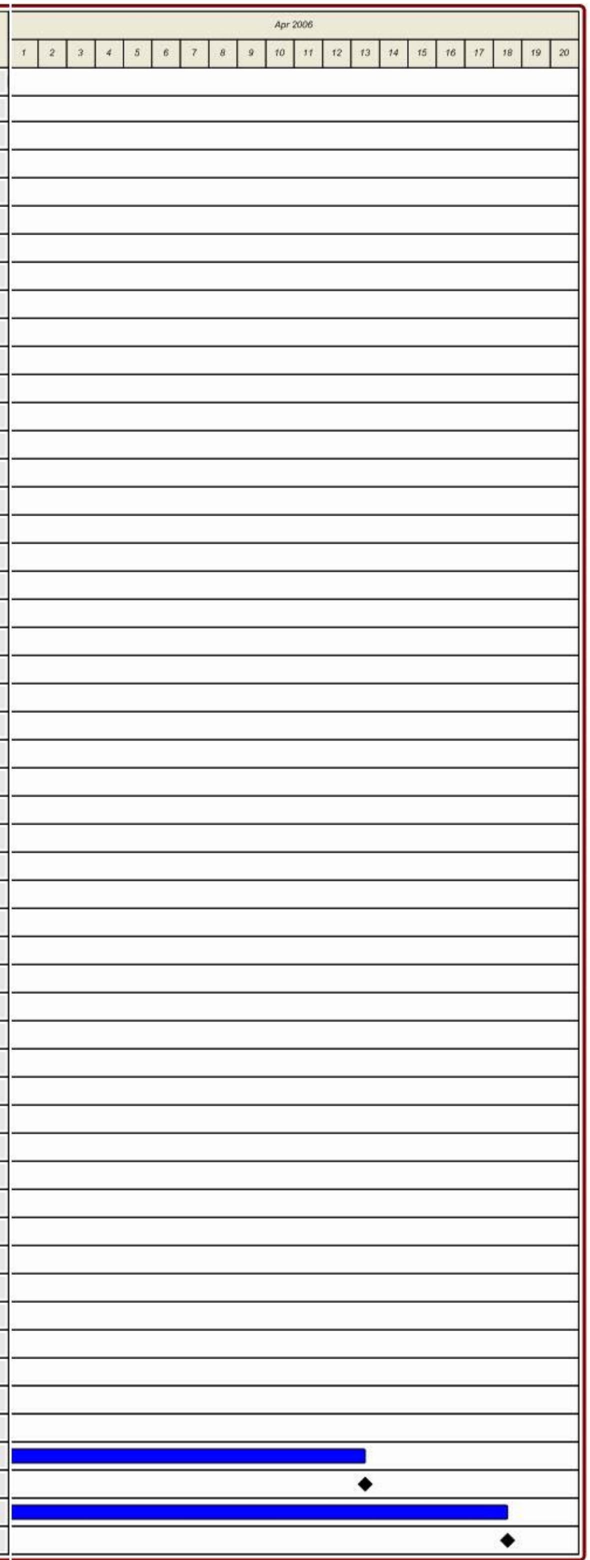
APPENDIX H.3
Gantt Chart – March

ID	Task Name	Description	Duration
1	Background Research	Find our more on hydraulic systems and hydraulic hybrids	4w 2d
2	Sponsor Meeting	Information Gathering	0w
3	**Prep for Design Review #1**		**1w 5.5d**
4	Create Executive Summary		4.5d
5	Work on Revised Abstract		1d
6	Meet with Sponsors	Meet with Neil Johnson and Steve Dockstader	1d
7	Work on problem description/definition		6.5d
8	Customer Requirements and Engineering Specifications	Create Initial QFD	6.5d
9	Create Project Plan	Gantt Chart	6.5d
10	Work on Problem Analysis		1w 4.5d
11	Document all Information Sources		2d
12	Complete Conclusions		1d
13	Finalize Design Review #1 Report		4.5d
14	Team Roles worksheet		1d
15	Prepare Design Review #1 Presentation		2.5d
16	Design Review #1	Engineering Specs and Literature Review	0w
17	**Prep for Design Review #2**		**4w .5d**
18	Revise Design Review #1 Report	Make corrections from comments on report	4d
19	Meet with Neil Johnson and Andy Moskalik	Obtain info on Expedition setup and deaeration concepts/feedback	1d
20	Meet with Challenge X Team to verify requirements		1d
21	Brainstorm Design Ideas		5.5d
22	Benchmark Coolers	Look at all brands/types available that meet our requirements	2w .5d
23	Benchmark Filters	Look at all brands/types available that meet our requirements	2w .5d
24			
25	Meet with Professors on Deaerator Ideas/ Calculations		1w 6.5d
26	Meet with Professors about Semi-permeable membranes		6.5d
27	Discuss pros and cons of each design		5.5d
28	Choose a design		1w
29	Meet with Challenge X to provide update on our status		1d
30	Develop Technical Aspects of Design		6d
31	Analysis Designs		1d
32	Design Review #2	Concept Generation, Selection, Preliminary Engineering Analysis	0w
33	Spring Break		1w 3d
34	**Prep for Design Review #3**		**2w 2.5d**
35	Meet with Challenge X team to Obtain Confirmation/Approval for parts	Make sure that they approve of parts order for the vehicle	1d
36	Finalize Design for Aeration Detection System	Start shopping around components and determine manufacturing process	1d
37	Perform research on mechanisms to actuate, measure, and control	Valves, plungers, housing, micrometers, servos, gearing	1w .5d
38	Meet with Professors about Fluid Monitoring	Prof Ceccio on cavitations and multiphase flows	4d
39	Order Cooler and Filter		1d
40	Perform Calculations and Analysis on Fluid Monitoring System	Make predictions for performance before manufacturing	1w .5d
41	Begin assembling testing apparatus for measuring Aeration Detection System	Need to be able to test amount of nitrogen in oil	2.5d
42	Test flow in vehicle and measuring performance of cooler		4d
43	Install Filter and Cooler in the Challenge X vehicle	Run hoses, install valves, and build mounting points	6.5d
44	Manufacture and assemble Aeration Detection System		4d
45	Design Review #3	Final Design and Engineering Analysis	0w
46	**Prep for Design Review #4**		**1w 4d**
47	Fix and improve design		3.5d
48	Continue in vehicle performance testing.		6d
49	Design Review #4	Alpha Prototype Review	0w
50	Prep for Design Expo		2w
51	Design Expo		0w
52	Prepare Final Report		2w 5d
