Dry Sump Lubrication of a Hydraulic Motor

Sponsored by the National Vehicle and Fuel Emissions Laboratory,
a division of the Environmental Protection Agency

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Project Abstract:

The National Vehicle and Fuel Emissions Lab part of the EPA has teamed up with UPS in order to create fuel efficient hybrid delivery vehicles. Preliminary estimates on the hybrid system show that UPS will save 35% on fuel expenditures. The hybrid system that is integrated into the delivery trucks consists of two hydraulic motors and a hydraulic pump, driven by the existing diesel engine. The hydraulic motors driving the rear wheels currently operate while immersed in hydraulic fluid for lubrication and cooling purposes. This lubrication method introduces efficiency losses due to drag on the moving parts. Our goal is to create a hydraulic motor lubrication system with increased efficiency.

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1. Introduction

The dry sump lubrication project is sponsored by Dr. Andrew Moskalik at the EPA's (Environmental Protection Agency) National Vehicle and Fuel Emissions Lab (NVFEL). The NVFEL is working for UPS on a hydraulic hybrid drive system that can be implemented into existing delivery trucks. The goal of the hybrid project is to lower fuel consumption of the delivery vehicles, thus lowering operating costs.

The existing delivery trucks are driven by 6.0 liter diesel engines. In the new hybrid system, there will be two hydraulic motors, and a hydraulic pump being driven by the diesel engine. The hydraulic system improves the vehicle's fuel efficiency due to the fact that during braking, the drive motors act as pumps and store pressurized fluid in accumulators. This pressurized fluid can then power the hydraulic motors when the vehicle starts moving again.

The hydraulic motors rotate inside cases and convert pressurized fluid to rotational power, driving the vehicle's rear wheels. The hydraulic pump also rotates inside a case. In order to lubricate and cool the moving parts, the cases are filled with hydraulic fluid. This method creates inefficiencies due to the viscous friction developed in the fluid. We are designing a dry sump system in which the motor and pump will be lubricated without being immersed in fluid.

The main advantage of the dry sump system is that the motor and pump cases do not fill with lubricant, which increases efficiency. Instead, the hydraulic fluid used for lubrication is stored in an external reservoir. An electric pump will remove the fluid from the motor case. Then, another electric pump will provide pressure to the fluid and return the oil to the motors and pump. There is limited space on the vehicle; therefore, no part of the design exceeds 15" in height. The existing pressure used for lubrication is 30 psi; the design achieves that. Also, under normal operating conditions, gas bubbles are introduced into the fluid by the rotating motor components. By swirling the oil around the inside wall of the reservoir, the oil will be de-aerated. The design needs to keep out ambient air, as well as be able to be integrated with a de-bubbling system being developed by a group of graduate students.

Dr. Moskalik also mentioned integrating a hydraulic fluid cooler in our system if it is feasible. The location and configuration of such a cooler will be investigated.

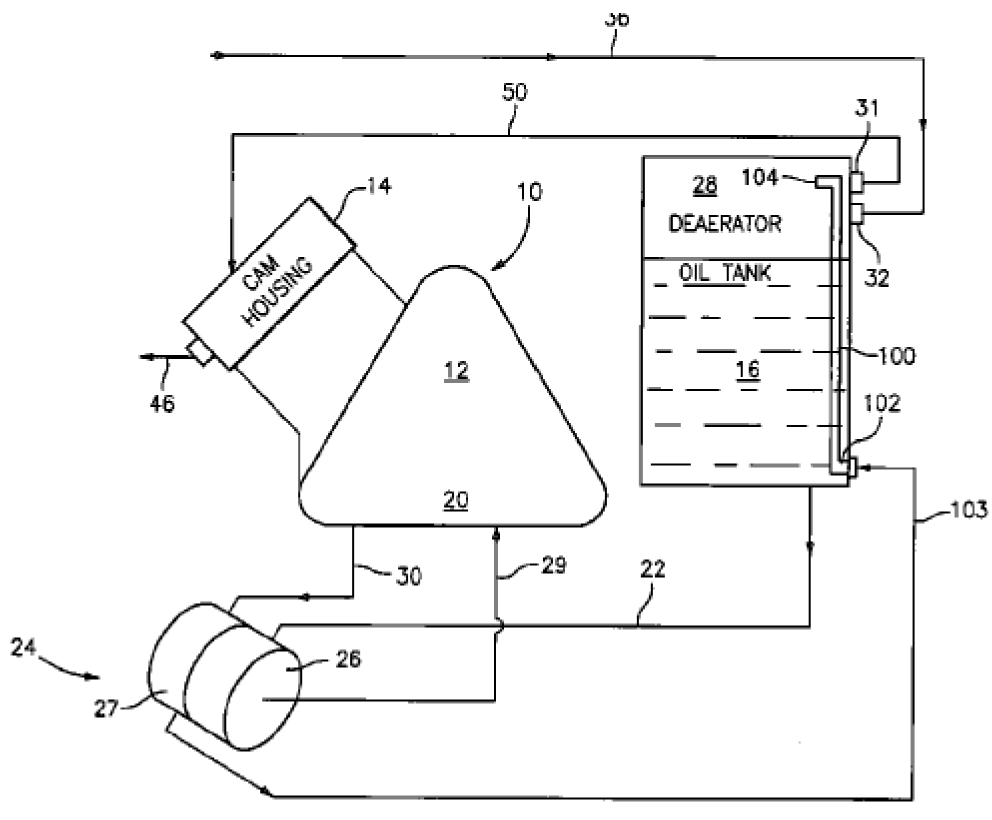
2. Information Search

Dr. Moskalik introduced this project by describing it as a dry sump lubrication system. Dry sump lubrication systems have been used in the automobile and aircraft industry for many years. Our preliminary search focused on finding patents of such systems.

2.1 Patents

Two patents were found that directly describe a dry sump lubrication used in the automotive industry. Patents 4,681,189 and 7,017,546 both show systems that use two gear type hydraulic pumps. One pump is connected directly to the shallow sump (20) underneath the engine block. This pump (27) is known as a "scavenge" pump and pulls the oil from the sump and sends it to a cylindrical reservoir (16) to be de-aerated (28) and stored. Another pump (26), called the pressure pump pulls oil from the reservoir, pressurizes it, and sends it back to the engine (12). Figure 1 outlines the system from Patent 7,017,546.

Fig.1: Patent 7,017,546



2.2 Information Gaps/Design Considerations

After evaluating the concepts generated, the system will utilize two diaphragm pumps. The oil container material and final geometry needs to be determined. The material chosen should have a heat high conductivity to facilitate oil cooling and should be able to be fabricated in the machine shop. This indicates the material must have properties that support welding and machining with in-house equipment. Based on previous experience, the tank will be made of either aluminum or stainless steel. Both these metals are corrosion resistant as well, so they can withstand the environment under the vehicle. The system will be installed on several different types of vehicles; therefore mounting points will be machined onto components for convenience.

There are currently no existing technical benchmarks for systems such as these. The patents provided above show systems designed for gasoline driven automobile engines, but not hydraulic hybrid systems.

3. Customer Requirements and Engineering Specifications

During our meeting with Dr. Moskalik, he outlined to us many specifications the dry sump system we will design has to meet. These are summarized below:

3.1 Customer requirements:

1.) Remove lubricating oil from the hydraulic motor case
2.) Consume the lowest possible power
3.) The system should be small and compact
4.) The design lifetime is ~10 years or 250,000 miles
5.) Should be able to fit in spaces existing on the undercarriage
6.) Should be compatible with 12 volt vehicle system
7.) The vehicles operate in wide range of climates. Our system should be able to as well.

Utilizing the QFD diagram and with further talks with Dr. Moskalik, we formulated preliminary engineering specifications. Although typically the customer provides general requirements, then the engineers formulate engineering specifications, this situation was different. Dr. Moskalik provided the team with specific engineering specifications to adhere to. Removal of oil from the motor case will require an outflow from the motor. Dr. Moskalik specified that the oil flow out of the motors and pumps was approximately 1.7 GPM. Low power consumption requires that we run the system off the vehicles existing charging system without a voltage convertor. After consulting Dr. Moskalik, a small system, fitting under the vehicle means the total height shall be less than 15 inches. The lifetime of the system will be highly dependent on the environmental conditions; therefore the system should be shielded from harsh surroundings. In addition, our sponsor gave additional engineering specifications, which are all summarized below:

3.2 Engineering Specifications:

1.) Oil flow to motors and pump is ~1.7 GPM (2 motors/1 pump in UPS vehicle)
2.) Oil supply pressure to motors and pump is ~30 PSI
3.) The height of the dry sump system cannot exceed 15”
4.) The system needs to be closed to the outside environment to prevent contamination of oil

5.) Needs to run off of a 12 Volt system
6.) The high pressure hydraulic fluid leak rate from each motor into the hydraulic lubricating oil is about 0.2 GPM (2 motors in UPS vehicle)
7.) The system needs to able to be integrated with a debubbler to remove air from the oil that is returned to the main hydraulic system.

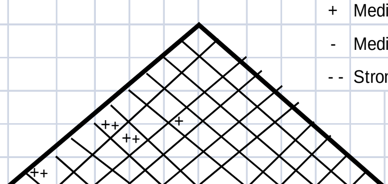
The QFD shown in Fig. 2 shows that the most important customer requirement is to keep the motor case free of oil. The roof of the QFD shows the relationship of the oil pressure and flows to the climate the vehicle is in. When the vehicle is operated in a warm climate, the hydraulic oil's viscosity will be lower, making it easier to pump, thus requiring less power. Conversely, in cold weather areas, viscosity will increase, reducing the flows and pressures to low values. This must be accounted for when designing the dry sump system. In addition, there is a strong positive correlation between the flow rates and pressures with the supply voltage of 12 Volts.

