Lifetime Engine Oil Filtration for Light Military Utility Vehicles

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ABSTRACT

Improving lubrication-oil filtration technology for military vehicle systems remains a significant challenge. Equipment failures due to improper or excessive periodic maintenance substantially contribute to the overall cost of maintaining military fleets, and reduce combat effectiveness during mission critical operations. Current systems have short filter life span and do not provide satisfactory particle removal, and in addition, disposal of the filter element and used oil presents an expensive and hazardous problem for maintenance personnel.

Analytical Engineering, Inc. (AEI) has pioneered the development of a filtration system providing previously unobtainable efficiency levels of particle and lubrication-oil soot removal. This revolutionary technology is being developed for lifetime lubricant filtration on the HMMWV vehicle. The filter system employs the use of a high capacity, high efficiency full flow section with integral additive replenishment and an ultracentrifuge bypass section. This integrated system utilizes oil pressure from the engine to power the centrifuge via high efficiency, micro turbine technology. The new spin-on replacement system transparently provides higher efficiency filtration for at least 200,000 miles, resulting in greatly reduced maintenance and significantly improved engine durability of military vehicles.

Prototypic hardware is being evaluated on a civilian H1 Hummer powered by a 6.5 liter GM diesel engine. The Phase II effort will culminate in the installation and on-vehicle demonstration of the third generation prototype system.

Paper presented at the RTO AVT Specialists' Meeting on "The Control and Reduction of Wear in Military Platforms", held in Williamsburg, USA, 7-9 June 2003, and published in RTO-MP-AVT-109.

Figure 1: AEI HUMMER Test Vehicle for Filter Research

Background

Fleet maintenance for military vehicles represents a significant fraction of the overall cost associated with maintaining an effective ground force. Engine lubrication oil maintenance intervals largely dictate the frequency of comprehensive practices which include induction air, transmission, battery, drivetrain and a host of miscellaneous checks and routine maintenance items. The logistics, manpower, backup equipment and infrastructure needed to effectively maintain these vehicles is huge and the costs associated with placing this composite task force into remote locations is staggering.

Maintenance costs in civilian fleets also comprises a significant fraction of vehicle cost of ownership. Intense competition in freight transport has minimized operating margins to such an extent that few options exist to shave costs, improve efficiency and enhance profitability. In order to achieve improved margins in profitability, medium to large sized fleets have placed extreme pressure on engine manufacturers to extend maintenance intervals. By stretching miles and time between maintenance intervals, fleet vehicles can remain in service without interruption and thus provide earnings. Moreover, this practice reduces costs of labor, garage infrastructure and routine maintenance parts, filters and fluids.

As a result, there is significant interest from military and civilian fleets in extending maintenance intervals and possibly eliminating them entirely. The most daunting requirement for approaching this goal is extending oil drain and oil filter replacement intervals. For most applications, oil life is the principal factor that dictates time and/or mileage based maintenance intervals. In diesel engines, lubrication oil soot is the single largest contributor to oil degradation. Reserve alkalinity is a far less severe driver, albeit the next problem when drain intervals are stretched with soot removal filtration.

Soot Removal Filtration

Unlike all other conventional oil contaminants, lube oil soot accumulates in dramatic quantities. Condemning limits for soot ranges across industries between 1 and 6 percent by weight. For an average heavy duty diesel truck engine, this equates to between 0.8 and 4.8 pounds (0.36 – 2.2 kg) of solid soot dispersed in the oil. There exist few filter systems that can store more than a small fraction of this quantity, and none exist today for mobile applications. Decades of research have rendered few options for effective lube oil soot removal. Bypass barrier filtration refinements have resulted in incremental improvement in soot removal but the small size of soot particles and the associated capacity constraints represent a fundamentally impossible requirement.

Cyclonic and centrifugal filtration systems address the capacity issues but, to date have not provided removal efficiency needed to effectively remove soot from highly dispersant oils. The principal reasons for these inefficiencies stem primarily to insufficient mechanical removal forces and dwell time in the rotational environment.

This document describes an emergent technology that addresses the requirement for effective soot removal and overbase maintenance. Focusing primarily on the soot removal criteria, the technology utilizes a high speed centrifugal force with lengthy residence times to allow for total soot particle migration and subsequent particle capture. This “ultracentrifuge” concept has matured into several related “ultrafiltration” systems being developed and commercialized by Analytical Engineering, Inc. (AEI) for use in a wide variety of military and civilian diesel platforms. To address the requirement for reserve alkalinity during extended and/or indefinite filter and lube oil life, a solid support alkalinity reserve module is incorporated into the full flow filter section of the overall system. The presence of this material maintains acid protection long after native alkalinity is consumed, thus protecting the engine from acidic related wear.

The composite performance of effective soot removal and overbase protection opens a new chapter in extended or indefinite life lubrication oil and oil filtration on diesel engines. As this technology matures and is accepted in diesel applications across military and civilian industries, the costs associated with overall vehicle maintenance will be significantly reduced.

Introduction

In 2001 AEI embarked on the development of a lifetime filter for the HMMWV for the US Army. The goals for this development program were to employ the use of ultrafiltration technologies that could be packaged into an envelope capable of transparent replacement of the existing oil filter on the AM General vehicle. It was to be installed by field mechanics and never removed over the normal lifetime of the vehicle. Additionally, the following criteria were established as goals:

1. Full flow and bypass functionality in one package
2. Oil pressure activated – no electric function or direct mechanical power from the engine
3. Soot level maintenance below 0.5% over lifetime
4. Less than 2 psi rifle (gallery) pressure reduction at all operating conditions

5. Integrate overbase alkalinity reserve capability
6. Provide equivalent or better durability performance to existing barrier filter
7. Sealed from water or atmosphere
8. Compatible with all vehicle operational capabilities (i.e., angularity requirements)
9. Non-mission disabling in the case of filter failure

The HMMWV vehicle employs the use of a horizontally configured spin on filter as is shown in Figure 2. While this design performs well as a full flow spin on filter, it introduces several challenges for application of a centrifugal element. Package constraints required that the new filter system be approximately cylindrical with only slightly larger outside diameter. Some allowance could be made for additional length but only through increased mechanical loading on the spin-on filter head.

Figure 2: HMMWV Spin On Filter Configuration

Initial concepts and iterations for a spin on replacement design included a horizontally stacked configuration. This concept provided the optimum collection of attributes that satisfied goal criteria set forth in the beginning of the Phase I work. The energy needed for the centrifuge rotation would come from an optimized pelton based turbine and a directed jet of pressurized engine oil.

Turbine Design

The world of converting fluid energy into rotational energy almost always involves a pelton turbine. These types of impulse turbines are used exclusively in hydroelectric generating facilities. While these wheels range from 12 inches diameter to over 33 feet in diameter, they share an almost identical design.

That which separates this application from hydroelectric peltons, is the shaft rotational speed. For big wheels, the wheel speed seldom exceeds 1000 rpm. For the filter application, a shaft speed approaching 10,000 rpm is desired for optimum performance. Therefore, the design is very important not only for the turbine but also for the nozzle. Figure 3 illustrates an early design for the high speed pelton. Solids modeling design is used extensively in the design of complex turbines.

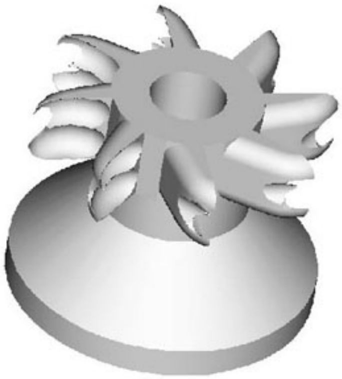

Figure 3: Early Pelton Wheel Turbine Design

The pure pelton design has a few advantages and some disadvantages. Key advantages are that the nozzle jet is directed directly at the blade without any vertical angle. This provides improved efficiency because none of the jet energy is lost in a vertical vector component. Conversely, the fluid that strikes the blade then exits does so both above and below the blade. When the turbine is mechanically affixed to the rotating can as seen in Figure 4, a significant amount of fluid strikes the rotating element, resulting in viscous losses and subsequently poor speed performance.