53	Final Report Due		0w



APPENDIX H.4
Gantt Chart – April

ID	Task Name	Description	Duration
1	Background Research	Find our more on hydraulic systems and hydraulic hybrids	4w 2d
2	Sponsor Meeting	Information Gathering	0w
3	**Prep for Design Review #1**		**1w 5.5d**
4	Create Executive Summary		4.5d
5	Work on Revised Abstract		1d
6	Meet with Sponsors	Meet with Neil Johnson and Steve Dockstader	1d
7	Work on problem description/definition		6.5d
8	Customer Requirements and Engineering Specifications	Create Initial QFD	6.5d
9	Create Project Plan	Gantt Chart	6.5d
10	Work on Problem Analysis		1w 4.5d
11	Document all Information Sources		2d
12	Complete Conclusions		1d
13	Finalize Design Review #1 Report		4.5d
14	Team Roles worksheet		1d
15	Prepare Design Review #1 Presentation		2.5d
16	Design Review #1	Engineering Specs and Literature Review	0w
17	**Prep for Design Review #2**		**4w .5d**
18	Revise Design Review #1 Report	Make corrections from comments on report	4d
19	Meet with Neil Johnson and Andy Moskalik	Obtain info on Expedition setup and deaeration concepts/feedback	1d
20	Meet with Challenge X Team to verify requirements		1d
21	Brainstorm Design Ideas		5.5d
22	Benchmark Coolers	Look at all brands/types available that meet our requirements	2w .5d
23	Benchmark Filters	Look at all brands/types available that meet our requirements	2w .5d
24			
25	Meet with Professors on Deaerator Ideas/ Calculations		1w 6.5d
26	Meet with Professors about Semi-permeable membranes		6.5d
27	Discuss pros and cons of each design		5.5d
28	Choose a design		1w
29	Meet with Challenge X to provide update on our status		1d
30	Develop Technical Aspects of Design		6d
31	Analysis Designs		1d
32	Design Review #2	Concept Generation, Selection, Preliminary Engineering Analysis	0w
33	Spring Break		1w 3d
34	**Prep for Design Review #3**		**2w 2.5d**
35	Meet with Challenge X team to Obtain Confirmation/Approval for parts	Make sure that they approve of parts order for the vehicle	1d
36	Finalize Design for Aeration Detection System	Start shopping around components and determine manufacturing process	1d
37	Perform research on mechanisms to actuate, measure, and control	Valves, plungers, housing, micrometers, servos, gearing	1w .5d
38	Meet with Professors about Fluid Monitoring	Prof Ceccio on cavitations and multiphase flows	4d
39	Order Cooler and Filter		1d
40	Perform Calculations and Analysis on Fluid Monitoring System	Make predictions for performance before manufacturing	1w .5d
41	Begin assembling testing apparatus for measuring Aeration Detection System	Need to be able to test amount of nitrogen in oil	2.5d
42	Test flow in vehicle and measuring performance of cooler		4d
43	Install Filter and Cooler in the Challenge X vehicle	Run hoses, install valves, and build mounting points	6.5d
44	Manufacture and assemble Aeration Detection System		4d
45	Design Review #3	Final Design and Engineering Analysis	0w
46	**Prep for Design Review #4**		**1w 4d**
47	Fix and improve design		3.5d
48	Continue in vehicle performance testing.		6d
49	Design Review #4	Alpha Prototype Review	0w
50	Prep for Design Expo		2w
51	Design Expo		0w
52	Prepare Final Report		2w 5d
53	Final Report Due		0w