Fig. 2: QFD

Quality Function Development (QFD)

Relationships

++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative



(+) => more is better
(-) => less is better

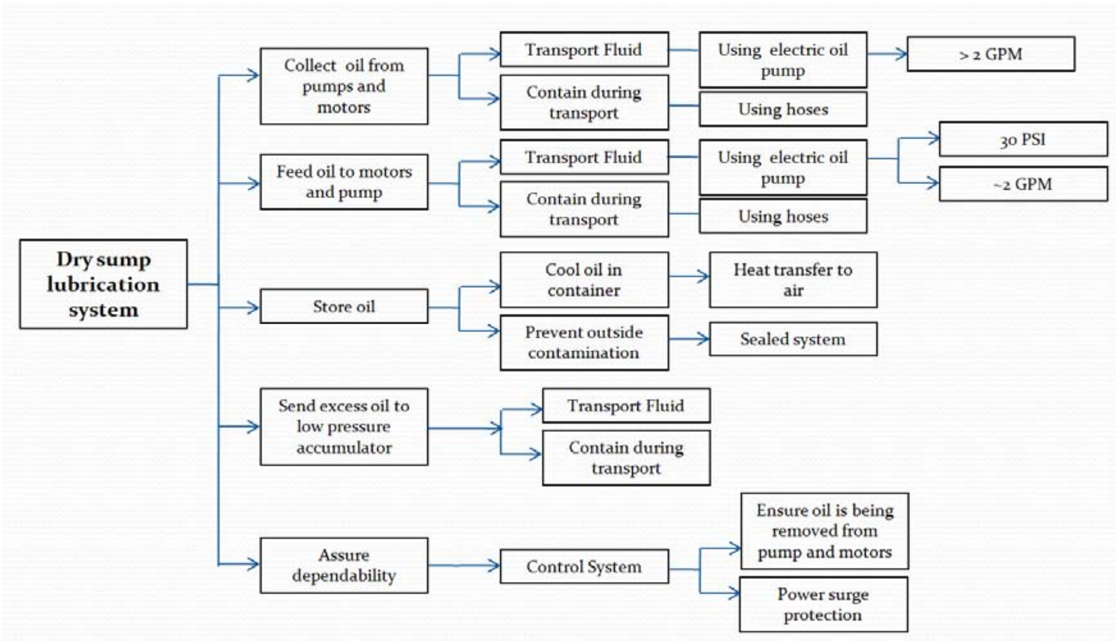
		Weight*	Oil Flow is 1.2 GPM per motor	Oil supply pressure to motors is ~30PSI	Height of system not to exceed 15"	System is closed to the outside environment	System should be powered by 12 volts	Hydraulic fluid leak rate ~.2 GPM per motor	Be compatible with existing debubbler				Benchmarks: *Unknown as of yet*
1	Keep oil out of motor	6	1	1	3			9					
2	Consume low power	2	9	9			9						
3	Small, compact system	4	3	3	9	3			3				
4	Lifetime of 10 yrs.	0	1	1		1	1						
5	Run off of 12 V system	1	9	9					1				
6	Be compatible with existing vehicle setup	4	3	3	9	3	9		1				
7	Operate in a variety of climates	4	9	9			3						
	Measurement Unit		GPM	PSI	"		V	GPM					
	Target Value		1.2	30	12		12	0.2					
	Importance Rating		**5**	**5**	**3**	**2**	**4**	**5**	**4**				
	Total		93	93	90	24	66	54	17	0	0	0	
	Normalized		0.21	0.21	0.21	0.05	0.15	0.12	0.04	0.00	0.00	0.00	

4. Concept Generation

To identify the key functions and sub-functions needed for the prototype, a FAST diagram was constructed. The five main functions the prototype will have to perform are:

1. Collect oil from hydraulic motors and pump
2. Feed oil under pressure to hydraulic motors and pump
3. Store oil
4. Send overflow oil to low pressure accumulator in vehicle
5. Assure dependability and reliability

Fig. 3: FAST diagram



The main functions were identified using the QFD customer requirements. The highest weighted requirement was to keep oil out of the motor, which lead to the generation of Function #1. Function #2 was developed because the motors and pump require a supply of pressurized oil for lubrication and cooling. Function #3 was a direct request from our sponsor. Function #4 was needed to keep the system self contained. Function #5 is required for the system to function under different environmental and vehicle conditions, such as temperature variations.

To develop high level concepts, a morphological chart was used to map concept ideas to specific functions they can fulfill. The concepts generated were divided into 3 categories: *Mechanical, Fluid* and *Other* power sources. The morphological chart is shown in Fig. 4 below.

Fig. 4: Morphological Chart (Part 1)

Function	Concept	Concept	Concept	Concept	Concept
Collect oil from motors and pump	Non-linear flow/speed pump (centrifugal)	Linear flow/speed pump (gear or diapraghm)	Gravity Feed	Piston/Resovoir pump	Venturi effect
Feed oil to motors and pump	Linear flow/speed pump (gear or diapraghm)	Use existing high pressure oil supply	Non-linear flow/speed pump (centrifugal)	Piston/Reservoir pump	
Send excess oil to low pressure accumulator	TBD				
Store oil	Metal tank	Plastic bladder	In piping		
Cool oil	Air cooled heat exchanger (external)	Air cooled heat exchanger (using tank as HX), high k	Finned piping		
Deaerate oil	Swirl airy oil around tank inner wall	Make tank large enough to allow bubbles to settle out			

Fig.5: Morphological Chart (Part 2 - divided into different power sources)

	Mechanical	*Fluid*	*Other*		
Collect oil from motors and pump	Non-linear flow/speed pump (centrifugal)	Venturi effect	Gravity Feed		
	Linear flow/speed pump (gear or diapraghm)				
	Piston/Resevoir pump				
Feed oil to motors and pump	Non-linear flow/speed pump (centrifugal)	Utilize existing High Pressure oil supply			
	Linear flow/speed pump (gear or diapraghm)				
	Piston/Reservoir pump				
Send excess oil to low pressure accumulator	TBD				
Store oil	Metal Tank				
	Plastic bladder				
	In piping				
Cool oil	Air cooled heat exchanger (external)				
	Air cooled heat exchanger (using tank as HX), high k				
	Finned piping				
Deaerate oil	Make tank large enough to allow bubbles to settle out	Swirl airy oil around tank inner wall			

4.1 *Mechanical*

In order to collect and feed oil to the hydraulic motors and pump, a centrifugal pump was considered. It converts mechanical power into fluid power. In addition to the centrifugal pump, a positive displacement diaphragm type pump was investigated. This type of pump has the characteristic of a linear flow/speed curve. A centrifugal pump has a non-linear curve, and power requirement would be higher for the same pressure and flow rate.

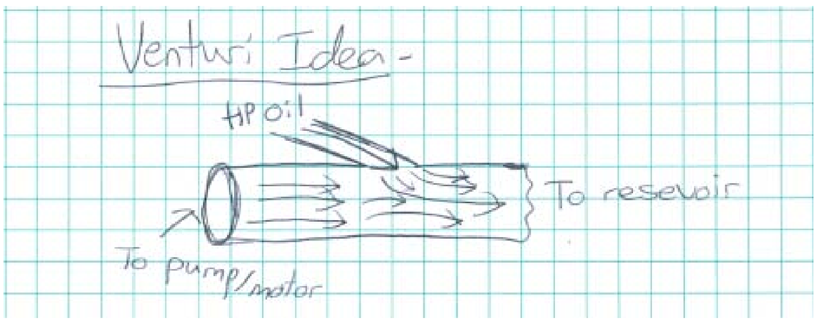
A mechanical system for de-aerating the oil was considered. The system would swirl the oil around the inside of the cylindrical reservoir tank. The swirling action would help remove air bubbles from the oil.

4.2 *Fluid*

To feed oil to the hydraulic motors and pump, the use of the existing high pressure oil available on the vehicle was considered. The truck uses high pressure (5000 psi) oil to power the hydraulic motors. The high pressure oil would go through a pressure reduction valve (orifice) and supply the motors and pump with oil at 30 psi.

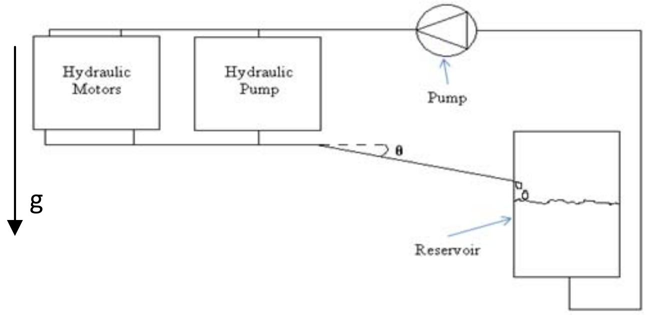
To remove the oil from the hydraulic motors and pump cases, a Venturi system was considered. The Venturi vacuum system would utilize the high pressure (5000 psi) oil from the power train of the truck to create a vacuum that would draw oil out of the motor and pump casings. This concept is shown in Fig. 5.

Fig 5: Venturi



A gravity return system was conceptualized. This would entail locating the reservoir below the hydraulic motors and pump. Fluid would flow from the bottoms of the hydraulic motors and pump casings by gravity. This is shown in Fig. 6.

Fig. 6: Gravity return

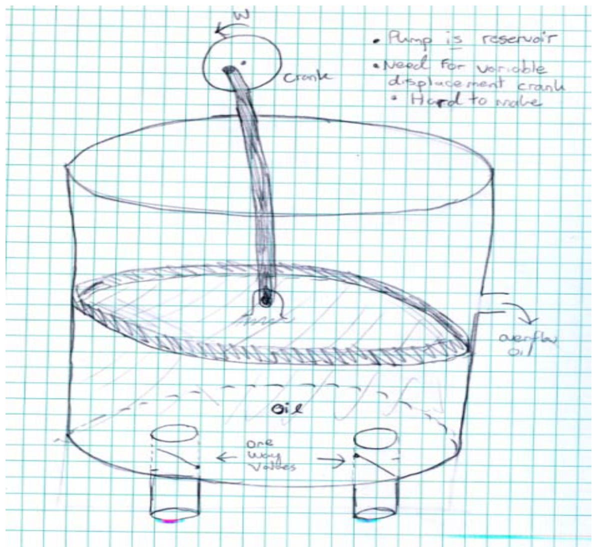


5. Concept Evaluation and Selection

After developing concepts to fulfill the functions needed for the prototype, they were combined and integrated into five prototype concepts. These are summarized below, and the advantages and drawbacks of each design are discussed.