Figure 4: Pelton Wheel and Rotating Element Configuration

Modified Axial Impulse Turbine Design

Research in the early stages of development indicated that the modified axial design would achieve the highest angular velocity, despite the fact that literature studies suggested the opposite. It has become evident that most if not all of the published research on hydraulic turbines has focused on slow speed applications to maximize horsepower and not velocity. Therefore, several of the assumptions and design guidelines from the literature are not applicable to the high-speed designs necessary for soot removal.

Over the course of several months, AEI engineers iterated on several turbine designs in order to achieve the highest performance nozzle / turbine combination possible. Computational fluid dynamics models were generated in order to optimize nozzle configurations. Departures from published literature were observed on many instances during the turbine development. As turbine speeds approach 10,000 rpm, influences from splash, windage and viscous losses greatly contribute to parasitic power losses in the overall system. In Figure 5, four mini-hydraulic turbines are shown.

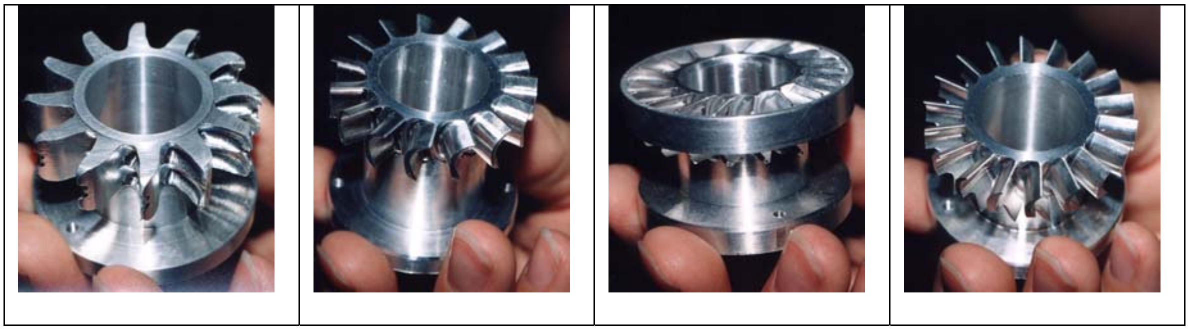

Figure 5: Examples of Modified Pelton and Axial Impulse Turbines

Initial Prototype System

Figure 6: Efficiency Testing and Rapid Prototyping of Turbines at AEI

Lube system pressure at nominal operating temperature is between 35 and 45 psi above idle. The sump capacity of the vehicle is between 7-9 liters depending on vintage, engine displacement and dipstick safe range. A substantial effort was implemented early in the design in order to achieve the smallest pressure drop across the overall system in order to assure a vehicle-transparent replacement of the current filer assembly. This is a significant challenge due to the requirement to aspirate the turbine activation flow back into the full flow gallery. The venturi design and pressure recovery strategy are key to the successful implementation of this design.

A primary design criterion for the centrifugal element is that it achieve a higher soot, and other particulate matter removal rate, than the nominal contamination rate seen in the field from vehicle populations, thereby maintaining the oil in a constant 'clean' state. This fundamental requirement is the key feature that will greatly extend or provide for lifetime filtration with exceptionally increased engine durability performance. Additionally, with a higher performance bypass (centrifugal) element, the full flow capacity requirement is reduced, thus improving pressure drop throughout the operational life of the vehicle.

The anticipated average soot contamination rate, based on previous testing, is approximately from 0.001 weight percent per hour of operation to a maximum anticipated rate of 0.005% per hour. The average rate, based on engine duty cycle falls at approximately 0.002%. The target removal rate for the centrifugal element is 0.003% per hour during nominal above idle operation and warm temperatures, thus the nominal operational soot concentrations in the sump will be maintained at target or lower levels.

Cold start performance of the lubricant system is an important consideration. The full flow element was designed to provide sufficient surface area, combined with minimal restriction to insure adequate lubricant flow under cold start, using an SAE 40 oil specification as a worst-case example. Microglass media, the basic component material of the full flow section, will greatly enhance cold start performance over conventional filters, due to the inherently exceptional capacity / restriction performance of the cloth.

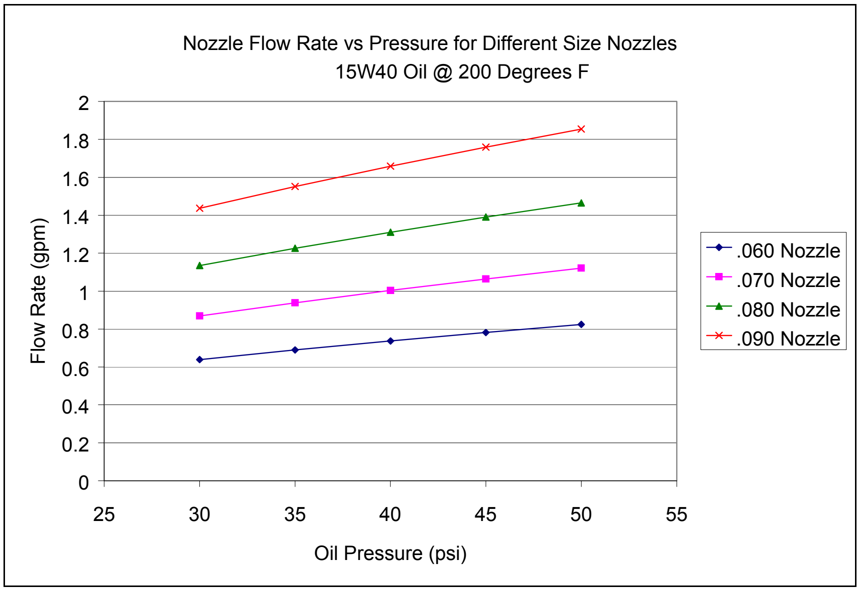

Figure 7: Nozzle Flow Rate plotted against Pressure

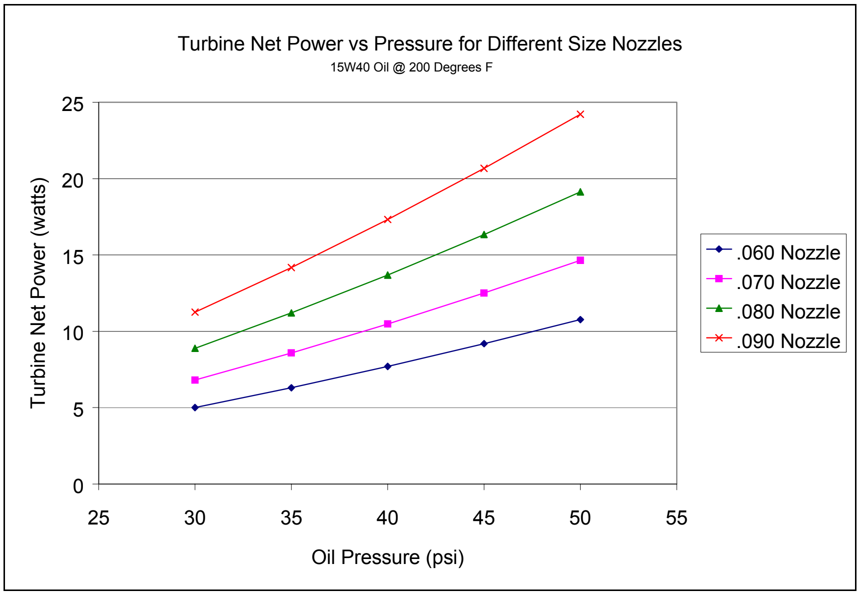

Figure 8: Turbine Net power plotted against Pressure for Varying Nozzle Sizes

From Figure 9 it can be seen that an applied power of approximately 8-12 watts will result in rotor speeds of between 8000 – 9000 rpm. Once this model was completed, the next key element of the design was to establish the turbine pitch diameter. In general, larger pitch diameters provide better starting torque but lower terminal speed for a given oil pressure.