APPENDIX I.1
DesignSafe 3.0 Report

designsafe Report

Application:	Xcellent	Analyst Name(s):	Sakib Elahi
Description:	Aeration Detection System	Company:	University of Michigan
Product Identifier:	Team 21	Facility Location:	X50 Lab
Assessment Type:	Detailed		
Limits:	Complete assessment for using ADS		
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users normal operation	mechanical : break up during operation separation of welded joints	Serious Remote Negligible	Low		Serious Remote Negligible	Low	
All Users normal operation	electrical / electronic : energized equipment / live parts high power solenoid valve	Serious Occasional Possible	High	insulate valve	Minimal Remote Negligible	Low	
All Users normal operation	electrical / electronic : water / wet locations fluid can leak and wet circuits	Catastrophic Remote Possible	High	insulate electronics with waterproof cover	Minimal Remote Negligible	Low	
All Users normal operation	slips / trips / falls : slip leakage of fluid onto floor	Slight Remote Unlikely	Low		Slight Remote Unlikely	Low	
All Users normal operation	fire and explosions : flames overheated motor could burn oil	Catastrophic Remote Unlikely	Moderate	enclose motor in casing	Minimal Remote Negligible	Low	
All Users normal operation	fluid / pressure : high pressure air pressurized accumulator	Slight Remote Unlikely	Low		Slight Remote Unlikely	Low	
All Users normal operation	fluid / pressure : fluid leakage / ejection leak through cracks	Slight Remote Unlikely	Low		Slight Remote Unlikely	Low	
All Users installation/removal	mechanical : drawing-in / trapping / entanglement rotating motor and rack/pinion	Slight Remote Unlikely	Low	enclose motor in casing	Minimal Remote Negligible	Low	
All Users installation/removal	mechanical : pinch point rotating motor and rack/pinion	Slight Remote Unlikely	Low	enclose motor in casing	Minimal Remote Negligible	Low	

APPENDIX I.2
Design Safe 3.0 Report

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users installation/removal	electrical / electronic : water / wet locations fluid can leak and wet circuits	Catastrophic Remote Possible	High	insulate electronics with waterproof cover	Minimal Remote Negligible	Low	
All Users installation/removal	slips / trips / falls : slip leakage of fluid onto floor	Slight Remote Unlikely	Low		Slight Remote Unlikely	Low	
All Users installation/removal	heat / temperature : burns / scalds overheated motor can burn hands	Serious Occasional Possible	High	enclose motor in casing	Minimal Remote Negligible	Low	
All Users installation/removal	environmental / industrial hygiene : hazardous waste improper disposal of oil	Serious Remote Unlikely	Moderate	warning signs alerting user to properly dispose of oil	Serious Remote Negligible	Low	
All Users installation/removal	environmental / industrial hygiene : irritants hydraulic fluid	Minimal Occasional Unlikely	Low	warning signs alerting user to wash hands thoroughly after contact	Minimal Occasional Negligible	Low	
All Users installation/removal	environmental / industrial hygiene : wastewater contamination improper disposal of oil	Serious Remote Unlikely	Moderate	warning signs alerting user to properly dispose of oil	Serious Remote Negligible	Low	
All Users installation/removal	fluid / pressure : fluid leakage / ejection spill of fluid from hydraulic line when removing cylinder	Slight Occasional Possible	Moderate	instruct user to clamp line before removing cylinder	Slight Remote Negligible	Low	Complete [4/18/2006]