5.1 *Design #1 – Reservoir/Pump Combination System*

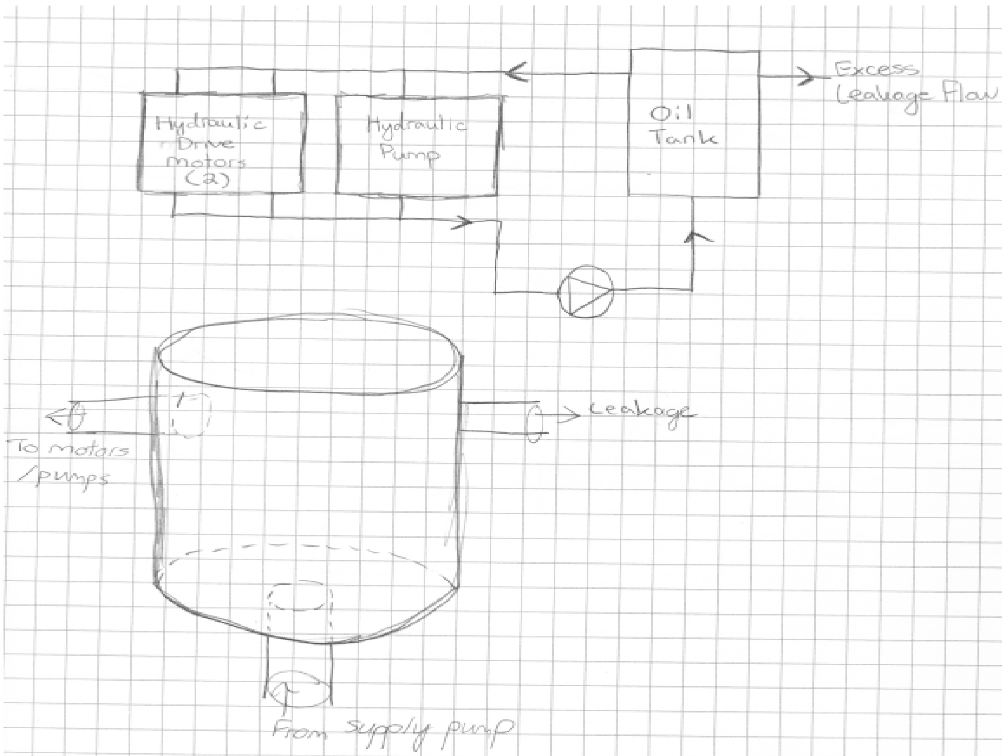
Fig. 7: Reservoir/Pump Combination System Sketch



In Fig. 7, the pump acts as both a pump and a reservoir. The crank will move the piston up and down. By using one way valves at the base, the movement can be made to produce a net flow of fluid. The stroke of the piston will be short enough that the cylinder is never emptied of oil, hence it acts as the reservoir. Drawbacks of this system include high input power needed to move the piston with all the fluid stored below it. The system would be light and only need one motor, which is an advantage.

5.2 *Design #2 – One electric pump system*

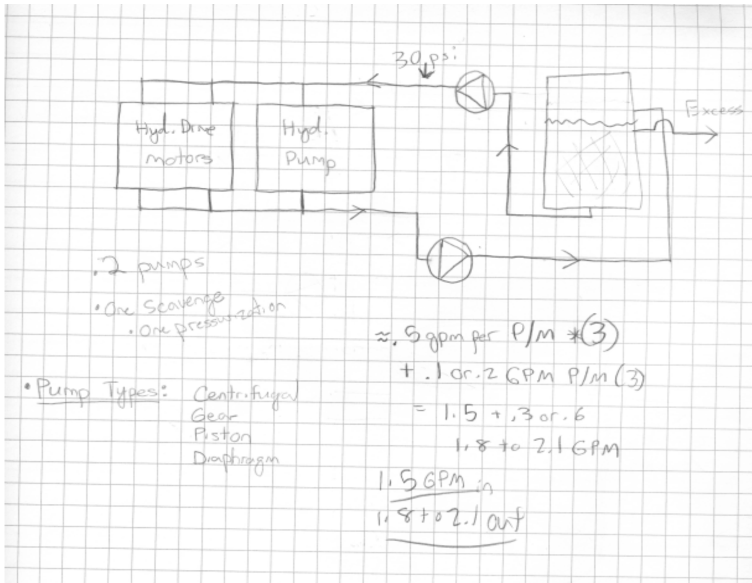
Fig. 8: One Electric Pump System Sketch



The one pump system shown in Fig. 8 will utilize one electric diaphragm pump to both remove oil from the hydraulic motors and pump, as well as pressurize the oil and feed it back to them. This system will rely on a pressurized reservoir. The reservoir will be made of metal, and will be circular in design. By utilizing metal, the reservoir can help remove heat from the oil as the high thermal conductivity will promote a high rate of heat transfer. As in the previous design, an outlet will have to be provided on the reservoir to allow for excess leakage flow. As stated earlier in the report, the leakage is cause by high pressure oil from the motors and pump combining with the low pressure lubricant flow. The net effect is that more oil is removed from the motors and pump than is provided by the dry sump system. A drawback of this system is that since the reservoir will be completely filled, the return oil cannot be made to swirl down the sides of the reservoir, thus eliminating the de-aerating effect.

5.3 *Design #3 – Two electric pump system*

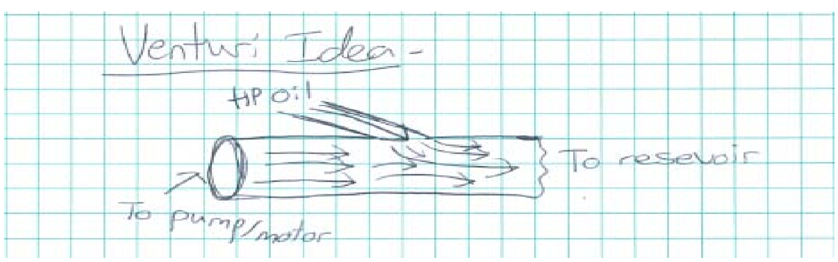
Fig. 9: Two Electric Pump System Sketch



The two pump system shown in Fig. 9 will use two electric diaphragm pumps. One pump will be a dedicated scavenge pump, used only to remove oil from the hydraulic motors and pump. This pump will move oil to the cylindrical metal reservoir, where it will swirl down the inside and de-aerate. Then, a pressurization pump will supply oil back to the motors and pump. A return outlet will send leakage oil to the low pressure accumulator in the truck.

5.4 *Design #4 – Using the Venturi effect to power the system*

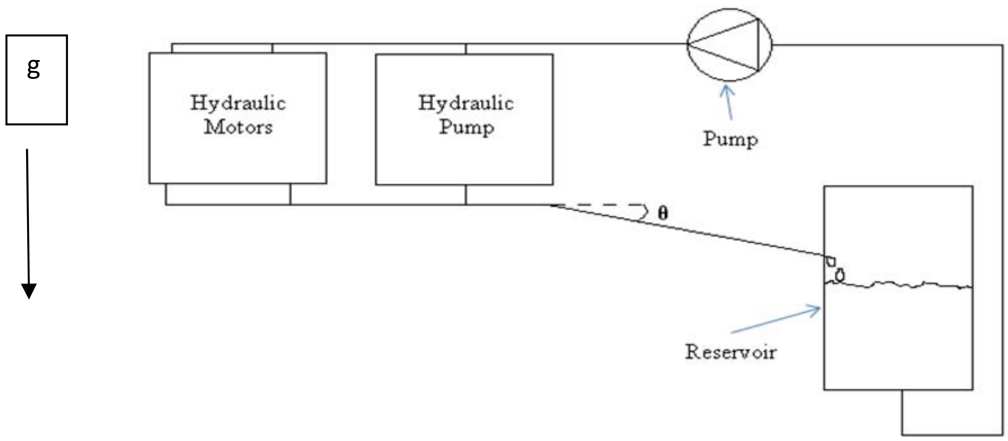
Fig. 10: Venturi Effect Sketch



This system in Fig. 10 will use the same reservoir design as #2 and #3, but will use the Venturi effect to remove oil out of the motors and pump. Supply oil would be provided by an electric diaphragm pump. The disadvantage of this system is the large waste of high pressure oil used to power the Venturi pump.

5.5 *Design #5 – Using gravity to power the system*

Fig. 11: Gravity Feed System Sketch



In Fig. 11, the oil is returned from the pumps and motors using gravity and allowing the fluid drain back. Supply oil would be provided by an electric diaphragm pump. This design would also utilize the same reservoir as #2 and #3. The main disadvantage of this setup is the possible failure of removal of oil from the motors and pump. If the truck were to be on a downhill slope, the system would not function.

Fig. 12: Pugh Chart

Customer Requirement	**Weight**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**	**Datum**
		1 pump	2 pump	Venturi	Piston/Reservoir	Gravity feed	0
Keep oil out of motors/pump	6	-	+	-	-	-	0
Consume low power	2	+	0	+	-	+	0
Small, compact system	4	+	0	+	-	+	0
Lifetime of 10 yrs.	0	0	+	+	-	+	0
Run off of 12 V system	1	+	+	+	0	+	0
Be compatible with existing vehicle setup	4	+	+	+	+	+	0
Operate in a variety of climates	4	+	+	-	0	-	0
Sum +'s		15	15	11	4	11	0
Sum -'s		6	0	10	12	10	0
Total Sum		9	15	1	-8	1	0

A Pugh chart was developed in order to assess how well each conceptual solution satisfied the original customer requirement. After using the weighting scale from the QFD, it was found that the two pump system (Fig.9) would be the choice that best satisfies the customer requirements.