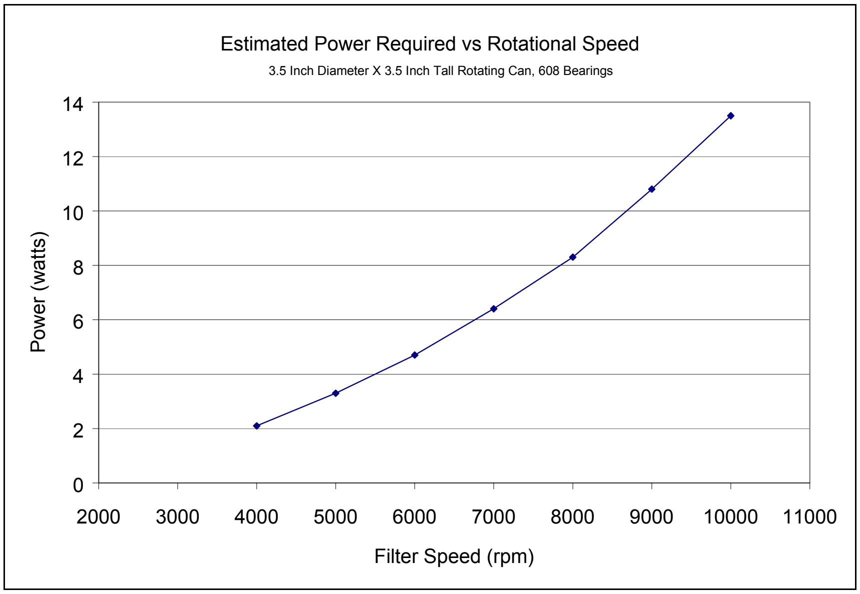

Figure 9: Power and Speed

Figure 10 shows the maximum efficiency speed as a function of applied oil pressure for a set of turbines. The 1.10 inch pitch diameter turbine provides the best efficiency speed over the determined operating ranges. However, a significant concern about starting torque was identified – especially in light of the horizontal configuration for this filter.

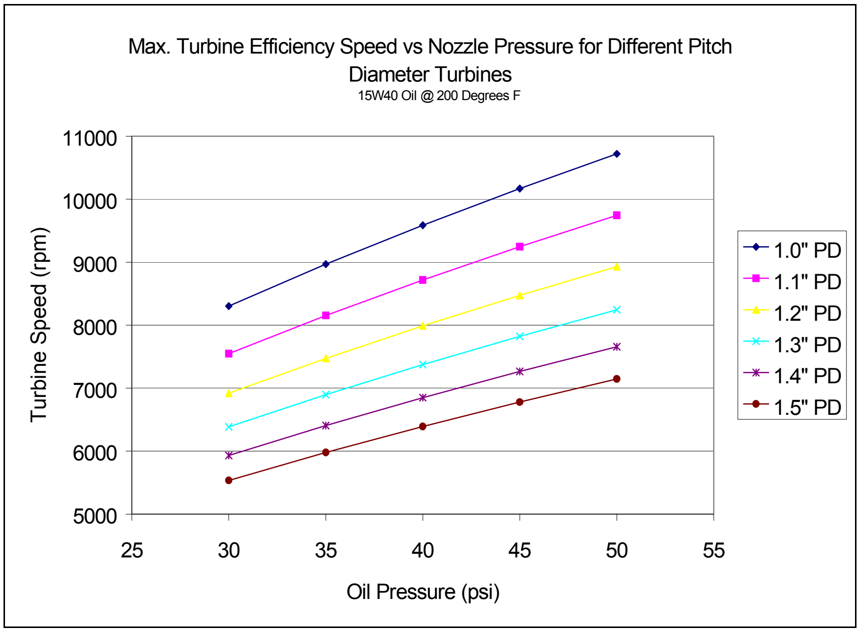

Figure 10: Efficiency vs. Nozzle Pressure

A model was constructed to identify the required starting torque for the intended rotor at operating conditions. 0.02 lb-ft starting torque was calculated from previous experimental data, and a set of pitch diameters was studied. Figure 11 shows starting torque as a function of applied oil pressure for several pitch diameters.

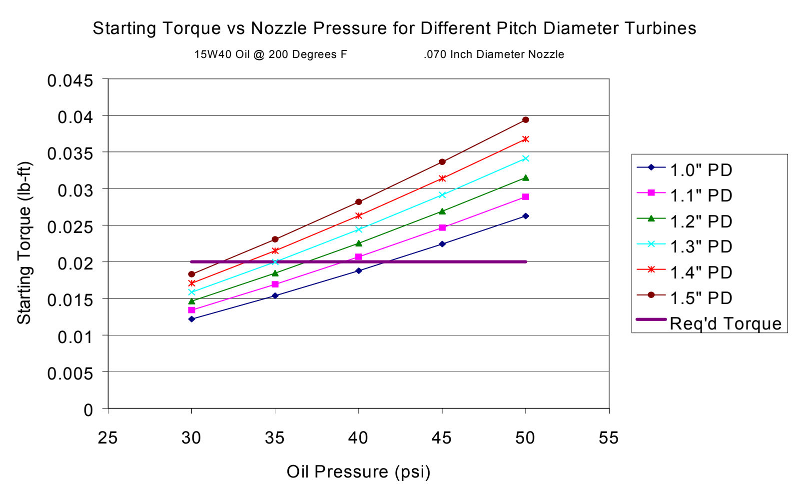

Figure 11: Starting Torque vs. Pitch Diameter

From this graph, it is seen that the 1.1 pitch diameter system may be insufficient for reliable starting. A decision was made to increase the pitch diameter to 1.2 in order to achieve the best compromise between best efficiency, highest speed, and starting torque. It can be seen from the same graph that the 1.2 pitch diameter system will reliably start when the engine speed increases above idle.

By returning back to the nozzle models, it was shown that the 1.2 inch pitch diameter turbine system would work well with the 0.070 inch diameter nozzle. It was therefore confirmed from this model work that the overall system would be based on a 1.2 inch pitch diameter, 0.070 inch nozzle and that the system will consume approximately 1.0 gallons per minute oil flow rate. The results of the computational model are shown in Figure 12.

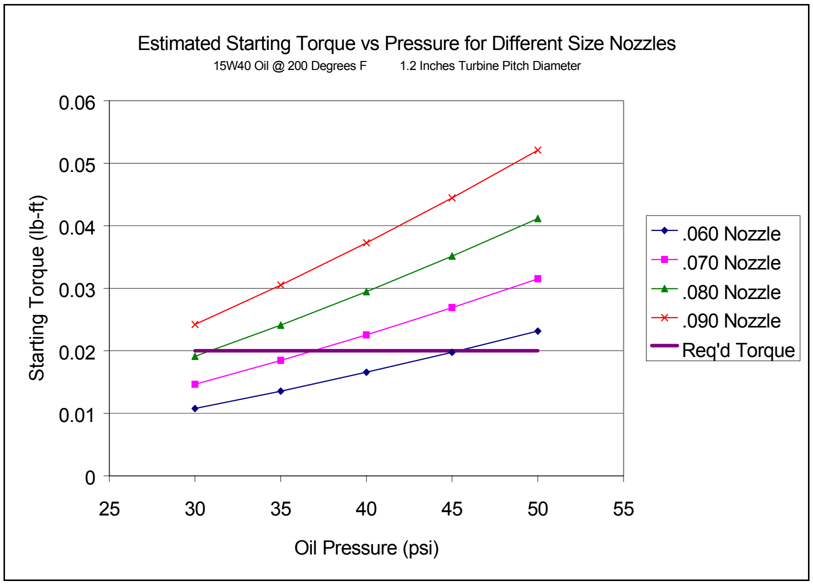

Figure 12: Starting Torque vs. Nozzle Size

A significant portion of the work performed to date in the Phase II effort has been focused on the component design and machining. Optimum designs were made based on experience to date through the Phase I effort and other research programs currently underway at AEI. Based on envelope specifications, the centrifugal portion of the overall filter has been designed and the first prototype pieces have been made. Figure 13 shows the design for the compete assembly.