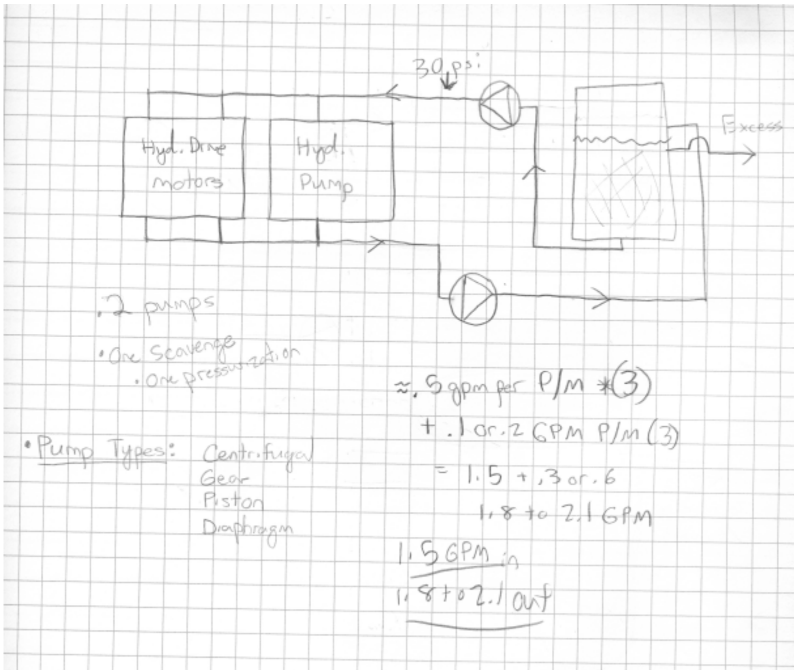
6. Selected Concept

The concept chosen consists of two pumps along with an oil reservoir. The system setup is shown below in Fig. 13 and appendix B.1. A diaphragm pump is located between the hydraulic drive motor outlets and the oil collection reservoir inlet. This pump (called a scavenging pump) removes the lubricant from the hydraulic motors and pump and sends it to the reservoir. Oil pumped into the cylindrical reservoir enters tangent to the circular walls, creating a swirling fluid flow. The goal of this tangential flow is to force dissolved air out of the oil. The reservoir will not fill completely with fluid as there is a return outlet that exits to the vehicle's existing low pressure hydraulic fluid accumulator. In addition to fluid exiting through the return outlet, another diaphragm pump (called a pressure pump) takes fluid from the reservoir and delivers it to the motors and pump.

The scavenging and pressurization pumps must be able to pump Mobil 1 Automatic Transmission Fluid (ATF) at 30 PSI, tolerate intermittent air pockets, supply a constant flow rate, run off a 12V DC power supply, and have as low an amperage draw as possible. Diaphragm pumps were selected namely due to the fact that they satisfy the above requirements and have better dry operating characteristics than other pump types, thus air pockets will not affect the performance. We have found two pumps that satisfy the system's requirements: the Flojet 04105501G and the Tilton 40-524-1. The Flojet pump delivers approximately 3.0 GPM @ 25 PSI and the Tilton delivers approximately 1.7 GPM @ 30 PSI. For both hydraulic drive motors and the hydraulic pump (driven by the diesel), the total required lubricant scavenging rate is approximately 2 GPM and the lubricant supply rate is 1.5 GPM. The Tilton pump is the pressurization (supply) pump, and the Flojet, with its larger flow rate, is the scavenging pump.

Dr. Moskalik has specified that the reservoir must have a capacity between two and five gallons, therefore our design contains a cylindrical reservoir with a four gallon capacity (10 inch diameter and 12 inch height). A cylindrical reservoir was chosen so that the oil inflow can be directed tangent to the reservoir walls, thereby releasing dissolved gas from the oil. The material chosen for the reservoir is aluminum pipe.

Fig. 13: Two pump system



7. Engineering Analysis

The engineering analysis that was performed on our final design consists of two major parts. The quantitative analysis focuses on ensuring that our system meets the customer design requirements fully. It also determines losses in our system.

The qualitative analysis focuses on failure modes and effects, manufacturability, and environmental impacts our product will have during its lifecycle.

7.1 Quantitative Analysis

7.1.1 Oil De-Aeration

After the oil is scavenged from the two hydraulic motors and hydraulic pump, the oil is entrained with air bubbles. The entrainment occurs due to the rotating components inside the motors and pump. Dr. Moskalik had requested that the system try and de-aerate the oil if possible. The oil is sprayed onto the reservoir wall tangentially. It is expected that this will help de-aerate the oil due to centrifugal force. If bubbles still remain in the oil after it collects in the basin, the time it takes for the bubbles to rise to the surface needs to be calculated.

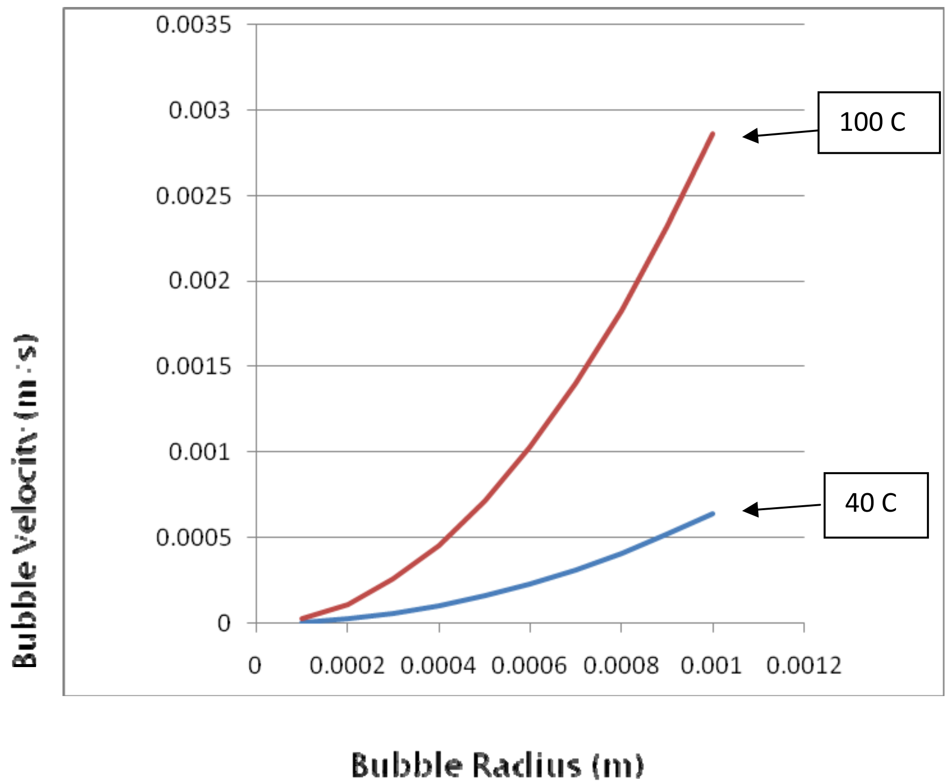
The velocity of a rising sphere in a fluid due to buoyant force can be determined by using Stokes Law, expressed as follows.

$$V_s = \frac{2}{9}\frac{r^2 g(\rho_p - \rho_f)}{\eta} \quad , \qquad \text{(Eq. 1)}$$

where r is the sphere (bubble) radius, g is the acceleration due to gravity (9.81 m/s^2), ρ_p is the density of the sphere, ρ_f is the fluid density, η is the kinematic viscosity, and V_s is the sphere velocity.

Plotting sphere rising velocity as a function of radius and temperature yields the following relationship:

Fig. 14: Bubble velocity increases with increasing radius and increasing temperature



Assuming a bubble radius of .0005 m, and an oil temperature of 100 C, the bubble velocity will be .00075 m/s. Since the aerated oil is entering from the top of the reservoir, is it a logical assumption that the air bubbles will not have to rise all the way from the bottom of the reservoir. Assuming the bubble only has to travel upwards .05 m, the time taken will be 1.1 minutes. Since the reservoir holds approximately 4 gallons, and the outflow rate is 1.8 GPM, the bubbles will rise faster than the oil level drops. This will de-aerate the oil.

7.1.2 Heat Transfer Analysis

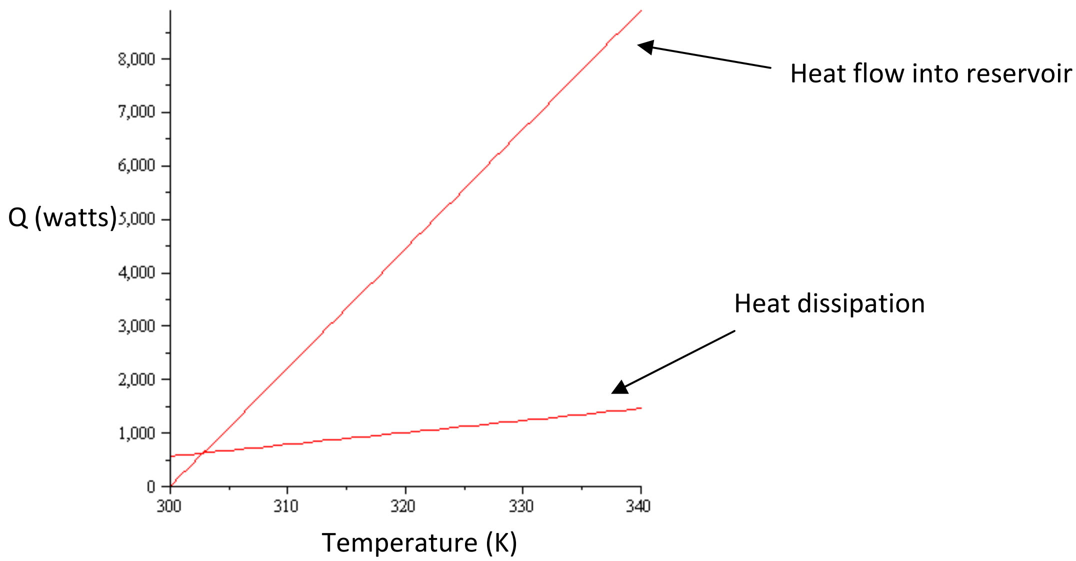
Dr. Moskalik had requested that the dry sump system be able to integrate with an oil radiator, in order to cool the heated return oil from the hydraulic motors and pumps. Instead of adding a radiator to the system immediately, we investigated the potential use of the aluminum reservoir as a radiator.

The reservoir is an aluminum pipe, 10 inches ID, with a wall thickness of .365"

To determine the heat dissipating capability of the reservoir, the surface convection heat transfer was investigated. Assuming airflow velocity of 8.9 m/s, the heat flow in and out of the reservoir is modeled below.

Due to the fact that the heat flow into the reservoir is larger than the outflow, a radiator will need to be installed in the system to increase the heat rejection capabilities.

Fig. 15: Heat flow into reservoir is greater than heat flow out



Eq. 2: Surface Convection Heat Transfer for a Cylinder

$$Q_{ku,L} = A_{ku}(T_s - T_{f,\infty})\frac{<Nu>_L k_f}{L}$$

7.1.3 Piping pressure losses

The oil flowing to and from the hydraulic motors and pump to our reservoir will encounter drag in the pipes. This drag reduces the pressure of the oil flow. In order to ensure adequate supply pressure is provided to the motors and pump, pressure loss calculation were carried out for two temperatures: 40 C and 100 C. Pipe diameter was assumed to be ½".

Table 1: Summary of variables

Name	Symbol	Units	40°C	100°C
Kinematic Viscosity	υ	$\frac{m^2}{s}$	34	7.6
Density	ρ	$\frac{kg}{m^3}$	850	850
Specific Weight	γ	$\frac{kN}{m^3}$	8.33	833
Dynamic Viscosity	μ	$N*\frac{s}{m^2}$	4.00*10^-2	8.94*10^-3
Reynolds Number	Re	n/a	282	1410
Pressure losses	P	Pa/m	8.30*10^3	1.66*10^3

Eq.3: Pressure loss in piping

$$h_L = \frac{\text{Re}}{64}\frac{l}{D}\frac{V^2}{2g}$$

The pressure loss per meter of ½" piping at 40 C is 8300 Pa, or 1.2 psi per meter. At 100 C, the loss drops to 1660 Pa, or .24 psi per meter. The supply pump is capable of supplying to 45 psi, so the losses from 5-6 meters of piping used will not affect the supply pressure to the hydraulic motors and pump.

7.1.3 Pressure Vessel Analysis

The reservoir (made of 6061-T6 aluminum) was analyzed to ensure it could withstand up to 30 psi of internal pressure without failure. The reservoir **will not** be pressurized during operation because of the supply pump removing oil and the atmospheric vent. However, if the vent should fail, and the supply pump fails, it is conceivable that pressure will rise in the reservoir.
Using the hoop stress equation, the stress in the cylinder wall was found at a pressure of 30 psi.

Eq. 4: Hoop stress in reservoir

$$\sigma = \frac{pr}{t} = \frac{2.07 \cdot 10^5 Pa \cdot 0.13625m}{9.27 \cdot 10^{-4} m} = 30.4MPa$$

The yield stress of aluminum (alloy 6061-T6) is 275 MPa. Thus, the reservoir will not fail from the internal pressure.

7.2 Quantitative Analysis

7.2.1 FMEA Chart

FMEA (Failure Modes Effect Analysis) was utilized to understand how different failure modes of system components would affect the system. The dry sump system was broken down into six main parts: supply pump, scavenge pump, reservoir, mounting plate, hoses, and polycarbonate reservoir cap. It is important to note that the PC reservoir cap is only used in the prototype; it allows viewing of the oil as it enters the reservoir. For the production model, this would be replaced by a ¼” 6061-T6 aluminum disk, 10.73” in OD.

The major failure modes of both pumps are the same. Bearing failure, winding failure, and pump failure are the three major modes. The failure modes for the reservoir are due to hoop stresses and weld area crack propagation. The mounting plate can fail in bending and the cap can fail by fracture. The hoses can fail by fraying or blowout. The effects and causes of these modes are summarized in Appendix A.1. By having visual inspections for cracks and pressure sensors in the supply and return lines, the occurrence of these types of failures can be reduced.

7.2.2 DFMA Chart

To ensure our system is easily manufactured and assembled, Design for Manufacturing and Assembly principles were applied. These principles cover all areas of manufacturing and assembly. As such, only the principles that applied to our system are summarized below.

The system is expected to be mass produced eventually. Using thick walled aluminum pipe will not be the most cost effective solution for mass production. Production systems should have thinner walled aluminum to construct the reservoir. This type of aluminum is typically seam welded. The holes in the reservoir must be drilled opposite the weld seam to ensure adequate strength and crack growth inhibition. Standard hole sizes are used to streamline assembly processes. The 12 inch width dimension on the mounting plate is a standard size and will be easily obtained. Not having to cut the plate along the width saves money during manufacturing. Welding metal tabs on the reservoir will be useful because it provides mounting locations to attach the reservoir to the mounting plate.

Table 2: DFMA Table

Reservoir	**1. If reservoir is eventually made out of sheet metal, then ensure the holes for the oil flow are located opposite the weld seam (DFSF-6).** **2. If reservoir is eventually made from aluminum pipe (as in prototype), then ensure flats or mounts are added to pipe to aid in fixturing (DFMC-13).**
Mounting Plate	**1. Use standard hole sizes. Holes for mounting pumps will be 3/16", a standard size (DFMC-3).** **2. Use standard plate sizes (DFMC-2).**
Attachment of reservoir to mounting plate	**1. Use of metal tabs on reservoir facilitates orientation during assembly (DFPI-2).**

7.2.3 DFE Chart

Design for the environment consists of seven major components of product design, as they relate to the environment. For each component of DFE, parts from the dry sump system were investigated to see if DFE could be applied. In the areas of Physical and Material Optimization, using a cylindrical aluminum reservoir saves material. By containing the oil and using electric power, the system has little impact on the environment.

Table 3: DFE Table

DFE Strategy:	*Implementation:*
New Concept Development	**N/A**
Physical Optimization	**Use of cylindrical reservoir reduces surface area to volume ratio, leading to less material use.**
Optimize Material Use	**Use of recyclable aluminum facilitates recycling at products end of life.**
Optimize Production Techniques	**Use of welding to seal ends of reservoir eliminates need for mechanical fasteners**
Optimize Distribution	**N/A**
Reduce Impact During Use	**Dry sump system powered by existing vehicle electric system. No direct emissions.** **Containment of oil prevents spills which are an environmental hazard.**
Optimize End-of-Life Systems	**Design system for entire vehicle lifespan (10 years). Use of aluminum, thermoplastics, and steel: All recyclable.**

8. Final Design

The final design of the dry sump lubrication system was manufactured and will become the initial prototype for use on delivery trucks. Shown in Appendix B are the CAD assemblies for the entire hybrid system, the reservoir and pumps, and the engineering drawings for the reservoir and base plate. The prototype has the reservoir, scavenge and supply pumps mounted to an aluminum base plate (¼" thickness x 12" width x 18" length). The reservoir is an aluminum pipe with the following dimensions: 10" inner diameter, 12" height, and 0.365" wall thickness. This reservoir has an aluminum disc welded onto the bottom while the top end was sealed using a silicone gasket maker, and a circular piece of polycarbonate bolted to the top pipe opening. The reservoir is bolted to the base plate with four brackets that have been welded to it and the pumps are mounted next to the reservoir in opposing directions. Additional components that were installed included the electrical power controls and hosing that carries the oil between components. The electrical portion of the system will consists of some wiring and switches to control the pumps and the hosing is simple clear plastic tubing for easy viewing of fluid flows.

Table 4: Bill of Materials

Quantity	Part	Manufacturer	Part Number	Price (each)	Price
1	6061-T6 Al Cylinder (10" diameter, 12" height)	Alro Steel	N/A	$116.09	$116.09
1	Polycarbonate Sheet, 3/8" thick	Alro Steel	N/A	$22.50	$22.50
1	1/4" 6061-T6 Al Plate (12" x 30")	Alro Steel	N/A	$47.60	$47.60
1	Tilton Transmission/Differential Oil Cooler Pump	Tilton Engineering	TIL-40-524	$214.69	$214.69
1	General Purpose Circulation Pump	Flojet	04105501G	$92.40	$92.40
5	Automatic Transmission Fluid	Meijer	N/A	$6.69	$33.45
10	1/4" machine screws (3/4" length)	Home Depot	TBD	$0.10	$1.00
8	1/4" bolts (1/2" length)	Home Depot	TBD	$0.15	$1.20
1	TIG Welding	Hosford	N/A	$150.00	$150.00
2	SS Hose Clamp	Home Depot	N/A	$1.05	$2.10
2	SS Hose Clamp	Home Depot	N/A	$1.15	$2.30
3	SS Hose Clamp	Home Depot	N/A	$0.95	$2.85
1	50' 16 gauge wire	Home Depot	N/A	$10.98	$10.98
1	Electrical Box Cover	Home Depot	N/A	$1.53	$1.53
2	20 Amp SPST switch	Home Depot	N/A	$5.23	$10.46
1	Electrical Box	Home Depot	N/A	$2.32	$2.32
2	3/4" x 3/4" adaptor	Home Depot	N/A	$3.64	$7.28
1	5/8" Flare Cap	Home Depot	N/A	$2.78	$2.78
1	3/8" Elbow	Home Depot	N/A	$3.72	$3.72
1	1/2" Elbow	Home Depot	N/A	$2.56	$2.56
1	Hosing adpator	Home Depot	N/A	$3.14	$3.14
1	5/8' x 1/2" elbow	Home Depot	N/A	$3.08	$3.08
1	3/4 Adaptor	Home Depot	N/A	$1.74	$1.74
1	Tubing, Vinyl	Home Depot	N/A	$16.64	$16.64
1	Tubing, Vinyl	Home Depot	N/A	$6.99	$6.99
3	3/8" 2" long nipple	Home Depot	N/A	$3.20	$9.60
1	3/4" Boiler Valve	Home Depot	N/A	$4.47	$4.47
4	1/4" Hex Nuts	Home Depot	N/A	$0.04	$0.16
4	1/4" Hex Bolts	Home Depot	N/A	$0.09	$0.36
			Total =	$773.99	