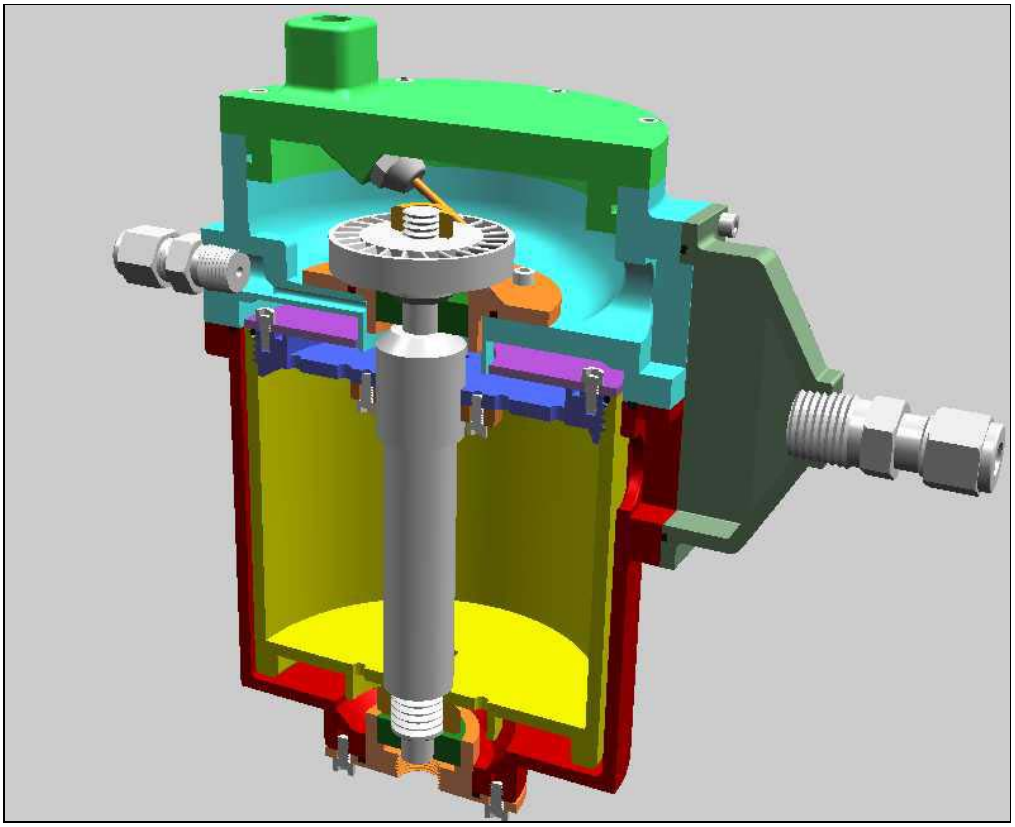

Figure 13: Solid Model of the Centrifugal Section

This new design is a derivative design from work done in Phase I. The rotating element is supported by two bearings. The turbine resides in a protected location and the spent oil from the nozzle / turbine is collected in a small sump. The oil is aspirated from the sump via the venturi.

From this fundamental design, each of the subcomponents were optimized, designed with solids modeling and evaluated. Following engineering evaluation, changes to the model were made and the parts were machined. Where possible, direct model transfer was made to the machine shop and CAM was used to calculate machine tool paths. Figure 14 shows an example of the CAM process in the machining facility.

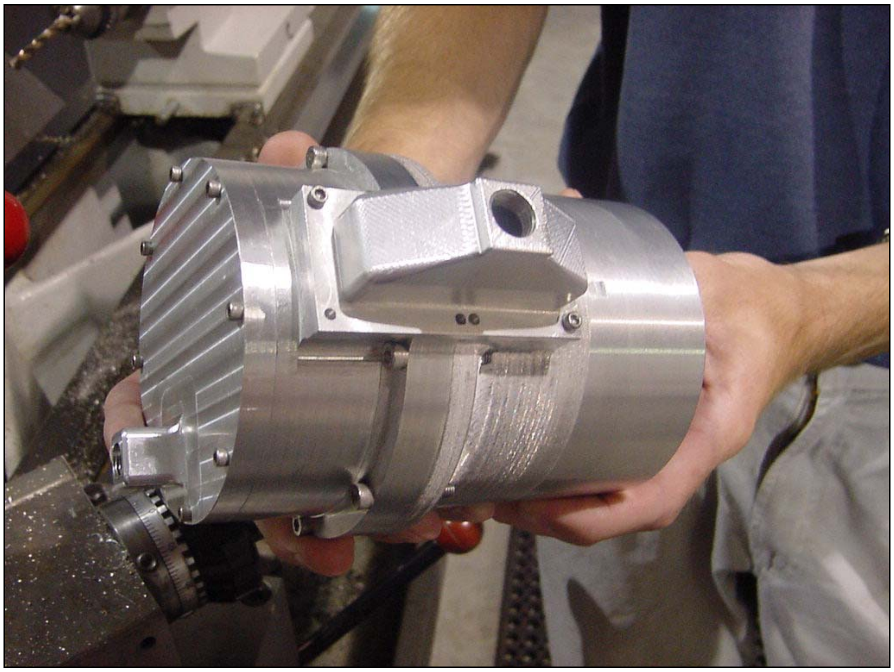

Figure 14: CAM process in Machining Facility

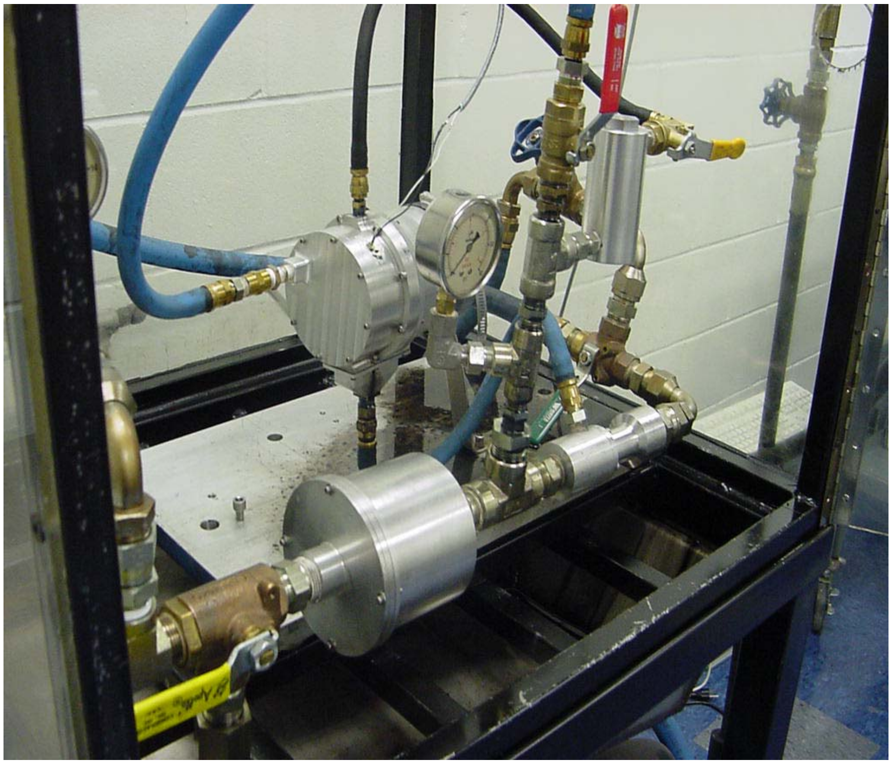

Figure 15: Centrifugal Filter Test Rig

Prototype I was installed in a filter test rig, Figure 15, that was constructed to closely simulate the engine installation on the HMMWV. The orientation of the components, the sump size, and the temperature and pressure of the oil are all controlled to approximate HMMWV operating conditions. This allowed for very representative testing of the performance parameters.

Soot removal is the basic performance parameter used to determine filtration efficiency. Previous testing has demonstrated that soot is the most difficult particulate to remove from the oil, so successful filtration of soot indicated successful filtration of all particulate matter. When soot is being removed at an acceptable rate, then it is projected that all other contaminants are being removed at an acceptable rate. The soot removal rate for Prototype I was between 0.002%/hr and 0.003%/hr for a bulk soot percentage of 1%. This is slightly above the anticipated soot loading for the Hummer, so the current Prototype I filtration efficiency is considered acceptable.

The rotational speed achieved during testing, 6,000 rpm, was below the expected speed of 7,500 rpm, however, the soot removal was acceptable. It was noticed that with the oil supply to the centrifugal filter element shut off, the speed of the filter increased significantly. It was therefore surmised that oil was splashing on the centrifugal rotor and causing parasitic drag, decreasing filter rotational speed. An oil shield was constructed and installed to correct this problem, and it did result in higher rotational speeds, 6,800 rpm, than without the shield. Further changes to reduce the possibility of oil splash on the rotating filter may be warranted.