9. Manufacturing and Testing Plan

The dry sump lubrication system was manufactured in-house and will function as the initial prototype for the final dry sump system implemented in the hybrid drive train. The only contracted work done on the prototype was the welding of an aluminum base plate to the reservoir. All other manufacturing was done in the University's machine shop. Other core manufacturing processes included attaching the reservoir to the mounting plate via brackets and attaching pumps to the plate with mounts provided in the pump assembly. Both of these processes were achieved using a drill press for mounting holes. The inlet, outlet and overflow valve were drilled and tapped using NPT coarse thread taps. The polycarbonate cover was cut out on the mill, and then 12 1/8" holes were drilled 1/8" from the outside circumference. The holes are spaced 30 degrees apart for equal stress distribution. The wiring for the motors is 16 gauge conductor and 2, single pole single throw switches were installed to control the system.

A mass produced dry sump system will differ quite drastically from the prototype. Reasons for these discrepancies include cost, material availability, and the fact that people will be observing the inner workings of the system on this prototype, thus the use of a PC cover. Aluminum piping used for the reservoir on a production system will have a much smaller wall thickness, as illustrated in the engineering analysis (section 7.1.3). The prototype's materials were based namely upon availability, whereas a production system's would be based upon the engineering analysis provided in section 7. The PC reservoir cover is used in our prototype simply for flow visualization purposes. To keep costs low, the production run of this system would most likely include an investment cast reservoir. The system mounting plate is currently ¼" 6061-T6 aluminum alloy with a width dimension of 12"and a length of 14". This would easily allow the manufacturer to purchase large plates of the alloy and cut only the length dimension, as the width of 12" is suitable for the current reservoir size.

If the final design is made available for public use, no ethical issues need to be taken into consideration. The design is made entirely of non-toxic materials. Environmental concerns include leaking hydraulic fluid; however this will not be an issue due to the use of hydraulic grade fitting and hoses on the final design.

10. Testing

In order to verify the system met the engineering specifications, various measurements and inspections were performed, and are summarized in Table 6 on the next page:

Table 6: Engineering Specification Verification

1.) Oil flow to motors and pump is ~1.7 GPM Test: Used a clock to find the time it took for supply pump to fill a graduated bucket with one gallon of oil
2.) Oil supply pressure to motors and pump is ~30 PSI Test: Not able to verify pressure specifications due to the lack of equipment
3.) The height of the dry sump system cannot exceed 15" Test: Top of reservoir stands 12.875" from the bottom mounting plate
4.) The system needs to be closed to the outside environment to prevent contamination of oil Test: Used caulk to seal system then inspected for leaks with soapy water
5.) Needs to run off of a 12 Volt system Test: Ran system using a 12V car battery charger
6.) The high pressure hydraulic fluid leak rate from each motor into the hydraulic lubricating oil is about 0.2 GPM Test: None available
7.) The system needs to able to be integrated with a de-bubbler to remove air from the oil that is returned to the main hydraulic system. Test: This will be connected to the overflow valve

The only problem encountered during testing was that the reservoir was not air tight. We remedied this problem by caulking the polycarbonate cover and the bolts.

11. Discussion for Future Improvements

The system as it is currently assembled is not ready for installation on the vehicle. The PC cover plate, while useful for flow and oil height viewing, would need to be replaced by an aluminum cover of the same dimensions if it were to be installed on the vehicle. The aluminum cover is more damage tolerant than the PC. The reservoir volume is more than adequate; this would not need to be changed. Pressure and flow gauges should be installed on the reservoir, as well as the two connections to the vehicle from the pumps. Pressure monitoring would ensure that the system is providing adequate lubrication to the hydraulic motors and pump. Flojet, the manufacturer of the scavenge pump, should be contacted to see if they can provide a supply pump with the same specifications as the Tilton supply pump. Unless further testing proves otherwise, the Flojet scavenge pump fulfills the flow requirements, however it costs nearly half as much as the Tilton. The hosing that is currently used is not suitable for use on the vehicle. While it provides good flow visualization, it is not suitable for long term use.

Conclusion

Our dry sump hydraulic motor lubrication project has the potential to increase the fuel efficiency of hybrid UPS delivery trucks. By keeping hydraulic oil out of the drive motor and pump cases, viscous friction in the oil will be reduced. Our system removes this oil, stores it in a cylindrical metal reservoir, and pumps it back to the hydraulic drive motors and pump. It sends excess leakage oil through a de-bubbler and back to the main low pressure accumulator. The system will operate off of the vehicle’s 12 volt system, and provides at least 30 psi of pressure and 1.5 GPM of flow over a range of climate conditions.

Acknowledgements

First off we would like to thank Dr. Andrew Moskalik for the opportunity to work on this project. Our team would also like to thank Professors Bogdan Epureanu and Kazu Saitou for their guidance and encouragement throughout the semester. We would also like to thank Bob Coury and Marv Cressey for their extensive help in the machine shop.

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Appendices

Appendix A: Engineering Analysis – FMEA, DFE, DFMA

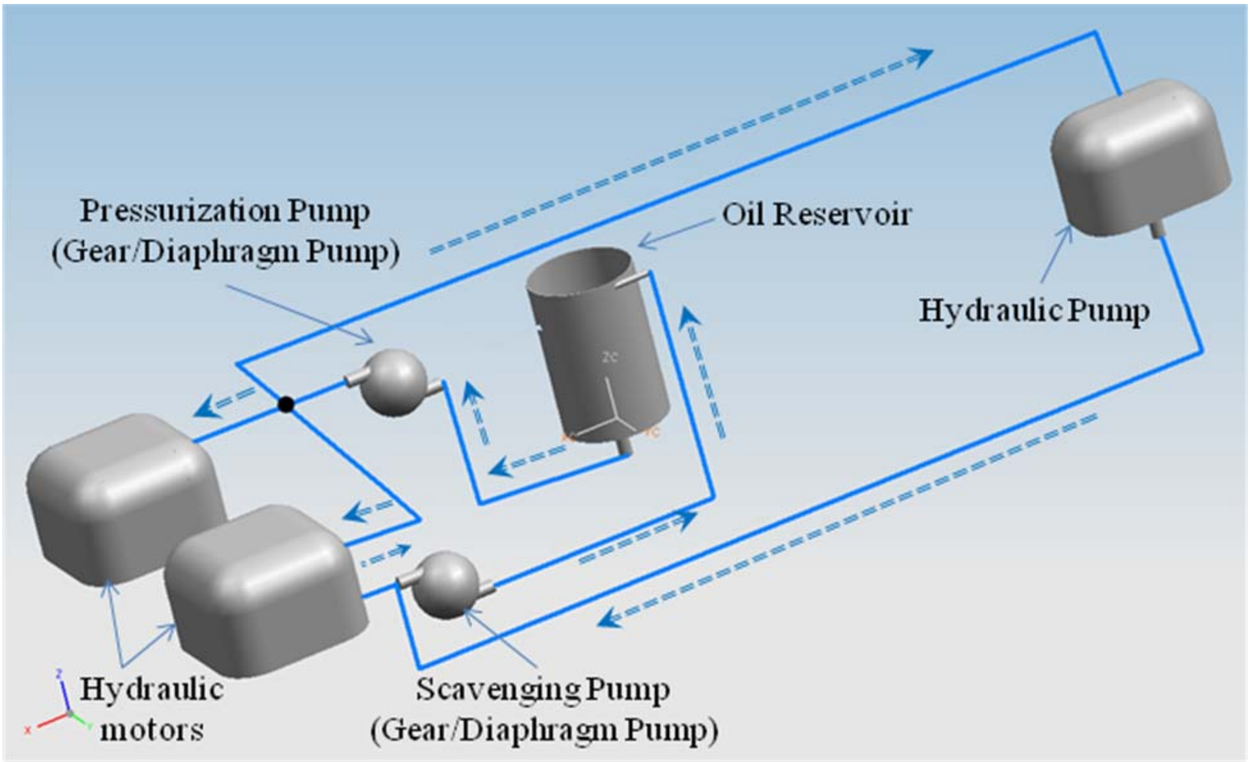
A.1: FMEA

1	**Product Name:** Dry Sump Lubrication		**Development Team:** Ben Schweitzer Michael Romanelli Peter Kalinowsky												
2															
3															
4	**Part # and Functions**	**Potential Failure Mode**	**Potential Effects of Failure**	**Severity (S)**	**Potential Causes/Mechanisms of Failure**	**Occurrence (O)**	**Current Desgin Controls/Tests**	**Detection (D)**	**Recommended Actions**	**RPN**	**New S**	**New O**	**New D**	**New RPN**
5	**Scavenge Pump**- Flojet P/N 04105501G . Function is to remove the oil from the 2 hydraulic motors and 1 hydraulic pump and return the oil to the resevoir.	1.) Motor Failure - Bearing seizure, winding short, armature crack	Oil accumulates in hydraulic pumps and hydraulic motor	9	Improper motor lubrication, maunfacturing defects	3	Pressure sensor (expected)	1	Ensure manufacturer quality controls are established and in use	27	9	1	1	9
6		2.) Pump Failure - Leaking or no pressure developed	Oil accumulates in hydraulic pumps and hydraulic motor	9	Run at too high a pressure, i.e. flow blockage	3	Pressure sensor (expected)	1	Ensure manufacturer quality controls are established and in use	27	9	1	1	9
7		3.) Loss of power	Oil accumulates in hydraulic pumps and hydraulic motor	9	Vehicle power failure	3	Onboard Vehicle Diagnostics	1	Ensure vehicle power supply is adequate for motors, and is reliable	27	9	1	1	9
8	**Supply Pump**- Tilton P/N TIL-40-524. Function is provide oil at 30 psi to the 2 hydraulic motors and 1 hydraulic pump.	1.) Motor Failure - Bearing seizuere, winding short, armature crack	No oil supplied to hydraulic pumps and hydraulic motor	9	Improper motor lubrication, maunfacturing defects	3	Pressure sensor (expected)	1	Ensure manufacturer quality controls are established and in use	27	9	1	1	9
9		2.) Pump Failure - Leaking or no pressure developed	No oil supplied to hydraulic pumps and hydraulic motor	9	Run at too high a pressure, i.e. flow blockage	3	Pressure sensor (expected)	1	Ensure manufacturer quality controls are established and in use	27	9	1	1	9
10		3.) Loss of power - Electrical supply failure	No oil supplied to hydraulic pumps and hydraulic motor	9	Vehicle power failure	3	Onboard Vehicle Diagnostics	1	Ensure vehicle power supply is adequate for motors, and is reliable	27	9	1	1	9