Starting capability was another element of filter performance which was tested. The ability of the horizontal shaft filter powered by a turning to start rotating from rest when full of oil was an initial concern. This scenario was modeled as described in the previous report, but Prototype I was the first test of how close the model came to the actual performance. It was discovered that from rest, with no external forces acting on the filter, the filter required in excess of 55psi nozzle pressure to start with 200 °F oil. If the filter was vibrated to simulate being installed on a running Hummer, the filter would start at pressures between 45 and 50psi. In order to improve the starting capability of the filter, a larger pitch diameter turbine may be considered.

The Prototype I venturi, Figures 16 and 17, worked very well as installed in the filter test rig with no backpressure imposed on the outlet. The aspiration capacity was more than adequate to evacuate the nozzle flow and the filter flow, and the cold oil performance was better than the previous design from phase I. However, when backpressure was imposed on the outlet of the venturi to simulate the presence of an engine lubrication system, the venturi performance suffered greatly, to the point that it would not aspirate oil at all. A revised design is currently underway to correct this problem.

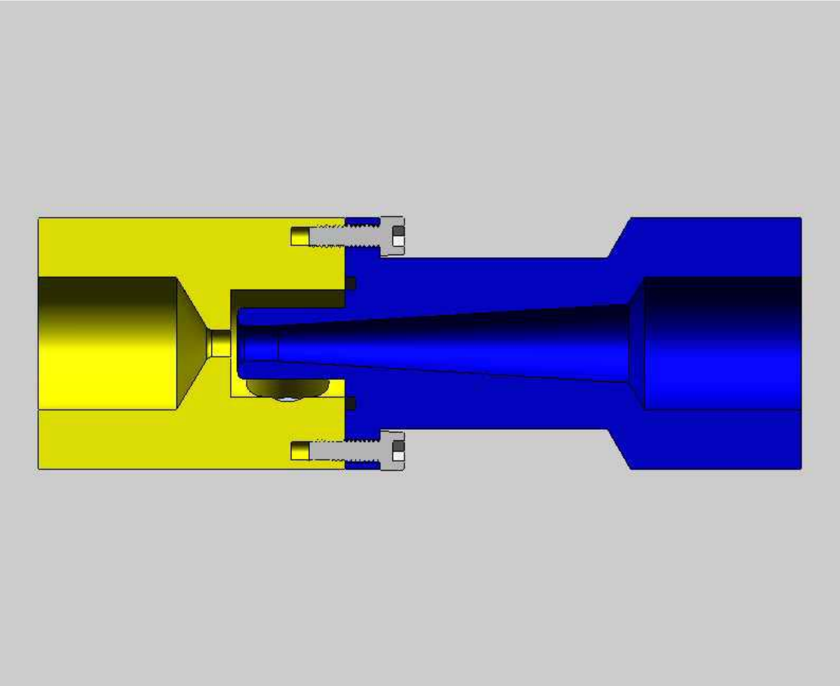

Figure 16: Prototype 1 Venturi 3D Solids Model

Figure 17: Fabricated Prototype 1 Venturi

The flow restrictor is used to supply a controlled flow of oil to the centrifugal bypass section of the filter. It is designed to provide very low oil flow, (.015gpm), at high pressures, (45psi), under all engine operational conditions, without plugging. This is accomplished by using a very long passage of low cross sectional area to obtain the right amount of head loss due to friction. The passage consists of a threaded connection between a housing and screw with a controlled clearance of triangular shape between the minor diameter of the housing and the minor diameter of the screw as shown in Figure 18 (inlet flow restrictor). This design is very compact, yet provides a very long helical passage of sufficient flow area to eliminate plugging as a problem, while at the same time providing adequate restriction from friction losses.

The flow restrictor is the critical component controlling oil residence time inside the centrifugal filter section. Experiments have demonstrated that 600 seconds is the optimum time for effective filtration, and this is achieved by maintaining a controlled feed of oil at .015gpm. The current flow restrictor design has fulfilled all the design criteria objectives, and functioned flawlessly throughout testing.

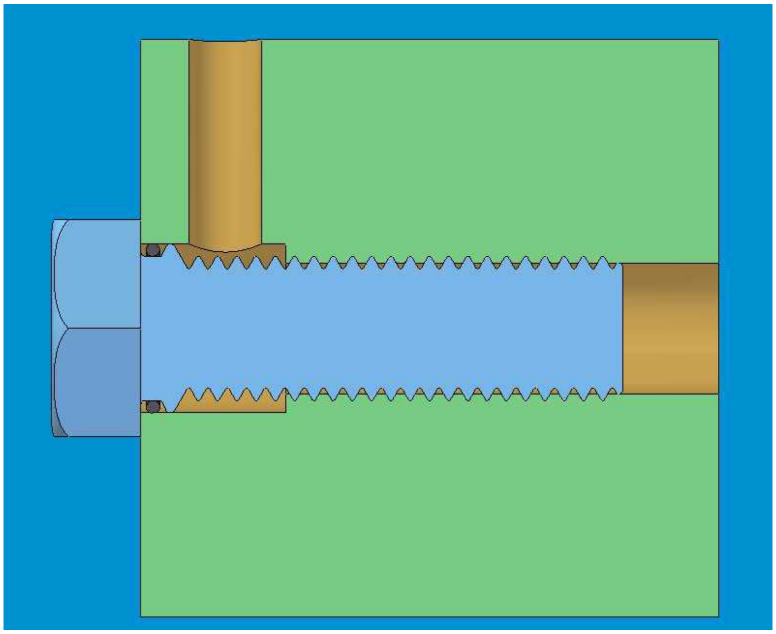

Figure 18: Inlet Flow Restrictor

Revision 18 of the Prototype I venturi design, seen in Figure 19, is a modification to revision 17. The diameter of the throat was further increased in this iteration. The aspiration and backpressure performance of this venturi is shown in Figures 20 and 21.

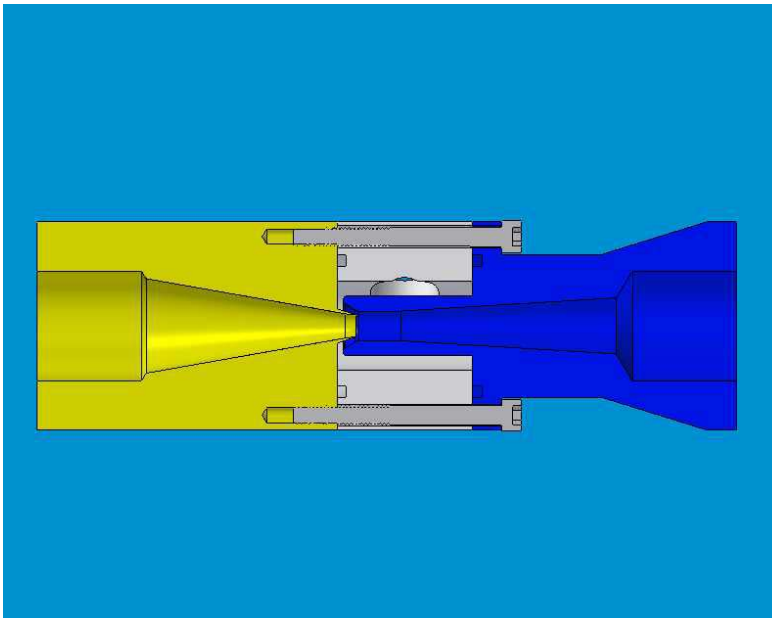

Figure 19: Revision 18 of Venturi Prototype I

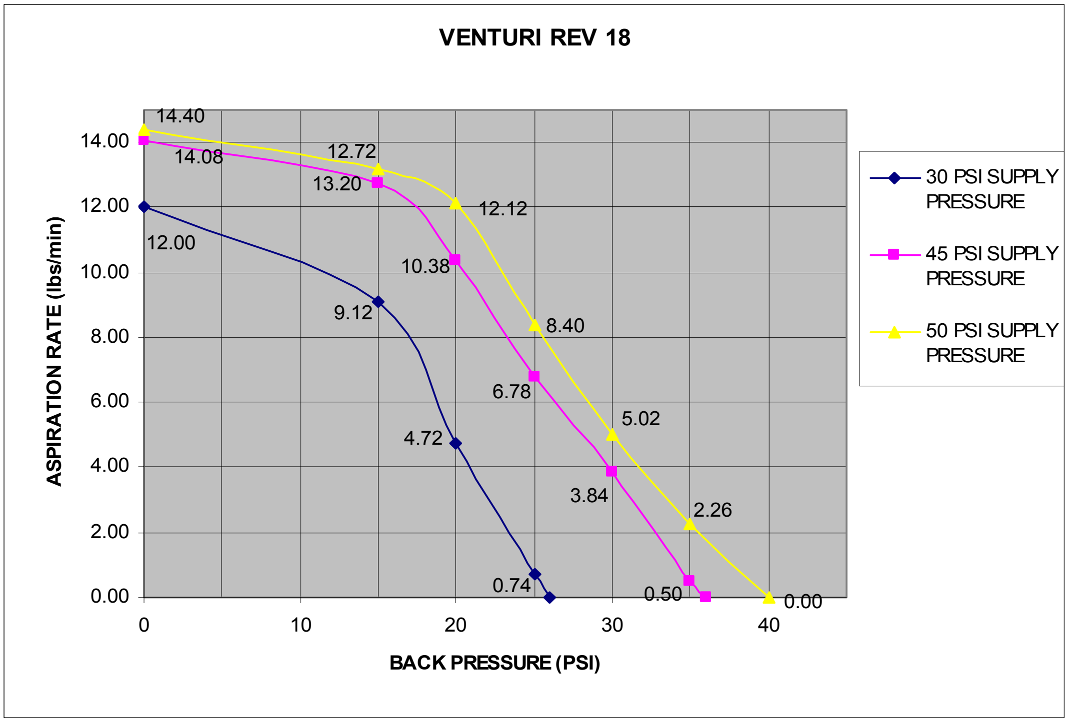

Figure 20: Venturi Revision 18 Aspiration plotted against Backpressure

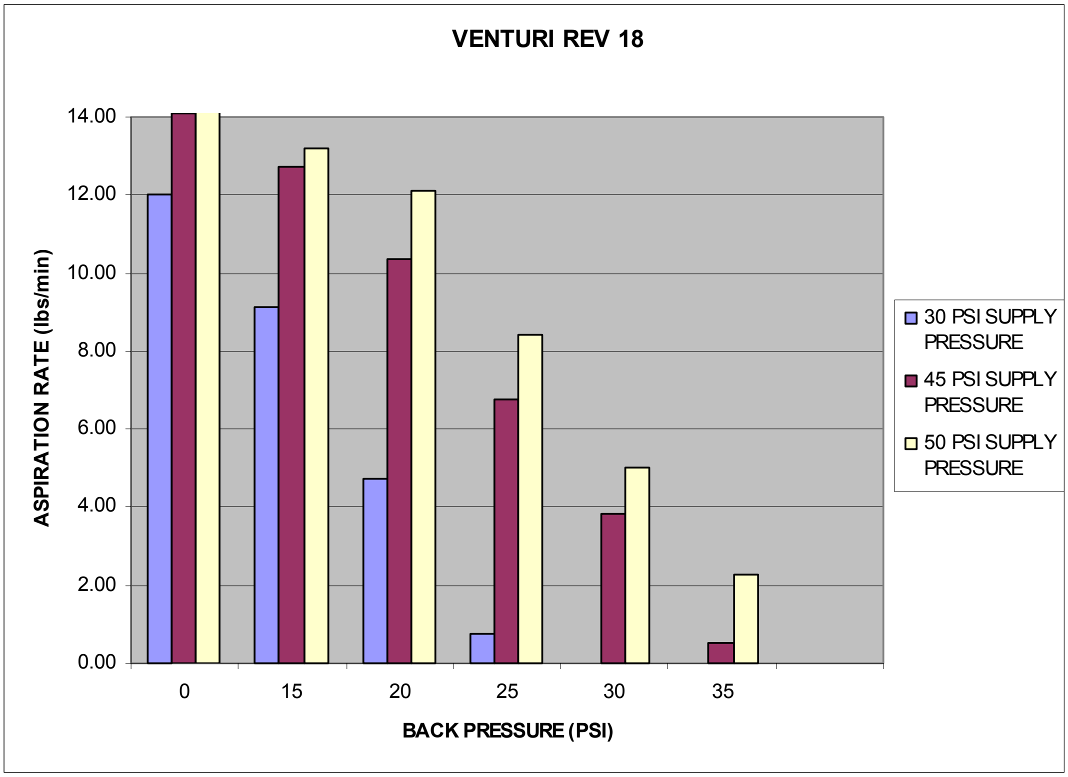

Figure 21: Venture Revision 18 Aspiration and Backpressure Performance

Top Mount Filter Design

To address the issues associated with insufficient drainage with the under-vehicle full flow and bypass filter configuration, a new iteration was designed and built. In the latest design, the filter assembly is mounted inside the hood location on an inside body panel. This chassis mount design takes advantage of greatly enhanced gravity drainage for the turbine activation oil and restored oil (centrifugate). This completely eliminates the need for a venturi based aspirator for the activation oil, thus it significantly reduces the pressure drop in rifle oil pressure. Figure 22 shows the solids model design of the filter assembly including the full flow and bypass sections.

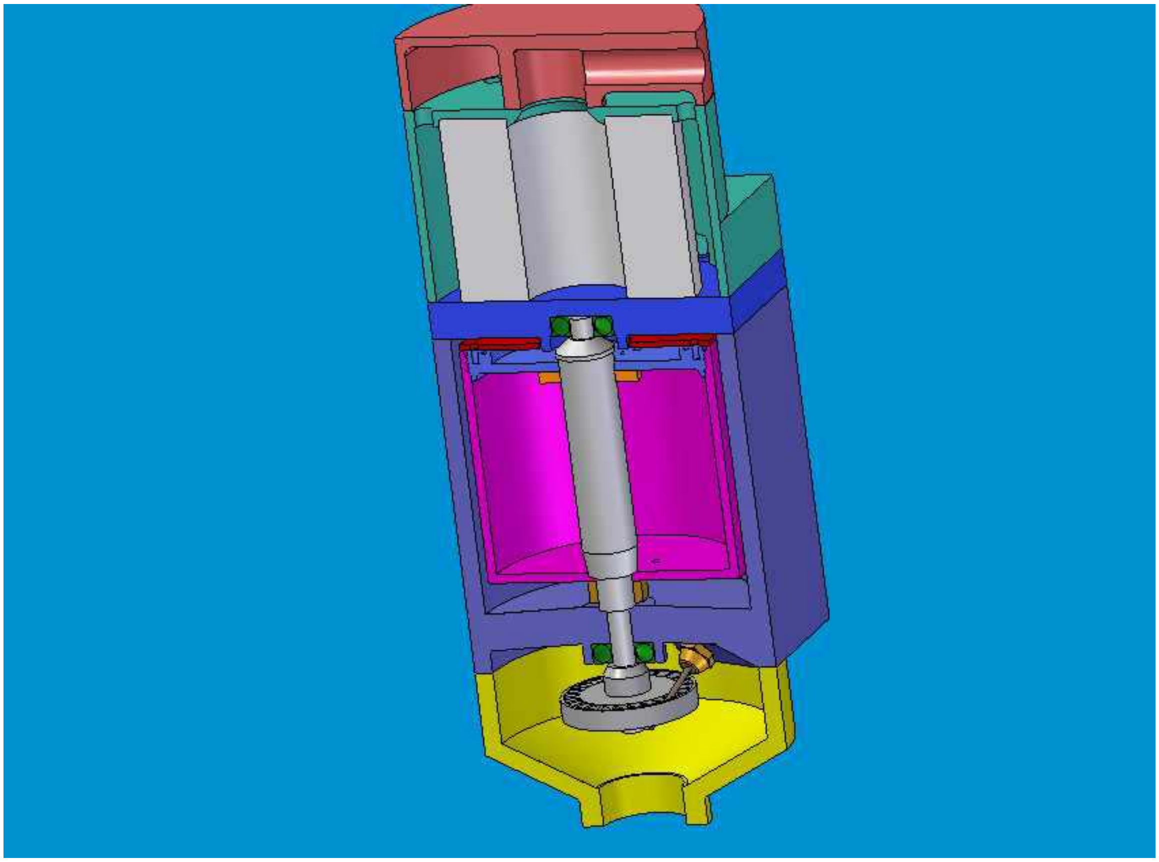

Figure 22: Top Mount Filter Design

In this design, the turbine now resides below the centrifugal section and the full flow section is on top. This stack-up configuration offers several advantages, but the primary benefit stems from the bottom located turbine housing. The turbine gallery is the location where most of the turbine / oil interaction occurs and that which needs the best gravitational draining efficiency. By locating the turbine gallery on the bottom location, a highly efficient drainage funnel can be designed onto the bottom, thus optimizing drainage and splash prevention. This feature also improves cold performance because it allows for the turbine to accelerate at cooler temperatures, thus achieving removal at cooler temperatures.