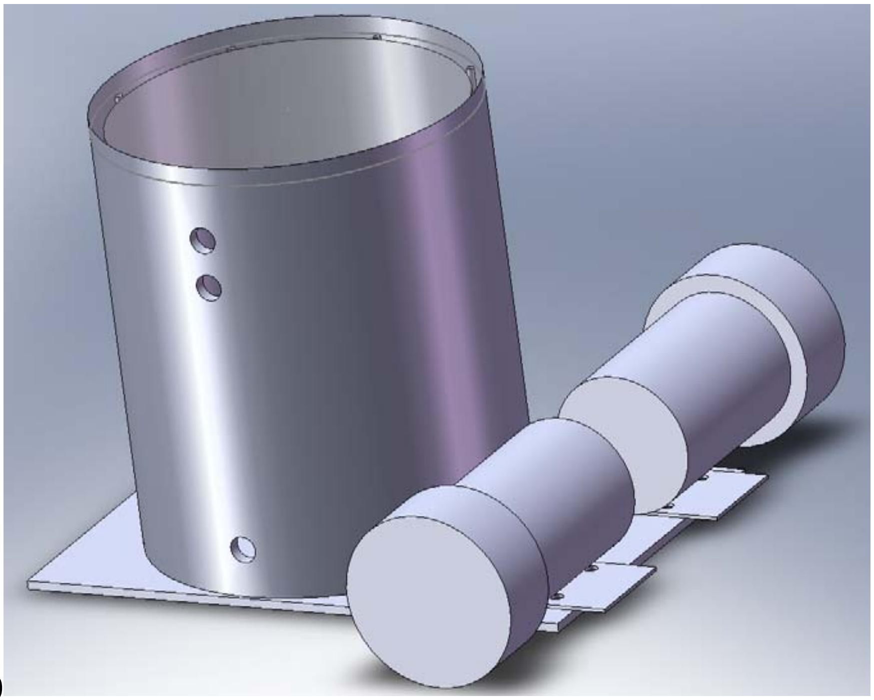
1	**Product Name:** Dry Sump Lubrication		**Development Team:** Ben Schweitzer Michael Romanelli Peter Kalinowsky											
2														
3														
4	**Part # and Functions**	**Potential Failure Mode**	**Potential Effects of Failure**	**Severity (S)**	**Potential Causes/Mechanisms of Failure**	**Occurrence (O)**	**Current Desgin Controls/Tests**	**Detection (D)**	**Recommended Actions**	**RPN**	**New S**	**New O**	**New D**	**New RPN**
11	**Reservoir** - Function is to contain the oil and remove heat from the oil by conduction.	1.) Cracking -Due to extreme pressure buildup	Oil loss. Loss of supply oil to hydraulic pumps and hydraulic motor. Allow contatanmination of oil	7	Overpressurization caused by flow blockage to or from hydraulic motors and pump	1	Visual inspection - Probably not necessesary due to low occurrence	1	None. The resovoir wall thickness is .365". It won't crack from 30 psi.	7	7	1	1	7
12		2.) Weld crack - Fatigue crack growth in stressed area	Oil loss. Loss of supply oil to hydraulic pumps and hydraulic motor. Allow contatanmination of oil	7	Crack growth would probably start at the stressed area near the welds. The growth could be intitated by an impact from road debris, or improper installation (dropping it)	1	Visual inspection - Probably not necessesary due to low occurrence	1	None	7	7	1	1	7
13	**Mounting Plate** - Function is to support the reservoir and pumps, as well as provide a secure mounting base for the pumps and reservoir	1.) Bending	Possible stress to reservoir, may lead to cracking	5	Impact from road debris could cause the plate to bend	1	Visual inspection - Probably not necessesary due to low occurrence	1	None	5	5	1	1	5
14	**Reservoir Cover Plate** - Function is to keep contaminants out of oil and allow viewing of oil in reservoir	1.) Cracking -Due to extreme pressure buildup	Allow contamination of oil. Oil loss as well	5	Overpressurization caused by flow blockage to or from hydraulic motors and pump	1	Visual inspection - Probably not necessesary due to low occurrence	1	None	5	5	1	1	5
15	**Hoses**- Function is to contain the oil during transport to and from hydraulic motors and pump	1.) Fraying	Oil loss. Loss of supply oil to hydraulic pumps and hydraulic motor. Allow contatanmination of oil	7	Rubbing on abrasive surfaces - Leads to leaking	2	Visual inspection - Probably not necessesary due to low occurrence	1	None	14	7	2	1	14
16		2.) Blowout due to overpressurization	Oil loss. Loss of supply oil to hydraulic pumps and hydraulic motor. Allow contatanmination of oil	7	Overpressurization caused by flow blockage to or from hydraulic motors and pump	1	Visual inspection - Probably not necessesary due to low occurrence	1	None	7	7	1	1	7

Appendix B: CAD Assemblies and Drawings

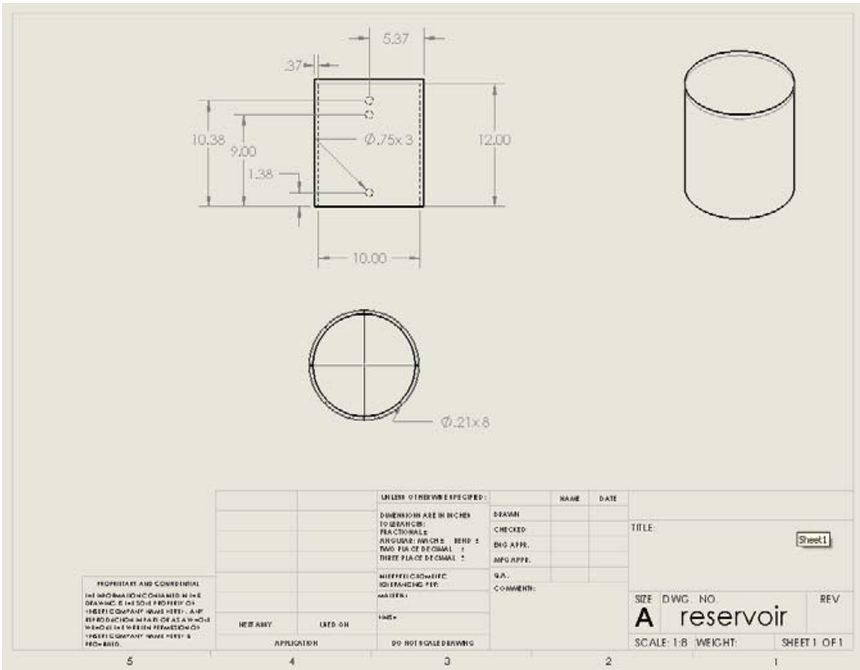
B.1: Hybrid System Overview (CAD Assembly)



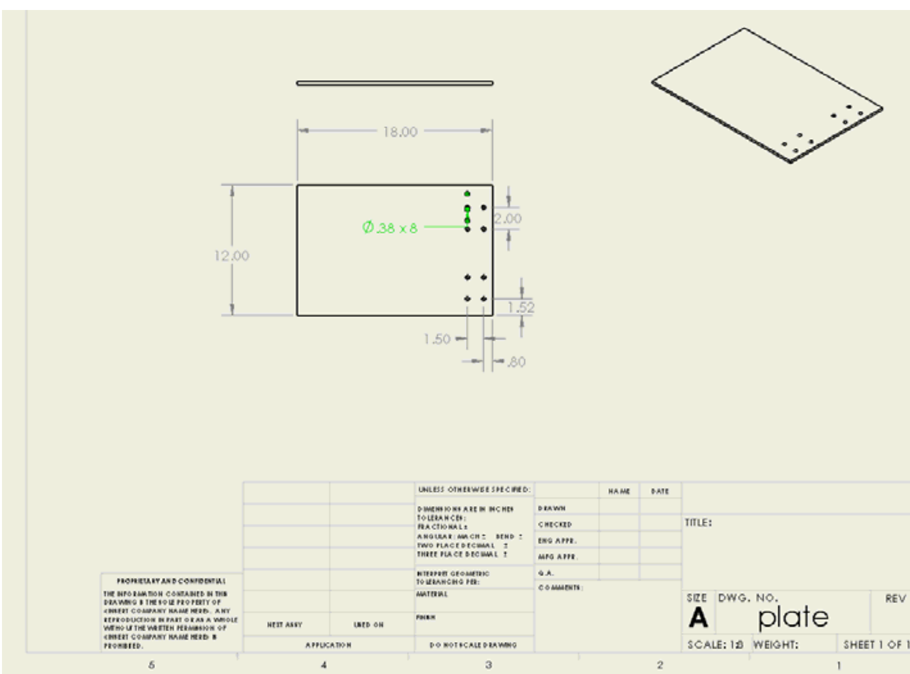
B.2: Reservoir, Base Plate, and Pumps (CAD Assembly)