The rotating element is filled with a spiral wrap material similarly to that which was done in earlier generations. Centrifuge capacity from earlier revisions was determined to be sufficient for most HMMWV life duty cycles, thus it was kept the same. The top of the assembly houses the full flow section of the filter. The center location of the full flow section contains a solid pellet of active additive replacement. A wire mesh support is used to hold a micro filament fiberglass element media. This combination of efficiency and capacity are needed to provide lifetime capacity along with pressure drop performance in most conditions.

Figure 23 and Figure 24 show the machined prototype. Material construction of the prototype is 6061 aluminum and it was machined from billet. It is anticipated that production manufacturing for the housing will be diecast aluminum. Shaft material is Fatigue Proof® steel, although production will likely utilize a lower cost steel.

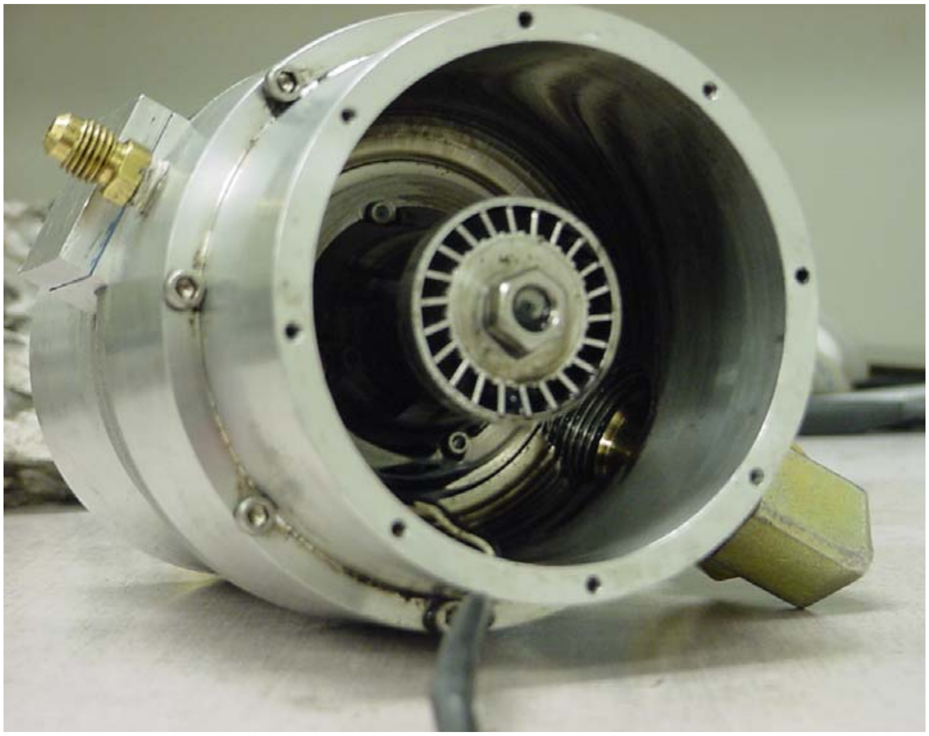

Figure 23: Machined Prototype

Figure 24: Machined Protoype

Plumbing Arrangement

The remote mount filter requires three hoses. For the purpose of simplicity, the filter head is replaced with a manifold that routes oil from the pump directly to the filter assembly and back to the engine rifle. The third hose is used as a gravity drain for activation oil and restored oil back to the engine sump. Installation and installed filter system are illustrated in Figures 25, 26, and 27

Figure 25: Filter Installation on Hummer Vehicle Platform

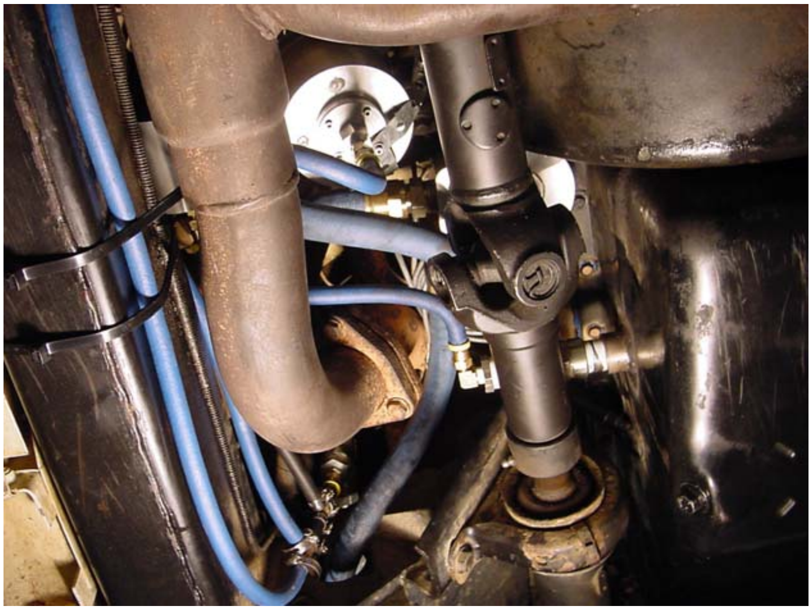

Figure 26: Filter Plumbing Arrangement

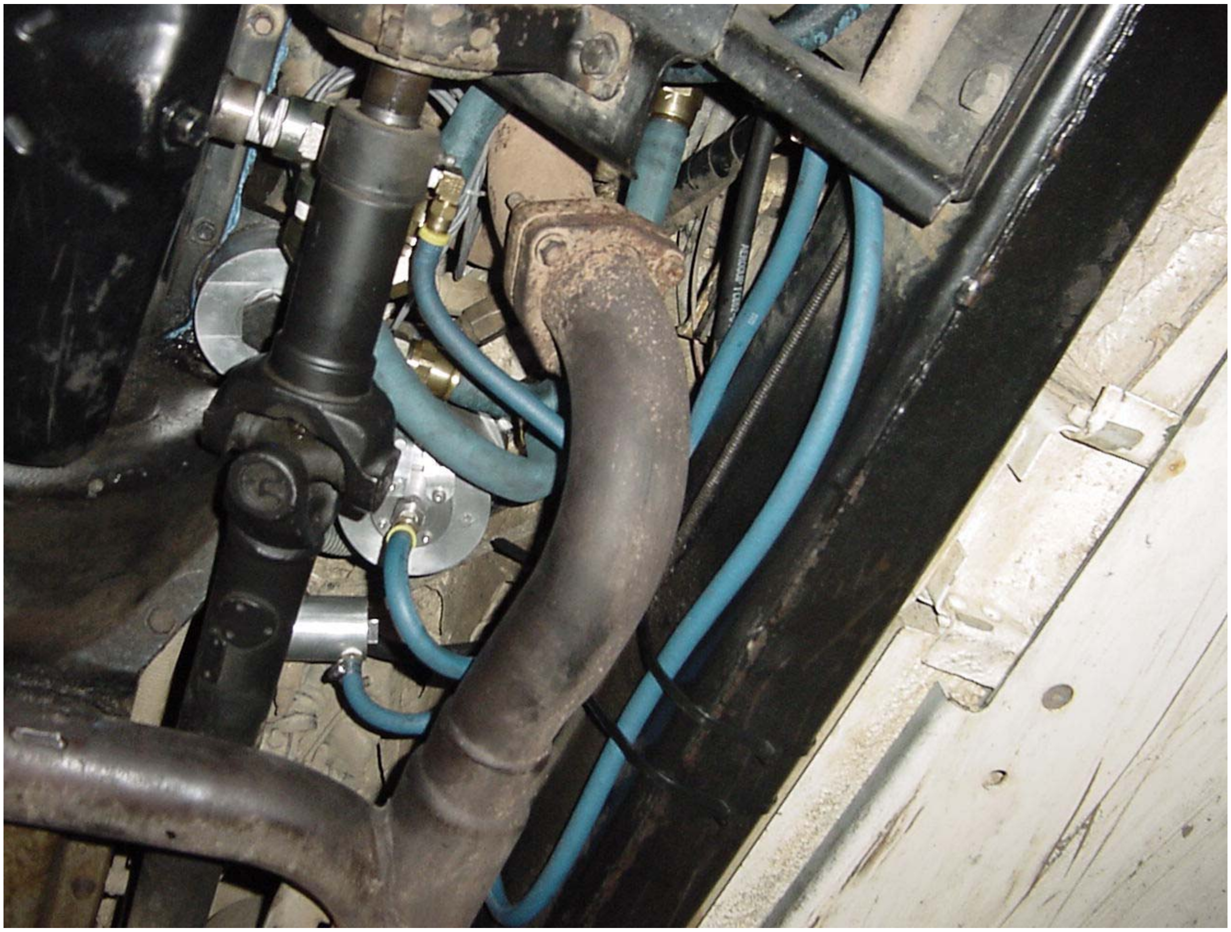

Figure 27: Filter installed in the Hummer Vehicle

Performance

The top mount filter design is undergoing testing and evaluation as this paper is being prepared. This information will be presented at the conference, and an attachment will be prepared for addition to this paper.

Electric Filter

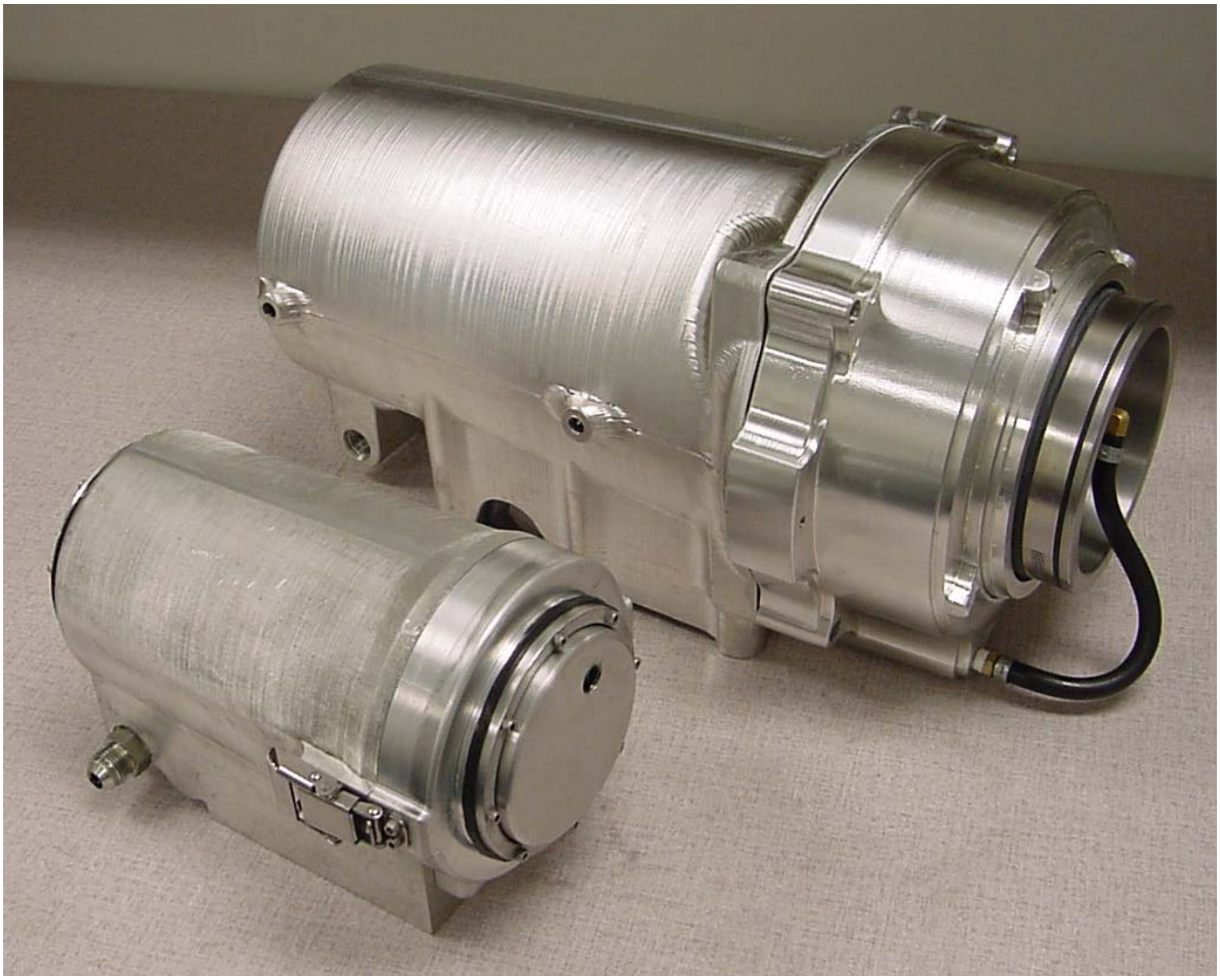

Figure 28: Large and Small Platform Smart Filters

Concurrent to HMMWV lifetime filter development at AEI, two related filter types were being developed. These two filters fall into a category referred to as “smart filters” and “cross platform compatible” filters. Figure 28 shows functional prototypes of both filters.

Both of these filters are based on the use of a highly efficient electric motor to power the ultracentrifuge. These bypass filter systems provide particle separation from liquid media. Like the HMMWV filter, oil and soot residence times are carefully controlled to optimize particle removal down to the smallest soot particles.

The heart of the system is a microprocessor based motor control and brushless DC motor. The motor control can be harnessed to the engine ECM and vehicle data link and/or CAN bus. With this capability, the filter is able to regulate rotor speeds as a function of vehicle operation, duty cycle, temperatures, battery voltage, oil soot level, filter rotor life and a host of other programmable features. Additionally, by calculating rotor acceleration, the degree to which the rotor is full of solid soot can be determined, thus enunciation capability exists. The microprocessor continuously monitors the motor and electronics to detect over and under temperature to effect countermeasures before damage to the motor.

Cross Platform Compatibility

The smart filter can be applied onto practically any diesel or natural gas engine, hydraulic system, industrial machining system or any other application that requires optimum small particle removal. Due to the very low oil flow requirement (i.e., approx 0.5 gpm), the filter can be applied to very large and/or very small powerplants. The filter requires 12, 24, 48 volts DC or with an auxiliary module it can be powered from 120-220 VAC. These features allow for the filter system to be applied into a broad range of applications and onto a large range of engines and vehicles without changes to the fundamental system. The controller can be field programmed in minutes, thus customization to a particular application is done electronically.

Target Markets

The larger filter is sized for application onto larger diesel powered vehicles such as Class 7 and 8 trucks, off-road construction equipment, generators, pumps etc. Normally, a single unit can provide exceptional bypass protection up to approximately 1000 horsepower. For larger engines, multiple systems can be paralleled.

AVT-109
Specialist Meeting on the Control and Reduction of Wear in Military Platforms

Summary of Discussion Sessions

The following presents a summary of the discussion of papers presented in the various sessions of the workshop. Only questions where the authors provided transcripts of their answers are reported.

Session 2 – Reciprocating Engines and Lubrication Systems
Chair: Ernest Chin, Army Research Laboratory, United States

Paper MP-AVT-109-8

Prof. John Nicholls, Cranfield University, UK

Q. How robust is the fitter system to wear debris?

Dr. Barry Czachura, TACOM-TARDEC, USA

A. All oil passes through a coarse, glass media, full flow filter prior to reaching the centrifugal section of the system. The only potential points of wear is the turbine section and this has been subjected to very high soot concentrations (5%+) for durability tests of 500 hours plus, without any sign of adverse wear. By use of the full flow filter, risk to the centrifugal section is expected to be very low, thus the filter is very durable and resistive to wear damage.

Dr. M. Woydt, FIMRT, Germany

Q. What is the particle size of the soot?

Dr. Barry Czachura, TACOM-TARDEC, USA

A. The primary particle size range from 40-100nm, but agglomerates can reach 1-8µm