B.3: Reservoir Dimensioned Drawing



B.4: Base Plate Dimensioned Drawing



Appendix C: Project Plan

C.1 Gantt Chart

Completed (solid black)
Pending (shaded)

TASK	9/20	9/27	10/9	10/23	11/1	11/13	11/20	11/29	12/4	12/6	12/11
Meet Sponsor	Completed										
Research Existing Systems	Completed										
Initial Black Box Design	Completed										
Presentation 1		Completed									
Design Review 1		Completed									
Chose system components		Completed	Completed								
Contact EPA about design			Completed								
Make necessary changes			Completed								
Design Review 2				Completed							
Begin Engineering Analysis				Completed							
Purchase Required Parts				Completed							
Begin Fabrication				Completed	Completed						
Design Review 3						Completed					
System Debugging						Pending	Pending				
Design Review 4								Pending			
Prepare Visuals for expo								Pending	Pending		
Design Expo										Pending	
Write Final Report								Pending	Pending	Pending	
Turn in Final Report											Pending

Appendix D: Operating Procedures

D.1 Operating Procedures

Dry Sump Operating Procedures

DO NOT OPERATE EITHER PUMP WITHOUT OPENING THE OVERFLOW VALVE (BOILER VALVE ON RESERVOIR)

- As stated above, operating without a means of pressure relief can cause the polycarbonate reservoir cover to fail
- Switches operate pumps independently
- Pumps can be operated both wet and dry without detrimental effects
- Flojet pump shall scavenge the oil from hydraulic motors and pump and empty to the reservoir
- Tilton pump shall supply oil to the lubrication system and empty the reservoir

Appendix E: Pump Specifications

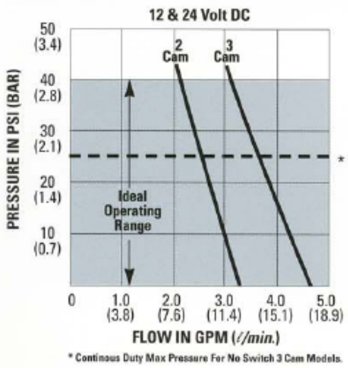
E.1 Flojet Specifications

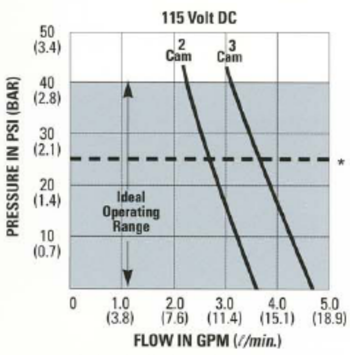
FLOJET 4000 SERIES QUAD PUMP

SPECIAL FEATURES

- FLOJET 4000 delivers up to 40 PSI 2.8 (bar) working pressure.
- Built-in pressure switch automatically starts and stops pump instantaneously when discharge valve is opened and closed.
- Compact design and plug-in port fittings make installation easy.
- Can run dry without damage and handle liquids up to 130°F (54°C).
- Quad Diaphragm Design eliminates troublesome shaft seal.
- No metal contact with liquid being pumped.
- Ball bearing drive throughout pump and motor assures longer pump life.
- Excellent self-priming capability. Pump may be located above the liquid level.
- Powerful, permanent magnet motor with low current draw and long life brushes.

PUMP PERFORMANCE





SPECIFICATIONS

Flow Rate	3.5 to 5.0 GPM (13.2 and 18.9 ℓ/min.) Nominal
Pump Design	Diaphragm
Shaft Seal	None
Motor	Permanent Magnet Motor
Standard	TEFC (fan-cooled)
Voltage	12 & 24 Volt DC, 115 & 230 Volt AC
Cycle	50/60 hertz for AC Models
Current	
12 Volt	14.0 amp max.
24 Volt	0.7 amp max.
115 Volt	1.5 amp max.
230 Volt	0.75 amp max.
Pressure Switch Setting	45 PSI (3.2 bar) cut out 30 PSI (2.1 bar) cut in
Maximum Operating Pressure	40 PSI (2.8 bar) (Demand Pumps only)
Maximum Fluid Temperature	130°F (54°C)
Self-Priming	Up to 8 ft. (2.4 m) Vertical Height
Ports	Plug-In Ports 1/2" or 3/4" Hose Barb Standard (Consult Factory for other type of Port Fittings)
Wetted Parts	
Housing	Modified Polypropylene - Standard
Elastomers	Santoprene® and Buna - Standard
Net Weight	4 lbs. (2 kg)

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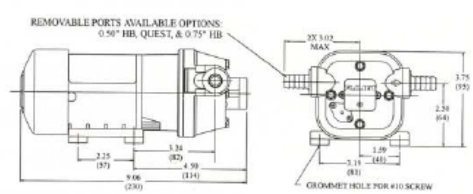
STANDARD MODELS		CAM NO.
115 VOLT 3.5 GPM 1/2" HOSE BARB		
4300-042	Santo/EPDM, Switch at 45 PSI	2
4100-500	Santo/EPDM, No Pressure Switch	2
115 VOLT 5.0 GPM 3/4" HOSE BARB		
4300-043	Santo/EPDM, Switch at 45 PSI	3
4100-512	Santo/Viton, No Pressure Switch	3
12 VOLT 3.5 GPM 1/2" HOSE BARB		
4300-142	Santo/EPDM, Switch at 45 PSI	2
4100-505	Santo/EPDM, No Pressure Switch	2
12 VOLT 5.0 GPM 3/4" HOSE BARB		
4300-143	Santo/EPDM, Switch at 45 PSI	3
4100-143	Santo/EPDM, No Pressure Switch	3

Note: All Motors Are Fan Cooled With A Thermo Switch Used On All Non-Pressure Switch Models.



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E.2 Tilton Specifications

INSTALLATION INSTRUCTIONS

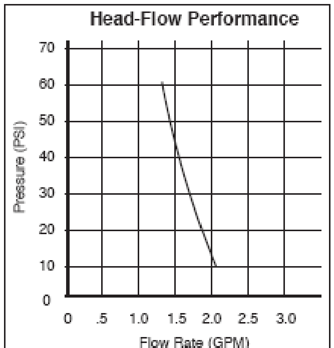
Transmission / Differential Oil Cooler Pump

· ***Flow rate:*** 1-2 gal/min (4.6-9.1 liters/min) · ***Working pressure:*** 60 PSI (3.5 bar) maximum • ***Power:*** 12-volt DC
• ***Temperature range:*** Fluid temperatures up to 265˚F (130˚C) constant · ***Prime:*** Self-priming up 8 ft (2.6 meters) vertical height

A. How It Works

The Tilton Differential Pump is a positive displacement type of pump, so its output is directly proportional to the motor speed. If a lighter load increases the motor speed by 25%, then the flow rate increases by 25%. The flow rate vs. pressure is shown in **Graph 1** with a maximum available pressure of 60 PSI. A fluid system will only flow as much as the smallest restriction will allow. Larger diameter lines and fittings allow more flow and place less load on the pump. This pump is self-priming and can be placed up to 8 ft above the source from which it draws. The typical application for the pump is in a differential or transmission cooling system. However, the pump can be used for other applications such as emptying fuel tanks. A 12-volt DC, 10-amp power supply is required. The current draw is 6.6 amps under a maximum load condition with a more typical current draw between 2 and 3 amps. This pump has a very light weight at 3.5 lbs and has a flow rate of 1-2 gallons per minute. There are two types of diaphragms available for the differential pumps; the BUNA type diaphragms are for standard coolants and the VITON diaphragms are for the more corrosive coolants.

B. Installation Notes



Graph 1

The Tilton Differential Pump is placed inline with the cooling system as shown in **Diagram 1**. Placing the pump on the outlet side of the cooler exposes it to lower temperatures significantly increasing the life and reliability of the pump. A 20-mesh strainer or filter placed inline before the inlet of the pump prevents foreign objects from damaging the pump. Heavy gear oil must be brought up to operating temperature before the pump is engaged. The cold fluid can be very thick and place an unusually large strain on the pump. Tilton recommends the use of an on/off switch so the pump can be turned off during warm-up periods. The pump includes an integral cooling fan to keep the pump cool during loaded conditions. If the pump is mounted in a vertical position, mount the pump with the motor above the pump inlet and outlet to prevent damage to the motor in the event of a fluid leak. The pump head can be rotated in 180-degree increments, allowing a variety of hose positions. Be careful not to damage the plastic pump housing by over tightening the fittings. If a check valve is placed inline with the pump, the check valve must have an opening pressure of no more than 2 PSI. The electrical hook-up is simple. Connect the pump to a 12-volt DC supply with a 10-amp fuse inline with the (red) positive lead. The black lead is the chassis ground.

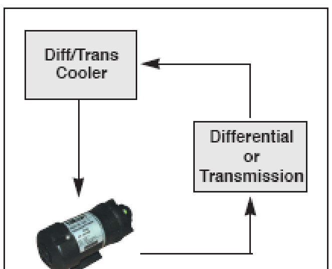


Diagram 1

Mounting Hole Dimensions
- 2.25" vertical centers x 3.25" horizontal centers.
- Drill hole diameter: 3/16", 4 places.
- Use high quality #10 bolts with lock nuts

Plumbing
- For best results, use AN8 steel braided flexible hose.
- Use only 3/8" NPT fittings at the pump inlet and outlet.

Operation
- Allow the pump to prime with the discharge line open to prevent airlock.
- The pump will not be harmed if it is allowed to run dry. It is self-priming.

Electrical
- Use a minimum of 16AWG stranded wire for power connections.
- Use a 10-amp inline fuse on the 12-volt DC (red) power connection.